Exploring the Neurocognitive Spectrum of Users' Information Needs in the Information Retrieval Domain

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

A body of *NeuraSearch* literature, comprised of interdisciplinary user-based investigations between Information Retrieval (IR) and Neuroscience, is growing. This research's novel perspective is driven by the increasing accessibility and applicability of neuroimaging techniques to objectively capture and understand the neurocognitive manifestations subserving the user's information search behaviours. One such is the complex concept of Information Need (IN). Given its fundamental role as a mental perception of the user's information anomaly that the user needs to resolve and the user's trigger to engage in search, it is timely to deepen the understanding of the origin of INs. The NeuraSearch perspective comes into place to explore the cognitive mechanisms behind the realisation of INs, which would be using the traditional techniques of user-based IR research not viable.

This thesis, in particular, explores the user's cognitive context utilising the paradigms of cognitive mechanisms to indicate different states of knowledge, analyses types of knowledge anomalies and discusses their implications on user search behaviour and expectations. Our enquiry is inspired by the theoretical IR concept of various user levels of knowledge supporting different variants of anomalies (i.e., insufficiencies) in the knowledge. Moreover, the functional framework of knowledge, memory and cognition synergies the user's informativeness about their current capabilities and, thus, shows potential in addressing the variants of INs in the IR context.

In summary, this thesis presents a series of investigations sourcing from a lab-based study modelled as an interactive textual Question-Answering scenario. The textual stimuli were controlled to evoke the information processing subserving the user's cognitive memory search. We acquired two categories of data from twenty-four (24) participants: 1) the behavioural data that describe subjects' interactions with the system and their responses and 2) the simultaneously acquired cortical activity of the same subjects using the Electroencephalography (EEG) technique associated with the outcomes of behavioural responses.

We aimed at two factors of neurocognitive memory mechanisms which offer different perspectives on the knowledge capabilities of the user. First, we approached the metamemory, which refers to the user's introspective epistemic feelings with the prospective (future) quality of knowing. Second, we approached the associated concept of memory retrieval to emphasise the user's ability to retrieve factual knowledge involving a more in-depth memory search. In addition, we accounted for a modality of memories in interaction with the variability of the user's subjective confidence, potentially impacting a further decomposition of memories and indicating an affiliation to INs. We also constructed a data-driven analytical framework and conducted a quantitative analysis of Event Related Potentials (ERP) components, namely N1, P2, N400, and P6. These were found to be activated over the timeline of information processing to obtain significant spatio-temporal differences between the levels of these factors and their interactivity.

In the light of the current understanding of the user's cognitive context in IR, this research aims to increase the informativeness about the variability of the perceived states of knowledge regarding INs by providing the evidence about their associated significant neurophysiological signatures and detectability in the brain. In addition, we used the links of ERP with cognitive operations to construct the qualitative models subserving the significant differences between particular levels of these factors.

Overall, the contribution of the research presented in the current thesis is twofold. Firstly, it provides a multidisciplinary view on the metamnemonic and mnemonic drivers of INs, not addressed to date, by developing a comprehensive framework that can advance the understanding of the behaviours linked to INs and the associated neural mechanisms. Secondly, it contributes towards the evaluation of objective user signals and reflects on their applicability in the domain of IR, for example proactive IR systems.

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List of Abbreviations

BCI	Brain Computer Interfaces
dDTW	derivative Dynamic Time Warping
EEG	Electroencephalography
ERP	Event Related Potentials
fMRI	functional Magnetic Resonance Imaging
FOK	Feeling-of-Knowing
HCI	Human Computer Interaction
HIB	Human Information Behaviour
IIR	Interactive Information Retrieval
IN/INs	Information Need/Information Needs
IR	Information Retrieval
IS	Information Seeking and Search
IS&R	Information Search & Retrieval
LIS	Library Information Systems
MR	Memory Retrieval
Q/A	Question/Answering
RJR	Recall-Judgment-Recognition
RCJ	Retrospective Confidence Judgments

ROI/ROIs Region/Regions of Interest

SERP Search Engine Result Page

UI User Interface

Part I

Thesis Outline, Background, Methodology

Chapter 1

Introduction

Information is necessary for a person's educational and personal development. Information has transformed us into personalities formed by the knowledge the information carries. In order to attain a level of functioning in our daily life and fulfilling our higher aims and desires, we manifest the need for information. In the context of information sources, this need is recognised as a fundamental factor providing valuable insight into the user's behaviour behind the localisation of the sought-out information. The present thesis will utilise perspectives from Information Science and Information Retrieval (IR), where the information need (IN) is notably researched as a standalone concept.

When we attempt to describe IN, we intuitively arrive at the idea that information is needed to commit to its intended purpose. The "need" is a term delineating the human as the subject who manifests the need. In the context of the information systems and other providers of information, they are known as users. They subjectively judge the outcome of the retrieval, whether satisfactory or not.

The user sets out criteria for information that satisfies their IN, following the contextual variables of the situation the IN arose in. These define IN dimensions, such as purpose, span, urgency, and impact, evaluated as user preferences and criteria to solve the need. Coupled with the notion that INs are subjective and alter with the carrier of IN, different criteria also cause differences in the final information product. From the IN perspective, impact and purpose are defined with respect to the information in question and how the information contributes to a resolution of a purpose. The scale of the impact alters with the purpose, and the scale of the purpose alters with the impact. Nonetheless, it is still the perceived IN that sets off the action of information seeking.

In the first place, the role of any information system is to equip the user with the right information, according to the user's description of IN, acting as the means to construct the satisfaction of the problem. Early system-centric developments resulted in early prototypes of automated systems searching for the information within the data collections [1]. Their true potential was exploited by incorporating the user as an added factor in the process. Moreover, it is the user who, in the end, judges the system's performance efficacy and interacts with the system. However, meeting users' ever-growing requirements and needs leads to barriers and issues appearing. As the computer technology is known to push the boundaries of what could be done at the time, the demand for sophisticated methods and applications expanding the capabilities of IR systems grows even more.

With online information at hand, the extensive use of information search and browsing became a pervasive human activity. Also, it remarkably contributed to transforming the ways of working, with a notable example being e-learning. As an effect of the ubiquitous nature of information, the users rely on external information sources just by knowing that the information is "somewhere online" available. From the perspective of IR, the fundamental goal did not change but is all the more relevant with the excessive space of information sources. On the top level of the IR objectives are the mechanisms of obtaining the relevant information for the user, i.e. getting a perfect information match to the user's IN. The advances in technology and the increase in the magnitude of information sources shifted the focus of IR systems towards the effectiveness of information delivery. Effectivity is, however, not a one-way product. To enhance this quality in the search process, IR needs cooperation from the user in terms of defining their INs. Again, this quality conforms to the vital role of the user.

Either a company executive needs to decide on an important enterprise-wide strategy or a biographical author needs accurate facts about the subject's childhood, or a mother in need of a set of ingredients to make a cake for her child's birthday. Regardless of their situational difference, these sample examples demonstrate the diversity of the purpose behind INs and the scale of the information impact as well. These factors contribute to the complex and faceted nature of INs. Nevertheless, the overarching intent of INs remains the same for any scenario, and that is to complement and modulate what we already know by developing a more coherent picture of the world [2]. However, the most critical element is the users themselves, as the carriers of INs. Mainly query, a construct to obtain the information from any IR system, is highly dependent upon the users' formulation of their IN. According to Belkin et al. [3], the query reflects the user's anomalous internal state of knowledge that brought the user to search in the first place.

This goal rests on the need for the user to figure out what they need to know in the context of their situation. In order to understand what is needed, the users direct their attention to what they already know [4] and how a piece of new information would fit within what they already know [5]. This premise creates the foundations of our research, which does not concern how to get the information in terms of the communication channels, but "what information we can get that would determine the nature of user's INs".

Given the contextual nature of research - to capture the circumstances of a phenomenon and to inspect its behaviour under different conditions and contexts - the variations of IN characterisation exist depending on the perspective [6, 7]. However, the formula for the IR process is incomplete without the user entity's inclusion. The body of cognitively-oriented literature processes the user as the cognisant entity in respect to the information they receive linked with the aspect of new knowledge generation [8]. The situation is more challenging when attempts are made to enquire into the internal events, and components of the realisation of IN, usually prior to an issued query [2, 3, 9]. A standard premise is that the user is in "a state" that sets off the IN, which then translates into query [10, 11]. As a cognisant and conscious-aware entity, the internal cognitive processes increase the users' awareness of the context of INs, updating thus the users' state of IN. Under this premise, we do not know we need something until we are exposed to a situation where IN arises. However, this is not always the case. For example, during a natural learning process and exposure to information media, the user's knowledge deficit might be instantaneously satisfied without the user even "having time" to realise that IN happened. From the conceptual perspective, this idea fits the class of Radical INs [12] when the user is unaware of all absent information that would satisfy their IN. In this sense, information browsing subconsciously affects the user's old unresolved, suppressed or not-yet realised needs. Therefore, the question now arises, "Is the user in a state of IN without its prior realisation?". From the IR perspective, if the user does not formulate query input, the search is not triggered, and consequently, IR would not be able to intervene and support the user. In spite of that, the use of recommendation services partially transformed this problem by artificially increasing the user's awareness and attention to the related items. In summary, the systems intervene and anticipate beyond the current queries.

The pivotal point is nonetheless the object of the realisation. The realisation of IN has been subjected to an event of user's inner discomfort and dissatisfaction [13], uncertainty [4] or insufficient knowledge [14]. Natural introspective insight of the users supports our earlier view that says that in order to determine IN, they must know what they already know [4]. It is often a challenge for the user to properly understand what they know and what they should know. The user places IN into their own knowledge context. Awareness, cognition and memory interplay supply the user with input information that determines their state of knowledge and formulate information missing (IN). Users are guided by introspective insight into their internal knowledge and cognitive abilities as a mechanism to cognitively process the input and output information. Even the introspective insight might sometimes bring only fuzzy outcomes, so explicating the IN becomes more challenging for the users. Similarly challenging are the ill-defined situations where the user receives only uncertain, vague information from the environment [8]they need to process.

Memory as internal storage of information helps the user to provide guides towards an accurate description of their state of knowledge in the context of a problematic situation and to identify knowledge gaps, potentially leading to the realisation of IN. As part of this thesis, we created a study that sets the user in a Question/Answering (Q/A) scenario intending to activate users' introspective memory mechanisms behind the knowledge retrieval. We now report on the body of literature that motivated our research. Next, we outline this thesis's conceptual framework and formulate our research objectives.

1.1 Motivation

The foundations of our research can be found in theories of Information Search & Retrieval (IS&R) concerning the cognitive aspects of IR where the user is being depicted as a cognisant entity in the IR process impacting the character of IN [8, 9, 11, 15, 16].

In general, the cognitively-oriented theory of IR represents quite a niche, likely due to a need for an interdisciplinary knowledge approach, offering a more holistic view of the user's entity. The associated works and theories mainly dealt with the aspect of post-retrieval assessment with a focus on retrieved information itself and the role of IR to impact the user's knowledge generation [9, 15]. As part of the cognitive-based works, only a few works attempted to describe the mechanisms of the internal stimuli processing as part of the IN realisation. The functioning remains hypothesised following some generally accepted frameworks. For instance, Minsky's Frame theory [17] adapted by Cole [8] was used to describe the interplay of user's memories as a preamble of IN.

A seminal Anomalous State of Knowledge (ASK) Model by Belkin et al. [2, 3] clarified the nature of IN from the point of why IN happens in the first place. Regarding the problem the user faces, the user has a specific stance given by the initial assessment of the problem. The cognitive abilities make the user realise and understand their state of knowledge with respect to the problem. Holistically, it is known as the cognitive context of the user [6, 7] that describes the user's (knowledge) readiness in a given situation. Suppose the state of the user's knowledge is determined as insufficient to provide enough input information to solve the problem. In that case, an "anomaly" is recognised, and the state is attributed as "anomalous". The stimuli the humans encounter at a certain point in time convey a piece of information they need to interpret and process using their internal abilities of the central nervous system [8, 15]. In this context, knowledge and cognition represent parts of the user's internal system of realisation that connects the users from the initial realisation through comprehension and understanding to INs. Cognition operates over the knowledge in order to deduce what is needed and how the new information would alter the current knowledge [5]. Therefore, knowledge is a hub that connects the cognitive mechanisms that orchestrate understanding of the present knowledge abilities.

The output of this process, also known as epistemic (knowledge) feelings, supplies the user with cues to guide their reaction - IS behaviour. A few works speculated how this exchange between the user's memory is organised and controlled [15], with a notable book by Cole [8] defining the key elements and functioning supporting this process. Uncertainty and confidence as a feeling- and sense-based manifest with different intensity throughout the phases of IR search [18].

Knowledge transfer to the user's consciousness increases the user's awareness of the current state of knowledge and reflects their capabilities in terms of internal information available. From a perspective of the graded nature of knowing [19] and individual levels of knowledge, variants of the states of knowing have been proposed, including the variants of ASK [3]. By understanding the integration of external and internal information processing, we can deduce a pattern of the activity specific to different states of knowing.

The dynamic aspect of IN specifies the IN from the perspective that contrasts the user's understanding of their IN (and ultimately of the information that would satisfy their IN) in different stages of the information search process. The retrieved information the user is exposed to during an IR session or session causes their INs to be refined. For instance, the IR helped the user to shape the focus on relevant information space and improve the articulation of their actual INs. As a result, the user's initial IN-state of knowledge, e.g. ASK, is modified. User's cognition is active on every stage of the IN re-evaluation where the user updates their knowledge base [20]. Our research aims to explore the aspect of the user's initial state of knowledge as part of the user's cognitive context. Similarly, as the variants of ASK [3], we hypothesise over the spectrum of states of knowledge and their role in the user's cognitive context in order to model an effective IR process. We hypothesise that different states are associated with different INs, as well as different users' needs and expectations in the context of the overall user experience and IR support. However, examining the cognitive experience, considering that we do not want to subject the users to cognitive overload, is challenging using traditional behavioural research methods. Instead, we need a solution that would objectively measure the cognitive underpinnings behind these states.

Evolutionary research of IS&R naturally provoked an inclusion of interdisciplinary knowledge from fields such as psychology, cognitive psychology and neuroscience in order to reveal a coherent picture of the user. Next, in approaching this objective, we were inspired by a relatively novel branch of IR research, *NeuraSeach* [21], presenting a cross-disciplinary work between neuroscience and IR aiming to capture and analyse the brain experiences of users in different IR situations. This approach seems promising in addressing the cognitive perspective behind the IR concepts, such as graded relevance [22]. A series of works by Moshfeghi et al. [11, 23] evidenced the neurophysiological pattern of activity evoking the IN realisation. We will specify a conceptual model following the evidence of the memory component [24] and further explore and evaluate the underlying functional mechanisms of the user's mnemonic input.

Once the experimental study is designed, the overall research can be split into a sequence of interconnected steps: 1) The use of brain data as the source to reveal the brain activity used to determine a state of knowledge for given stimuli and evaluate the objective manifestations of the variants in knowledge; 2) Association of the data features with the states and model the cognitive processes behind each of these; 3) Applicability of the data and the found significant data features to detect and predict the state of knowledge and finally, 4) Operationalisation of the outcomes to advance the IR process with elements of proactivity and anticipations [25, 26]. The current thesis and the experimental research answer Step 1 and Step 2.

1.2 Thesis Statement

This thesis states that by exploring the objectively measured activity of neurocognitive operations manifesting for different users' states of knowledge, we draw an objective portrayal of the variability on the spectrum of users' states of knowledge and use it to expand on the characteristics of the cognitive INs of users.

Specifically, the insight into how the user is accessing their "personal frame of reference" [5, 1991, p.361], referring to memory portraying the storage of internal information, means a vital point to identify the knowledge gaps that the user would likely need to satisfy, as the purpose of search and the retrieval of information.

Variability of knowledge refers to the variability of internal information available (as the degree of Belkin et al.'s anomaly [3]), which consequently alters the INs. The details about the user's cognitive context delineate the user's state of knowledge in a particular situation the user faces. It represents, thus, a vital input to the user upon which the user makes the decision, e.g. whether there is a need to enquire more information or not. The process begins with introspective questions referring to existing knowledge and certainty [4] - "What do we already know?" - as a trigger to determine the accurate state of knowing and derive the corresponding expression of INs. Recently, a new IN-state has been introduced, Tip-of-Tongue (TOT). The study calls for improved support on the system side. For this reason, it is essential to determine the signatures for distinctive states of knowledge and distinguish between the user search behaviour variables, such as expectations.

By creating a NeuraSearch-type [21] of study, we commit to dwelling on the complex neurocognitive mechanisms that support the functions behind the user's awareness that dictates their state of knowledge. In particular, we approach this objective by investigating the patterns of users' brain activity associated with the different states. We differentiate between two mechanisms operating over the source - memory - which offer different perspectives on the knowledge capabilities of the user. First is the concept of metamemory, referring to introspective epistemic feelings of the user with the prospective (future) quality of knowing. Second, the memory retrieval state retrieves the actual (factual) knowledge and involves a more in-depth memory search. Memory is, however, an "imperfect archive of our experiences" [27, 2005, p.4] and the strength of memories is subjectively manifested by the levels of perceived confidence or certainty. The states of knowledge might be, thus, modified by the confidence which impacts the further decomposition of memories.

The study format employed Recall-Judgment-Recognition (RJR) and Retrospective

Confidence Judgments (RCJ) paradigms to apply the sequential investigation of these phenomenons, which allows us to test these in interaction. Considering the heterogeneous nature of user knowledge, we expect to find a variability of the evoked knowledge states and to confirm the character of knowing as the spectrum. The variability between these states indicates the markers making each state unique. Considering the spectrum means having higher accuracy in understanding how these might contribute to different representations or formations of IN. For IR, this means the beginning of exploring the core questions - "What lies behind IN?" and "What is the input that drives the user's IN?". Monitoring of the objective measures of the brain activity represents a potential to improve the expectancy and adaptability and the overall efficacy of the retrieval and the information concerning their actual INs. As an illustration, it might help with the development in the areas of integration with BCI and the development of pro-active and adaptive system features and recommendations.

1.3 Research Objectives

To summarise our objectives, we constructed a single multi-level study addressing these objectives:

1. Review the current IS&R views on the concept of IN, specifically from the perspective of cognitive INs and the user's cognitive context.

2. Introduce a conceptual framework through which the identified cognitive concepts underpinning the IN can be analysed in a structural/systematic way.

3. Can the conceptual framework be used as a tool to support the cognitive foundations of Belkin et al.'s ASK Model and specify the ASK variants?

4. Analyse the brain activity on the spectrum of the user's state of knowledge and discuss the spectrum's impact on information search behaviour.

5. Explore the detectability of IN based on brain data. Does IN have a unique manifestation in the brain, and how does it differ from a noIN scenario?

6. Investigate the role of confidence concerning the searcher's memory information and explore its prospect in the searcher's cognitive context.

7. Explore the information exchange between the cognitive mechanisms that function in the context of the user's state of knowledge.

8. Review the framework's performance in the current setting and elaborate on its extension as a framework for new IR scenarios, considering the pragmatic challenges of its deployment.

Each of the experimental Chapters 4 - 7 contains Research Questions specific to a particular investigation, and together, they contribute toward answering some of the overarching objectives. Finally, the Conclusion Chapter 8 summarises our attempts in relation to how the outcome of the present thesis met its objectives.

1.4 Thesis Outline

The current thesis is organised into the following parts and corresponding chapters.

PART I: Thesis Outline, Background and Methodology

Chapter 1 - Introduction. It provides the outline of the thesis and explains the motivation behind the thesis objectives. It presents the thesis statement and overviews the research objectives and contributions.

Chapter 2 - Literature Review. This background chapter contextualises the subject of the thesis, Information Need, using theoretical and empirical research in IR with additional insight from HCI, Information Science and IIR. The chapter is divided into three sections: **Section 2.1** brings a historical and evolutionary overview of the IR research concerning the challenges that lead to the development of user-centred and cognitive approaches to the current development of IR and IIR. In this context, it introduces the role of the user's cognition and cognitive aspects of IN and extends the notion of the user-IR relationship. **Section 2.2** then focuses on a detailed depiction of the concept of IN. Building on a notion of a multifaced concept, it presents the challenges of the evaluation of IN. It discusses the cognitive notion in more detail with the support of ongoing research in this area. At last, it discusses at length the selected work of Taylor [13], Belkin et al [3] and Cole [28] as the main motivators of this thesis. **Section 2.3** introduces the NeuraSearch-branch of IR as the motivation behind the study's design behind the present thesis. NeuraSearch study integrates an IR scenario informed by subjective user experiences with the simultaneous capturing of objective measures of user experiences using neuroimaging techniques. We describe the most commonly used technique of data acquisition, in particular EEG, and review the relevant works. In detail, we analyse the works concerning the concept of IN, with a special emphasis on identifying the outstanding issues left to be investigated. We conclude the section by discussing the present challenges of this branch of research. At last, **Section 2.4** outlines the Research Goals informed by the prior literature review.

Chapter 3 - Methodology. It explains the methodological part of the user-based study. In particular, it describes 1) the general experimental setup of the study, including the used methodological paradigms and their relation to the thesis's research objectives; 2) the characteristics of the task the participants performed; 3) the derived metrics and factors, independent and dependent variables; 4) the constraints and challenges of EEG data and defines EEG data framework covering the i) pre-processing pipeline, ii) data-driven methods of EEG data analysis, and iii) interpretability of the outcomes; 5) the analytical framework used to quantitatively evaluate the investigated phenomenons in the chapters constituting Part II.

PART II: Investigations

Chapter 4 - Analysis of Behavioural Data. In this chapter, we first showed the manifestation of the metamemory-evoked states of knowing and evaluated their accuracy using the recognition test applying the factual memory retrieval with judgments of confidence. We also analysed behavioural data acquired during the study in the format of quantitative (participant performance metrics, i.e. response distribution, response times) and qualitative metrics (e.g., insights from the participant questionnaires). The outcomes are discussed in the context of implications for IR research. Identification of significant data trends and data issues (e.g., unbalanced data) increased our awareness and helped us to prepare the customised analyses of associated EEG data (Chapters 5 - 7).

Chapter 5 - EEG Study of Metamemory Informing Users' Information Needs. The first of the EEG investigations addresses whether there is a significant signature underlying different metamemory states to determine the prospective IN. (1) First, we start by justifying the metamemory inclusion in the concept of IN. In particular, we focus on its introspective function to supply the user with an initial input representing their state of knowing. Then, acknowledging the graded nature of epistemic feelings of knowing [19], we propose a definition of the spectrum of metamnemonic states of knowledge and derive cognitive representations of INs. In particular, we discuss the state of Feeling of Knowing (FOK), the cognitive state of temporary unavailability of knowing. (2) Second, we investigated the underlying EEG activity associated with the spectrum of three metamnemonic levels. Its outcomes inform our prior hypotheses related to the graded nature of INs.

Chapter 6 - EEG Study of Memory Retrieval and Confidence Judgments Further Informing Users' Information Needs. The second EEG investigation is based on the contrast of neural markers for three levels informed by the outcome of the recognition task. The chapter further presents the authentication of the MR levels as the IN and looks for markers that might be discriminative of the activity evoking IN. The analysis continues with the investigation of confidence concerning the MR outcomes. The chapter concludes with the presentation of the data-driven model explaining the differences in cognitive functions behind MR. Also, we open up a discussion in the context of the significant findings and make recommendations for further research in IR.

Chapter 7 - EEG Study of the Interaction Between Metamemory and Memory Retrieval. We conclude Part II of this thesis with the last EEG investigation combining the information from the two mechanisms, metamemory and memory retrieval. The chapter explores the spatio-temporal features informative of the significant interactivity between these mechanisms. In addition, we complement the outcomes with the clusters of interconnected electrodes and Regions of Interest (ROIs) based on a similarity matrix using the Derivative Dynamic Time Warping Algorithm (dDTW). The results contribute to the notion of the accuracy of the prior metamnemonic predictions concerning the post-MR outcomes as evidenced by the neurophysiological manifestations alone.

PART III: Conclusions

Chapter 8 - Conclusions. It concludes the research presented in this PhD thesis, draws the conclusions from the experiments in Part II, acknowledges its limitations and makes recommendations for future work. Finally, the thesis contains three appendices with complementary information for the study featured in this thesis: participant information sheets and consent forms (Appendix A), questionnaires (Appendix B), Q/A dataset (Appendix C), sample metadata file structure (Appendix D).

1.5 Publications

Research that resulted from this PhD has been published at or submitted to the following peer-reviewed venues, using only the parts of these papers that are directly attributable to the author. For each paper, we refer to the corresponding chapter where the content of the paper is included.

1. Dominika Michalkova, Mario Parra Rodriguez, and Yashar Moshfeghi. 2022. Drivers of Information Needs: A Behavioural Study – Exploring Searcher's Feeling-of-Knowing. *In Proceedings of the 2022 ACM SIGIR International Conference on Theory of Information Retrieval (ICTIR '22).* Association for Computing Machinery, New York, NY, USA, 171–181. https://doi.org/10.1145/3539813.3545125.

   The content of this paper is discussed in Chapter 4.

2. Dominika Michalkova, Mario Parra-Rodriguez, and Yashar Moshfeghi. 2022. Information Need Awareness: An EEG Study. *In Proceedings of the 45th International ACM SIGIR Conference on Research and Development in Information*

Retrieval (SIGIR '22). Association for Computing Machinery, New York, NY, USA, 610–621. https://doi.org/10.1145/3477495.3531999.

The content of this paper is discussed in Chapter 6.

3. Dominika Michalkova, Mario Parra-Rodriguez, and Yashar Moshfeghi. 2022. Confidence perceptions as Part of Searcher's Cognitive Context. Paper presented at *Advanced Online & Onsite Course & Symposium on Artificial Intelligence & Neuroscience*, Tuscany, Italy, 18/09/22 - 22/09/22.[1]

   The content of this paper is discussed in Chapter 6.

4. Dominika Michalkova, Mario Parra-Rodriguez, and Yashar Moshfeghi. 2022. Understanding Feeling-of-Knowing in Information Search: An EEG Study. *In ACM Transactions on Information Systems (TOIS).* [Under Revision]

   The content of this paper is discussed in Chapter 5.

[1]The paper will be published in a volume of the Lecture Notes in Computer Science.

Chapter 2

Literature Review

The concept of Information Need (IN) spans several areas, with the main sources of knowledge found in the fields of Information Retrieval (IR), Information Seeking and Search (IS) and Human Information Behaviour (HIB), combining the perspectives of psychology, sociology, cognitive science and neuroscience. This chapter introduces the key terminology and background information related to IN in the context of IR and Interactive Information Retrieval (IIR). These serve as the prerequisites to understand the ongoing development of a novel branch of IR research, *NeuraSearch* [21], used as the operational framework behind the presented behavioural-led research featured in this thesis. First, Section 2.1 provides a brief theoretical and historical overview of IR and IIR research. Next, Section 2.2 brings a detailed overview of the concept of IN, outlining the theoretical constructs and mechanics of IN assessment; it further contextualises IN from the searchers' perspective and discusses three user models depicting the cognitive aspects of searchers' IN realisation. In Section 2.3, we introduce the interdisciplinary *NeuraSearch* research which inspired the experimental framework of the investigations featured in this thesis. Then, we illustrate the techniques used in this type of research, review the outputs of the relevant investigations and, finally, discuss the ongoing challenges of *NeuraSearch*. As a result of the theoretical and empirical literature review, we construct a conceptual framework to investigate the underlying processes behind the realisation of IN and define the research goals of this thesis in Section 2.4. Finally, Section 2.5 briefly summarises the outcomes of the present chapter.

Establishing the Key Terminology In order to present the background information introducing our research topic, we have to establish the vital terminology and set our study in the context of existing research areas. Overall, the relationship between humans, information and information sources is the primary concern of HIB. It studies a range of human behaviours, usually represented as a part of user models and frameworks, involving physical actions, cognition and affective feelings employed during the user interaction with accessing, searching, and using the information and information sources [29]. Information is not limited to a textual format, but it takes other forms of media, images, videos or web links. Human Information Behaviour serves as an umbrella category for other derived research fields.

For our study, relevant subcategories of HIB are the seeking for (i.e., Information Seeking) and the retrieval of information (i.e., IR). Savolainen [30] differentiated between the content of these terms. Information Seeking encompasses a range of users' implicit and explicit behaviours and strategies in discovering the information. This behaviour can be either i) purposive or referred to as an active reception of information where the information contributes to a certain purpose [31], or ii) non-purposive, also known as a passive reception of information, often incidental without a prior purpose [31]. The distinguished and well-researched category of Information Seeking is Information Search which refers to human-human and human-system interactions involved in the information search process.

Contrastingly, IR is, at foremost, aimed at retrieving the relevant documents to a given query at the highest ranking positions in the list of retrieved documents, e.g. Search Engine Result Page (SERP). Information Retrieval operates with the given input, usually in the form of an issued query. On the contrary, Information Search takes into consideration the possible "uncertainty over whether the information being sought exists and whether the searcher, working in synergy with the system, will be able to find it." [30, 2017, p.4]. Although IR was principally developed with the system design and development in mind, it has been largely influenced and extended by the introduction of the user-oriented theories [29]. This conceptual approach integrates the user as part of an IR system, which promoted the rise of the IIR research [32].

Since many of the concepts, ideas and models, which will be presented in the following sections, co-exist in multiple fields of HIB research, a precise categorisation is challenging. Therefore, we will use Information Seeking and Search (IS) as a joint category and also use the acronym “IS&R” to refer to shared theoretical concepts of IS and IR. Additionally, we will use the terms “searcher” and “user” interchangeably, as every user of an IR system and its provided information sources is originally a searcher.

2.1 Information Search and Information Retrieval

2.1.1 Introduction

Information Search is a fundamental human activity where the information is sought with an information purpose [33]. After a person evaluates their present circumstances and recognises that information is needed to solve their situation, they are in a state of IN. Then, they are likely going to become the information searchers [29]. Concerning IR, the searchers are the users of the information sources retrieved by an IR system. The retrieved information and its perceived value [34] contribute to the satisfaction of users' IN and solving their information goals. The search goals can be described as a cascade of internal or external motivators [35] of the searchers and the situational context, each of which affect, to some extent, their information search activity. Here are a few examples: (1) The goal to facilitate learning might be motivated by a given school assignment (external) along with an urge to obtain the desired grade (internal). (2) Selecting a vacation resort might be driven by an internal need for holiday time and relaxation. (3) An immediate urge to quickly learn the postcode of the City of Glasgow might be posed by an external motivator (e.g. correspondence).

The contextual information about the aim of the search helps to predict the nature of the search task. The example above (1) is an instance of an exploratory search [36], which might likely i) demand to scan multiple information sources, ii) span across several search sessions, and iii) require the searcher's higher cognitive effort such as critical thinking and comprehensions. The example (2) is a mix of fact-finding and exploratory search as it likely involves some decision-making processes, such as consideration of the cost, travel time, and health regulations before booking. At last, the example (3) is a typical example of an ad-hoc fact-finding search, known as a known-item retrieval [37], typically described by a shorter search completion time. Each of these present (and somehow problematic) scenarios [38] have a common component of IN as the representation of the searcher's problem in this situation, i.e. lack of information.

Information Need and Query

Information Retrieval sees IN as a request or a clue provided by the user which indicates the nature of their INs [39] and is then translated by a retrieval mechanism to obtain the information that matches the request [10]. This request is termed as "query" [40]. The query is commonly associated with accessing data stored in relational databases using the syntax of SQL (Structured Query Language) commands [41]. In the area of natural language user interfaces, a standard for commonly available online search engines, the query input is often unstructured or semi-structured [42]. It takes the form of keywords, and natural language structures, such as complete sentences and questions predominantly in a textual, and more recently, a voice format [43, 44]. IN resides not only at the beginning of the search as the searcher's input to an IR system, but this role expands as the search progresses. In particular, during the phase of document judgment where the searcher evaluates whether the piece of information satisfies IN, i.e. is relevant to their IN [40, 45].

Foundations of IR modelling

Foundations of IR are built on the Look-Up model [46] with a query-document matching function. Basic prototypical Look-Up IR (known as ad-hoc search model [36]) contains the following components. First, on the system side is the document collection and its indexed representation termed as document surrogates with metadata (e.g. URLs, snippets). Second, on the user side is the IN and its textual representation, i.e. query. The IR system then calculates query-document relevance scores as the output returned by the matching function, which implements some document-query similarity measure, such as cosine similarity [47]. The user is then returned a ranked list of document surrogates that system-match their input query.

Working under the best-match principle [48], the model assumes i) the information (that would satisfy the searcher's IN) exists in the collection and ii) the searcher uses an appropriate query. Here, the query is static and treated as "a one-time conception of the searcher's IN" [35, 2016, p.25]. The user is treated as a static role in the process and their INs, which are not expected to change [12].

The limited attention to the user is paradoxical, as the user is the one who sets the expectation criteria of the relevant documents and judges the retrieval performance. The Look-Up model was further criticised as it did not resemble the dynamism of the search itself [2, 3, 46]. For example, the model did not account for the variability of the search context or the existence of ill-defined INs that, for the user, are ambiguous and hard to express [8]. As a result, explicit and implicit relevance judgments were embedded into the system design [12]. This transformed thinking led to the development of a new user-centred paradigm [29] internalising the user as an essential partner to the IR system. Instrumental for developing the user-centred paradigm shift in IR was the knowledge from psychology, sociology [49] and cognitive science [16]. These helped to shape the emerging subdisciplines such as Interactive Information Retrieval (IIR) [9] or Human-Computer Interaction (HCI) [50].

User-centred branch of research has long-standing support in IR research and has been shaped by numerous new perspectives and models [3, 20, 38, 51, 52]. A few to mention, 1) Belkin et al.'s Anomalous State of Knowledge (ASK) Model (see Section 2.2.3) utilised the searcher's lack of knowledge in the IR process, 2) Wilson's Information Seeking Behaviour Model [49] set out the context of the search task, 3) Kuhlthau founded her Information Search Process Model [5, 52] based on searcher's affective feelings occurring during their search experience, 4) Ingwersen's Psychological Aspects of IR [15] and Cognitive IR Theory [16] brought an elaborate interdisciplinary outlook on user's role in IR. Most of these models are discussed in Section 2.2 in relation to how they approached the concept of IN.

2.1.2 Interactive Information Retrieval

The cornerstone of IR research is the evaluation of performance and the efficacy of IR processes, i.e. retrieving relevant documents to a given query [53]. Traditionally it lacked an understanding of searchers' information behaviours and their interactions with the systems, as mentioned in the previous section. Interactive Information Retrieval (IIR) was driven by the emergence of the user-centred paradigm that integrates the elements of user behaviours, experiences and interactions within the IR model. Kelly summed up the overarching objective of IIR in a question: "Can people use this system to retrieve relevant documents?" [54, 2009, p.3]. The essential method for IIR research is the exploration of user-system interactions and user's information behaviours [55] evaluated in regard to the retrieval efficacy and the overall user experience, e.g. usability and retrieval satisfaction [56].

The theoretical foundation of the IIR process started as early as the late 1960s. "An interactive system requires a sequence of steps in which man and machine alternately take action" [57, 1971, p.313]. IIR promotes a system that goes beyond its reactive role and creates a "significant intellectual partnership in assisting the user in thinking about his problem... and assist him in modifying his solution space" [58, 1971, p. 361]. Early research of IIR presented the works by 1) Salton [59], who recognised the importance of user perceptions and attitudes in information tasks, 2) Cleverdon et al. [60], who accounted for the user effort as a complementary measure to IR-metrics of precision and recall, 3) Williams [57] who emphasised the role of the searcher's feedback to enhance the effectiveness of IR system and presented one of the first online IIR systems called BROWSER, whilst 4) Thompson [58] proposed a modified system built with hierarchical document structure resembling a structure of human cognitive thought.

As Williams [57] noted, IIR's effectiveness should operationalise the best qualities on both sides of the IIR process spectrum, i.e. human and machine. "Searching is the human decision-making process of finding or discovering something through careful examination, whereas retrieval is the mechanical process of bringing back identified information." [57, 1971, p.314]. He imagined that this potential would give rise to an IIR system that would diversify the system support based on i) user categorisation, ii) recognition of query types, such as broad (exploratory search) and narrow query (fact-findings search), iii) navigational strategies, iv) dynamic ranking based on detection of user's changes and relevance judgments as well as v) user's direct interference with the ranking, e.g. to override the ranking list.

Although more than fifty years have passed since these original IIR ideas were presented, they remain valid and still in demand. The early literature set out a framework that still inspires the current research. In particular, considering that "Interaction is the major component in all practical realisation of IR to such an extend that IR without interaction is hardly conceivable" [20, 1997, p.313]. Information systems have become widely available and accessible due to the spread of online technologies and their interactive user interfaces (UI), which promote ease of use and quick access to data to transform them into information and knowledge. Sophisticated mechanisms of IR and emerging technologies in HCI expanded the information services and improved the user search experience. For example, the online search engine Google practically established itself as a synonym for search by leveraging intelligent assistance, such as query auto-completion, query correction, data filtering, media queries, modalities of input-output, multi-language support, semantic assistance and data collections such as research catalogue Google Scholar[1]. Relevance feedback allows the searchers to provide implicit or explicit feedback about relevant information and uses these judgments to enhance subsequent searches [35]. Methods of gathering user activity, such as search or query logs [61, 62], are now broadly used in the evaluation of IIR systems [63]. Clicks and other mouse cursor movements [64, 65], dwell time [66, 67] are some of the most common behavioural signals and were used to predict user's implicit relevance judgments [68, 69]. They are, thus, an integral source of understanding of different search behaviours [70]. Consequently, they are utilised to model enhanced representations of the search process and, potentially, make the process of IN satisfaction more effective and refined. Next, the potential to improve the retrieval of relevant information and information recommendations means the underlying user historical data and information objects such as metadata. For example, e-commerce platforms have widely harnessed

[1] https://scholar.google.com/

them to promote the purchases of related products. Recommendations are driven by users' past online behaviours and search activity with implementors such as Goodreads, an online search database of books, quotes and user reviews or Spotify, a mainstream music platform. The intelligent IIR systems and the quick adoption by their users allowed for their ubiquitous influence and user's subconscious system-dependency [71].

Users and their context as the context of IR and IIR

The spectrum of user-native interactions with the IR/IIR system components comprises three categories [5, 54]: physical actions taken (e.g., web search, use of voice assistants), cognitive thoughts (e.g., document reading to determine its relevance, critical thinking) and affective features (e.g., motivation or uncertainty).

Ingwersen and Järvelin [7] introduced a comprehensive view of the importance of user context for effective IR and the need for a transformation of the dominative context-free manner. In light of the ubiquitous nature of smart technologies and search services at hand, recognising the task context is becoming more important [26]. Equally, current IR and IIR research reflect the embracement of "multi-media, multi-lingual, and multi-modal environments" [6, 2005, p.31] where the search is conducted.

Utilising the search context is not a novel proposition, but the research has struggled to operationalise it. Wissbrock [12] came up with a prototype of a multi-context-dependent interface for IR systems. However, this model does not provide the means to determine the context, which remains a challenge to move forward [72]. It might be a precarious situation when we know how to utilise the data, but the problem lies in how to objectively capture them. In addition, collecting the data should not pose any unnecessary burden on users, such as cognitive [73, 74] or information overload [75, 76]. Therefore, the only way is to make these functions native, depending on implicit interaction and ambient environment. In the ubiquitous mobile environments of search and communication, Benetka et al. [77], or Hinze et al. [78] utilised real-time data streams and their metadata (e.g., geographical locations) to derive the search context of INs of their users. Such contextual data can be used effectively to constrain the IR only to contextually-relevant IR, thereby reducing the complexity of the retrieval process. The underlying hypothesis is that by taking into account the context, the next generation of context-retrieval models will deliver performance exceeding that of context-free engines [6, 79]. A study [80] confirmed the context-dependency and prototyped the context-aware mechanism reaching an increase in performance by 20%.

As we will present in Section 2.2, search context is one of the facets of IN and also offers a large capacity for study. Contextual data surrounding the user and the situation in which the user needs to obtain information influences their INs and, in consequence, the information behaviour itself. Referring back to the work by Ingwersen and Järvelin [6], main contextual user variables concern 1) Motivations (further containing elements of internal and external motivators, task, goal, immediacy), 2) Knowledge (domain or subject-matter expertise), 3) History (search behaviour, judgments, strategies, queries) and 4) Individual differences (demographics, cognitive styles). These elements synergise the quality and effect of contextual information to improve the representation of the user in the user-centred IR model and help the system to adapt (e.g., in terms of resources, UI, underlying retrieval model) to improve the support of its users and their INs. **Our thesis will, particularly, aim to address the variable of the searchers' knowledge and its position in the realisation and modality of INs.**

Modelling Human Information Behaviour in IIR

Attention to the user's role in the IR process meant adopting HIB's thinking to IR [31]. As a result, conceptual theories were formed on the basis of a holistic outlook on users and their information behaviour, which even more deepened the relationship between HIB and IR [29]. Interactive IR modelling drew the knowledge from HCI theory to expand the view about IR as "an exchange of information" that is happening via an interface with interactions altering states of both parties of this exchange (i.e., users and system) [81]. Interactions can be seen as a sequence of processes [20] creating a pattern of exchange. Altering states on both sides are built on the notion of the connectivity between the participants of the IIR process that improves mutual understanding. It is reflected, for instance, in the methods of query refinement or query suggestions employed with the essential aim improve the retrieved results. Several pioneering frameworks emphasised the interaction aspects of IIR [9, 16, 54, 81, 82], among these notable works by Saracevic [20, 32] elaborating psychological, epistemic (knowledge-related) and physical characteristics of interactivity [29]. Saracevic's frameworks combined the attention to interactive elements of the IIR process intending to drive the symbiosis of the interplay between users and systems [20]. In his significant work "Stratified model of Information Retrieval interaction", Saracevic emphasised the user-system interaction to concentrate efforts in order to "make these systems more user responsive" [20, 1997, p.313]. Interactions can be interpreted as part of a dialogue between the user and a computer through an interface. In this sense, they depict early Taylor's question-negotiation process between searchers and librarians [13] (more in later Section 2.2.2), which makes it applicable in the current self-service IR systems. According to Saracevic [20], the levels (or strata) on both the user and the computer side govern the interactions and selection of search aspects. The user object is constituted by cognitive (interpretation of texts governed by cognitive processes), affective (feelings, motivations), and situational (problem-at-hand) levels, analogous to the user's contextual information [6]. The system side encompasses the available technology that supports the interactive retrieval process via levels of engineering (operational and design attributes), processing (software implementation, algorithms) and content (information objects, metadata, resources). According to Saracevic, "the interactive discourse follows a changing, shifting path." [20, 1997, p.10]. The shifts are the manifestations and events that occur as the interaction between the user and the system proceeds. For instance, a shift might signalise the user refocus manifested by narrowing down the query terms. The shift signifies the user's adaptive ability [8] to change the user's strata. Assessment of the strata in interaction is, thus, a key to understanding this adaptive process of a searcher. Much of the IR/IIR research has been developed to approach the variety of user strata in the IS process, e.g. cognitive perspectives [8, 9], affective feelings [18, 36] or situational information [6, 7]. In the further text, we will dedicate most of the attention to the strata - cognition and cognitive context - and their role in guiding the user's search behaviour.

Human Cognition Among the key elements emphasised in the IR/IIR process is the user's cognition [15]. It is triggered most notably at two phases of the IR. First, as a trigger to information seeking as part of "what the user brings with" [5], such as prior knowledge and the user's cognitive perception and understanding of the situation based on received information from the stimuli. The level of the user's overall understanding of the information problem changes the character of the IN [8]. The literature often differentiates between 1) ill-defined IN, characterised by a lack of clarity about the problem and the information that is required to satisfy it [8], and 2) well-defined IN where the user knows what to look for [83]. The second trigger for the employment of cognition is at the intersection of the seeking and information usage required to cognitively (and effectively) process the information resources and interpret the output information [20]. Engagement of deeper cognitive levels, such as analysis and comprehension of information [8, 16] is an unnecessary aspect of user's information search behaviour and user-system interaction [32]. **Particularly enlightening would be a deeper understanding of the involved cognitive operations linked with the knowledge processing and the definition of the user's state of knowledge, as one of the inputs of user's contextual search information** [6].

Cognitive Information Needs The critical input to perform an effective IR is still the user's expression of their IN. Moreover, the interactive character of the IR process well represents the dynamicity and the shifting nature of INs of their users. As interaction is a series of events during a single session or multiple single sessions, likely depending on multiple factors (e.g. difficult tasks take longer time to resolve [84, 85]), the expressions of INs shift during the course of these events as the user gets a more focused view. However, if not working through intermediaries, e.g. librarians, the user has to rely on their interpretation of INs to express them as queries. Here lies the key point that drives the success of the searcher's information searching. If we take Saracevic's model [32] as a prototype of level-dependent interactivity, we can further formulate the premise for cognitive INs. Users communicate with the system via the interface, which enhances the dynamic nature of INs and helps users express their INs. Information Needs coextensive over several user levels during the interaction session compared to the initial state of expression, i.e. before the search was triggered. The critical factor on the user side is the cognitive, affective and situational levels that altogether work as dimensions of INs or Saracevic's strata [20]. The INs are, therefore, likely to be determined by the current state of users' understanding of i) themselves, ii) the magnitude of affective feelings, and iii) the problem or situation. **How well the user understands their INs is determined by the cognitive mechanisms (e.g., the realisation of the state of knowledge [10]), which further specify them as cognitive INs.** From the system point of view, it is vital to realise the system's interference with the user's cognition, for instance, during document (cognitive) relevance assessment. Interactivity was created as a vital part to assist the user with the search and document assessments causing the user's INs to evolve across the three dimensions mentioned above.

So, one might ask about what in this process truly evolves. Is it IN itself or expressions of INs (e.g., queries)? A simple answer is both, as they are inclusive. Independent of the search context (e.g. task-based search or fact-finding), queries as system input representations of INs facilitate the search and retrieval process. INs can only evolve if the shift in IIR happens. The shift in queries means the user has developed a more specific view and, essentially, knows how to proceed in order to solve their INs. This view implies that both evolve. Interaction with the retrieved documents causes the cognition to be turned on to assess new documents. In a series of related queries, the last query would likely mean the last piece of information to contribute to the user's cohesive and complete picture of the problem, in contrast to the initial phase of search [13]. The final query is, however, not the result. Such as the Berrypicking approach [46] suggests, it is the journey of search and information interaction causing INs to be satisfied. Accordingly, the role of the iterative process of interactions and assessments is highly significant in keeping INs in motion.

Cognitive approach with the primary focus on the user's cognition and the knowledge aspect behind the rise of IN constitutes a vital source of information behind the topic of this thesis and its featured empirical inves-

tigations (Chapters 5 - 7).

2.1.3 Modelling IR

As we presented earlier, IR system design was historically approached from four design perspectives [29]: 1) system centred, 2) user-centred (also found as user-centered or user-centric), 3) interactive, and 4) cognitive. Each represents an extension of the previous one, aspiring to better model the user as an active participant in the IR process. We explained that interactive design concerns the symbiosis between the user and the system by bringing users' behaviours, experiences (physical, cognitive and affective), and the interactions [54] as an integral part of IR modelling. The cognitive design stands out as a self-contained approach. In contrast to more focal aspects of IR, such as relevant document retrieval and document ranking [8], the cognitive design depicts traditionally marginal aspects of the IR process, namely information use, information gain, knowledge generation or knowledge regeneration. The cognitive approach is mainly described from the user point of view, but it addresses the system side as well. We can analogise human cognition to the system's functioning. After all, any IR system is underneath a complex configurable system with computable logic and procedures. Its counterpart is human cognition representing the user's logic and processes employed before and during the information search. User input - the query - undergoes a series of algorithmic processes, and the system returns the output. This output represents for the user an input to their complex cognitive system that orchestrates the processing of this input (known as stimulus). Even if the user operates under intuition, they are at least partially guided by some cognitive operations of thinking, reasoning and risk evaluations [86]. The advances in the fields of machine learning and Artificial Intelligence (AI) [87] are currently significantly helping "to build the intelligence" of IR systems. In this regard, the systems aim to emulate the human-like ability to adapt and offer pro-active support for the user [25] to mitigate the user's errors and biases and improve the searcher's behaviours and finally, the overall outcomes [88].

Relevance and Satisfaction

Relevance is probably the most common measure of the quality of the retrieved output [89]. Relevance is an approximation of the user's criteria for a document satisfying their INs. Research [29] showed that users often use multi-criteria decisions to judge the document relevance to synergies the complex structures behind the user's context, such as personal knowledge, topicality, quality, novelty, recency or preferences. For instance, airline ticket booking is a typical instance of the problem where multiple criteria exist [90]. Having a set of criteria, relevance is not an impulsive judgment. According to Saracevic [20], relevance can be broken down into these subcategories:

- System/algorithmic relevance depends on the internal representation and organisation of information objects (e.g., texts) and algorithmic procedures that match the query to a retrieved document. Effectivity is the criteria to infer the relevance.
- Topical or subject relevance assumes that both queries and texts have a matching topic or subject.
- Cognitive relevance uses the relation between cognitive INs, state of knowledge and the information provided in the retrieved documents.
- Situational relevance is inferred by the relation between the situation or problem at hand and the retrieval outcome. The user likely judges how useful the information is (informativeness, novelty, information quality) in solving the problem.
- Motivational or affective relevance (satisfaction, success) of the retrieved outcomes is inferred in response to the user's intents, goals and motivations.

The presented categories of relevance reflect the contextual and personal preferences of the searcher and impact the final satisfaction of the searcher with the IR process and its outcomes. The function of relevance judgment is interconnected with the searcher's IN and the searcher's satisfaction as a subjective measure of the IR success as well [91]. All of these categories require a cognitive assessment to infer the final relevance and overall satisfaction with the retrieval outcomes and the IR process in general. The satisfaction goes beyond a single document assessment as it applies the user's subjective criteria to assess the IR's outcomes with respect to the user's initial state of knowing. For instance, the context of the user satisfaction criteria can deal with uncertainty reduction (Does the user still perceive uncertainty?). Next, the user can contrast expectations vs reality (Does the outcome match the user's expectations?).

The IR output interferes with the user's cognition (see earlier Section 2.1.2). The cognitive abilities are pervasive in the IR assessment; however difficult to capture and evaluate due to their involuntary and subconscious nature. For example, uncertainty and intuition that are often the triggers of the information search [3, 18] contribute to the cognitive bias of the searchers [88], where the patterns of deviations in thinking causing the searcher's judgements to be susceptible to these errors [86]. The present thesis will not review this branch of research in detail. Nevertheless, we remain aware of this phenomenon and consider its influence in the later chapters that formally investigate the user's cognitive mechanisms.

Cognitive outlooks on IS&R Ingwersen's work "Psychological Aspects of Information Retrieval" [15] from 1982 presented four parallel stages of IR and became one of the leading figures in theorising a new cognitive paradigm of IR research. First, the monadic approach handles the information entities independently, with a single descriptor, and IR works under the best-match principle [48]. Second, the structural approach adds complexity by acknowledging entities in relation and where one entity can have several descriptors. Third, the contextual approach considers entities affiliated with the context. Context remains a very current research topic and has been an established subject of numerous studies, with recent expansion in the research area of recommender systems [92]. The last one is the cognitive approach, which meant an experimental new route for future IR systems at the time of publishing. It stressed epistemology and its co-effect with human cognition in IS&R. It was largely based on De Mey's cognitive view [93] where he accounted for the role of internal models as the representations of the user's information processing which contributed to shaping the scientific perception about the user's cognition in IR.

Nevertheless, the cognitive prediction was correct. The rise of expert systems, such as ASK [3], which was built on knowledge anomalies (for details, see Section 2.2.3), meant the embodiment of the principles of cognitive user modelling as part of the overall design configuration [94]. As Brooks stated: "The influence of expert systems has shifted IR research from a paradigm concerned largely with retrieval algorithms to one in which users, retrieval heuristics, knowledge and human-computer interaction are key themes." [1, 1987, p.379]. Besides the fact that these ideas were indexed several decades ago, their aim is still current and impactful, evidenced by the recent approach to acknowledge a broader spectrum of INs requests [95].

Furthermore, according to Ingwersen [15], the IR process would likely prosper if people shared common knowledge structures. However, reality prevented such homogeneity. As a result, it causes variety in individual expectations, which adds another level of complexity to the user context modelling [6]. Ingwersen took the inspiration of knowledge structures from Popper's Three Worlds [96], which are interlinked models of a physical world (World 1) perceived and interpreted by the user's dynamic subjective knowledge (World 2) to use and access the resources of objective knowledge (World 3). User's subjective knowledge is a central part of coordinating the access to, the interaction with and the use of the objective resources (objective knowledge) embedded in the Internet, books, databases, and information systems, including their internal system structures, e.g. query language. He further stressed the knowledge-based systems with auto-generated knowledge structures to represent both subjective and objective knowledge. In the current environment of fast-paced retrieval, these emerge as highly relevant to allow for a transition towards more cognitive and user-centred retrieval. In the next section, we provide an expansive overview of the theoretical and research perspectives that formed the current understanding of the concept of IN, emphasising user-centred research and cognitively-oriented perceptions.

2.2 Information Need within the context of Information Search and Information Retrieval

Information Need (IN) is an essential concept in IR theory and research. Coupled with Savolainen's definition of IN as "the trigger and driver of information seeking" [30, 2017, p.2], the IN stands at the forefront of the IR process and keeps the searcher in the loop. After all, IR is an iterative process in which the user evaluates how well the IR performed, which means the sequential steps depend upon the theIN. IN has a long-standing presence in theoretical and empirical research. One of the earliest references provides the works by Taylor [13, 97], dating back to the 1960s, which motivated many studies in the following decades [3, 5] and still keep their impact on the current studies [28, 98]. Throughout this timelapse, IN has been referred to under alternative terms, such as question [13] or information want [99] requirement [100]. Others reflect the belief of their authors about what is the origin of IN, such as Anomalous State of Knowledge (ASK) [10], the gap in knowledge [51] or feeling of uncertainty [5]. This perception might increase the conceptual ambiguity for the external audience, but it also, in a positive way, captures a wholesome picture of a complex and dynamic phenomenon. According to Derr [99], an important characteristic of IN remains its information purpose, which affects the whole information-seeking behaviour. As the information purpose exists, the information in question should contribute to the achievement of meeting that information purpose.

Information Need (IN) is most commonly satisfied on the Internet. For instance, we split the term IN into separate word entities, "information" and "need". Both terms connotate the Internet, firstly, as a source of information and satisfaction for practically any need as well. The compound term IN only strengthens the position of IN and the IR mechanisms in the Internet age. Embracing the Internet as the largest source of data and knowledge made us comfortable and dependent upon its collection of external knowledge [71] to satisfy our INs. Queries, as the input to a search engine, posted as questions or a set of keywords, made the search experience informal and intuitive and generalised our perception of what the IN is.

However, in the light of these perceptions, issues with the unified definition of IN might arise, which makes IN somewhat of an intriguing concept. We often encounter literature introducing the IN concept with attributes as vague and inaccurate reflecting its theoretical definition [11, 12, 30, 38, 101, 102]. They source from a natural and intuitive perception of IN and the general understanding of IN as "what we do not know". Often, the user has a problem formulating what is "the what". Therefore, the question is user-dependent, bringing the uncertainty level into IN. Next, what about the situational context of enquiry? Does IN arise due to and should be, then, defined based on uncertainty, the searcher's individuality or the situation? More and more questions can be derived from further analysis; thus, the lack of theoretical clarity about IN, as we mentioned earlier, is only a reflection of its faceted nature. The investigations into IN therefore differ as they approach different facets of the IN, such as contextual factors [6, 38, 103], or uncertainty [5]. In the next Section 2.2.1, we mention some of the historical models and approaches to tackle the different facets of INs. For instance, in Section 2.2.2 - 2.2.4, we closely look at three interconnected theories, which are relevant to our study, as they aimed to objectify the searcher's cognitive perceptions and, thus, inform the origin of the realisation of IN.

2.2.1 Modelling Information Need

The history of IR models concerning IN assessment describes the progression of IN category in IR whilst reflecting the underlying motivation of the user-centred approach (see earlier Section 2.1.1). A transfer from being viewed as a standalone static input to IR to embracing its inter-relationships with other concepts within IR, most prominently the relevance, marks the irreplaceable position of IN as a factor and a measure for an effective IR process. To illustrate, the query approach, a typical representative of the system-oriented design developed in the late 1950s, considered IN as a static and well-defined input into IR. Later, a new component of relevance, as a first stage of developing user-centred design, was introduced. Obviously, user involvement became increasingly needed to judge the documents, i.e. provide explicit relevance feedback, as the system was unable to make the judgment itself as the system was not the carrier of the need part behind IN. In the expert systems [1], the user was recognised as part of the system process that triggers INs whilst their feedback is needed to take care of the IN assessment. The feedback allowed the evaluation of the documents, and the system accordingly adjusted the retrieved documents. Next, the dialogue approach proposed by Oddy [104] meant another step on the evolutionary journey, which embedded the user role in the IR process even more. In a sense, this can represent a prototype of Taylor's theoretical Question-Negotiation for librarians [13] (see Section 2.2.2). Dialogue acknowledges that the user is evolving in a search process through the gained knowledge and narrower focus which causes the shift in INs. The dialogue approach was further referenced in Belkin et al.'s ASK Model [2, 3]. Similarly, back in 1989, Bates [46] proposed an approach called Berrypicking, which promoted the search as a journey during which the user collects retrieved relevant documents and during which IN evolves. This proposition is most apparent during complex problems that often require and rely on multiple search sessions and stages, where the initial IN and query are enriched through the information flow.

Modelling Human Information Behaviour

Divergent views on IN concept exist. For example, Savolainen [30] conducted a conceptual analysis of past approaches towards the characterisation of IN. The resulting summary specified that IN could be conceptualised according to two characteristics, i.e. as a trigger and a driver for information seeking. To specify, IN as a trigger is seen to initiate the information search process to identify and access the information resources. Additionally, IN is determined and driven by the context in which it arose. Also, the context can specify the (contextual) category of IN, such as task-generated INs.

Another outlook on INs can be derived from the perspective of online search behaviours concerning the search intent [105]. As we mentioned earlier, INs are commonly satisfied online. For this reason, Broder [106] analysed users' online search behaviour and concluded three types of web-specific INs: i) navigational, ii) informational, and iii) transactional. Out of these, only informational INs mirror "the information" in its true sense as a product aim of the search, whereas navigational and transactional ones focus on the interactions with and access to information sources.

Informattion Need as the trigger of Information Search In general, an expression of IN is a statement of what the user does not know and needs to know. That is, IN is a subjective entity sourcing from recognising the users' (insufficient) knowledge [10]. The strength of these factors, such as awareness, topical knowledge level and associations, causes IN variants in terms of their specificity and formulation. The beginning of this interpretation dates back to 1962 and 1968, respectively, when Taylor's pioneering works conceptualised the IN [13]. The study is detailed in Section 2.2.2. In summary, Taylor approached the concept of IN as the continuum with differing levels of internal (user's awareness, recognition, understanding and interpretation of their IN) and external (features of IN, such as specificity, articulation and interpretation) manifestations. Taylor's approach, originally developed for librarians that operated library information systems (LIS), saw IN as a primary trigger for information search to locate the information resources. Without a primary intention, he also marginally touched on the idea of what is currently regarded as a "user's profile", i.e. a collection of metadata and information about the user.

Next, Atkin [107] and Krikelas [108] approached the concept of IN as a derivative category of uncertainty. They defined IN as a recognised uncertainty that the user achieves to reduce. The uncertainty is defined here as a function of the discrepancy between the user's current state of (possessed) knowledge, which implies a certain level of certainty, and the state they aim to achieve. Differing levels of uncertainty could be attributed to the variation of INs, which is supported by Rubin's [4] characterisation of the certainty-uncertainty spectrum as a continuum.

Confirmation need, defined by Cole [8], is a good representative of this uncertainty dimension. Here, the users already possess the information in question, but they need some form of reassurance to confirm their validity. Consequently, the search process would likely be shorter to obtain a quick match to the user's request. This approach is, therefore, built around the user's moderate or higher levels of subjective uncertainty and, presumably, low confidence [52]. Due to the problem of defining the feeling of certainty in linguistic terms, Yoon and Nilan [109] shifted the emphasis from uncertainty to the user's certainty. They noted that the users, paradoxically, specify a particular situation that causes their INs, i.e. uncertainty, largely in terms of what they already know, i.e. certainty. Taking Rubin's approach [4], certainty is just a level from the spectrum that can be broken down, and even small differences in certainty levels might trigger differences in INs. Establishing certainty as a variable of INs levels (which will be explained in further text) can, thus, help to address the question "What is the information (including a portion of information) that causes the user's uncertainty?".

The idea that IN does not fit a single description presents Wissbrock's [12] proposal of IN. He defined IN as an absence of information necessary for a user to achieve their goals and is a compound consisting of two parts, namely 1) Rational IN as the part of IN the user is aware of and 2) Radical IN as the part of the IN the user is not aware of. In a general model of information seeking [11], the occurrence of IN precedes the interaction with an IR system. In this case, we talk about purposive behaviour, where the information satisfies an information purpose [99]. However, IN realisation is omitted during a non-purposive or incidental behaviour, for example, when the user is browsing the information space without any specific target in mind. Illustrating the Radical INs, the user is aware of their IN, but lacks to define the full scope of IN prior to the beginning of the search. The user relies on IIR to fill these gaps [71, 110]. The engagement with IR and IIR subconsciously affects the user. If the user-system interaction is efficient and productive, it manifests through the user's increased awareness or narrowed focus on the problem. The initial knowledge level, both topical knowledge and knowledge about their INs, is shaped in the context of search [8]. In this case, we can conclude that the aim of search and IN assessment is to increase the degree (expressiveness and specificity) of Rational IN whilst decreasing the degree (from "not aware" to "be aware") of Radical IN.

Context of IN as the trigger and driver for Information Search "The concept is taken as given" [38, 2012, p.2]. Working under this condition and the general acceptance of IN prompted the researchers to take on a new approach to studying the specificities of IN. As we mentioned earlier, IN is faceted and is, therefore, subject to interpretation. Although this perception adds to IN's complexity as a concept, it also provides opportunities for diversified research. A synthesised view of IN merged from different directions allows us, thus, to capture different facets of the same concept.

One such facet is the involvement of context to provide a discussion of the context-sensitive nature of IN [6]. One of the earliest attempts at the contextualism approach represents the Information Seeking Behaviour Model by Wilson [49]. Here, IN benefits from the model's holistic approach integrating broader environmental factors that affect the user's information-seeking behaviour. The author drew attention to IN as a derivative need category triggered to satisfy other underlying and interrelated basic needs, such as physiological, affective or cognitive, with a variable dominancy in certain situations. For instance, in the context of the work environment and the user's work role, less to the extent of satisfying physiological needs, IN is likely to be triggered by cognitive needs (e.g., enhance professional skills, demonstrate problem-solving, as well as affective needs (e.g., promotion).

Savolainen, similarly, hypothesised that IN concept changes depending on the context in which it appears [38]. He identified three major contexts for IN: 1) situation of action, 2) task performance and 3) dialogue and provided an analysis of contextual factors of IN. In the first context, IN is described as temporally and spatially sensitive depending on the characteristics that describe the event that triggers IN awareness, e.g. long-term preparation for an exam might cause a time delay to act upon recognition of IN and produce, thus, deferred needs [108]. On the contrary, in a situation that calls for urgent information, e.g. accident, IN is manifested immediately [108].

In the second context, IN depends on related task attributes, such as complexity, expectancy, outcome determination and importance. IN reflects the subjective interpretation of task requirements using prior knowledge, which can determine the IN. Problem-solving situations with a higher task difficulty [84] often require intensive searching. Here, IN is seen as evolving as the work task is redefined or the problem becomes clearer and alternative ways of action emerge. Task difficulty [84] is a common context-linked factor that produces the differences in the types of information search behaviours - from simple fact-findings or known-item retrieval [37] to exploratory searches or information foraging [35, 111].

Several researchers argue that the task is the primary generator for IN, which, in turn, is seen as a way to determine how to handle the information requirements and task complexity posed by the task. The emerging corpus includes the works by Byström and colleagues [14, 103, 112] or the Information Journey model proposed by Du [113]. IN is redefined here as a dynamic category evolving as the user progresses through the information seeking. In this case, IN emerges as the driver that keeps the user in the loop of information seeking. It leads to an evolution in the understanding of IN and sense-making until the task is completed.

The third, dialogue approach, is mainly derived from the seminal paper by Taylor [13] (see Section 2.2.2). IN is viewed as a continuum on the question specificity (terminology, articulation) formed and changed as the conversation progresses. This context is highly linked to the previous two contexts as the reason to engage in the conversation is often to better understand the situational and task context. In summary, having IN connected to its context, even more, highlights its information purpose [99]. For instance, the existence of the task as an externally imposed factor, IN arises from, makes the search behaviour purposive [30], i.e. directed towards solving the task. In contrast to an incidental search that is fairly driven by spontaneity.

A similar opinion was brought up by Nicholas [114], who extended the range of contextual factors behind IN, including demographic factors, such as information awareness, time availability, and information overload. They created a framework for assessing IN and was used in developing a portrait of INs of a specific group - folk music library enthusiasts [115]. This brings us to another facet of IN related to its subjective nature. As it is not feasible to study INs on an individual basis, extensive research has been performed into understanding INs of users sharing a common interest or being of a particular occupation as they tend to have similar preferences and INs. These groups include students [5, 116], users of domain-specific libraries [115, 117, 118], patients [119, 120], nurses [121], musicians [122, 123], young mothers and fathers [124, 125], e-commerce customers [126] and many more. We learnt about micro-worlds of different socio-cultural and economic groups or cliques, often sourcing from interviews and in-field investigations. They inform about the within-group information-seeking behaviours and increase awareness about the information search barriers these groups face (e.g., social, personal, and information inequalities). Moreover, the variety of environments the INs have been investigated in, made the IN a transdisciplinary component studied as a part of pre-requisites for the design of information systems, such as health care IR [127, 128] or patient portals [129].

Cognition behind the realisation of Information Need

The previous studies classified IN as 1) the initiator of information seeking and search triggered by the user's realisation of the lack of information [99] or 2) a derivative term of contextual motivators [6, 31, 38, 49] with the interpretation of INs depending on the context of a specific research category.

In the context of internal manifestations of the realisation of IN, a few studies attributed IN to a gap in knowledge [10], uncertainty [5], feelings of unease [8] and feeling of dissatisfaction [97]. These abstract terms describe IN origins as very subjective manifestations, making it all the more challenging to conduct measurements on a large scale. One such was the investigation of user behaviours and experiences [52] which later developed into the Information Search Process (ISP) Model, which modelled the cognitive and affective behaviours throughout the phases of ISP [5]. ISP Model drew attention to the search as the process of sense-making for users who actively search for new information to fit into what they already know on a particular topic.

Therefore, topical knowledge, which Kuhlthau calls " a personal frame of reference" [5, 1991, p.361], plays a vital part in the constructive process of understanding and resolving the problem. Additionally, the evidence showed that natural for ISP are feelings of uncertainty and confusion, even feelings of anxiety, particularly intensive at the beginning of the ISP. These can be perceived as early signs of affective pre-manifestations of INs, possibly from the lack of knowledge, as Kuhlthau further suggests. IN can occur first as a feeling of a disagreement with the user's beliefs [3, 8, 13] that prompts the user to enquire more information. The cognitive formulation of the problem can be seen as a turning point in the evolution process, where incoming information increases confidence and enhances the user's ability to specify the problem. Concerning the variability of affective and cognitive manifestations, representing the user's underlying state of knowing and derived INs, is an important and still current challenge of search system design and user support [28]. Motivated by this study, an empirical study by Moshfeghi et al. [69] directly measured users' affective and physiological signals (e.g., facial expressions, heart rate and skin temperature) whilst the users performed image relevance judgments. The signals were used as a complementary input to behavioural data (dwell time). The outcomes showed that a significant improvement in relevance judgement prediction was achieved for the combination of affective signals with the dwell time.

The cognitive elements of IN appeared already in the early IR and information science research. The study by Taylor [13] (see Section 2.2.2) delivered one of the most respectful and highly influential outlook on IN concept. It described the development of IN, often initiated as a vague feeling of dissatisfaction, as a journey from the query back to the core of the actual need, so-called within-brain IN, existing in the user's mind. In this study, we first encounter the idea of the brain, which indirectly brings us to cognition and awareness mechanisms. Furthermore, the ASK Model by Belkin et al. [3] (see Section 2.2.3) hypothesised that variations of ASK and the associated anomaly exist depending on the level of an individual's knowledge.

As per Taylor's model [13], INs in their earlier stages are difficult to formulate as a query to a system. The searchers perceive their INs only as a gap in understanding. The understanding is attributed to the functioning and control of human cognitive and perceptual systems. Belkin et al.'s [3] modelled the user's conceptual state of knowledge consisting of concepts and beliefs accessible via the functions of the person's cognitive system. According to Cole [8], research must go beyond the investigation of single concepts and focus on how we naturally think through problems and how we make (un)reasonable decisions. Employing a broader picture of information seeking that goes beyond the input-output information model is a key to driving the memorable IR

[76] built on knowledge generation. The effectiveness of the processes to address the issue of the effective resolution of IN is even more pronounced in the current state of the computerised and automated environment.

Previous studies [52, 94] emphasised two areas, providing a guide towards a cognitive variety of IN in the context of cognitive-oriented IR research. The first area is the user's inner feeling of disagreement caused by the user's realisation that their current knowledge is insufficient to cover the current situation, which raises the opportunity for an IN to arise. Yet, states of knowledge as the source of users' INs have not been investigated in-depth and even less on the empirical basis. Second is the focus on reasoning as part of the human cognitive functions contributing to the realisation of IN. In addition to constructing the problem in the searcher's mind, they evaluate the available actions to resolve it. So, information search taken as an action to resolve the INs is rationalised. Both of these facets of IN originate from a deeper perception of IN. The importance of both is immense, as they affect the user's information search behaviour and the phases in the IR process, such as query construction or evaluation criteria for relevance [12].

Traditional behavioural-lead investigation with direct involvement of the users employ interviews [130], surveys or reflective diaries [5]. They require the dedication of the study subjects to pay attention to every detail in their experience to avoid missing anything potentially important. Also, they are highly subjective, and despite their informativeness in terms of description of subjective feelings and actions, the problem might appear very early in the study for the participants, such as information overload [75, 76] or cognitive overload [73, 74]. As has been established, initial stages evoke INs that are hard for the subject to articulate. New methods should be investigated in order to translate these subjective experiences into different and perhaps objective measurements. The issue might be addressed by employing interdisciplinary approaches, such as the prospect of neuroscience and cognitive psychology methods. The establishment of the NeuraSearch branch of IR research [21, 131, 132] is presented in the next Section 2.3.4, which deals with simultaneous monitoring of brain signals in an IR scenario and capturing the behavioural data.

This approach is beneficial to methodologically validate the abstract structures and theoretical paradigms related to the cognitive context of IN, such Cole's work about the information processing using knowledge frames explained in relation to IN [8]. Design of natural and intuitive thinking behind the information search must progress by 1) utilising deeper levels of IN that are driven by the context of the user's knowledge [6], and 2) considering the transfer of INs and retrieved information on the spectrum of data-information-knowledge [8]. **In summary, all these works can be seen as a transition towards more peculiar investigations that use built on the user's cognitive context information as a source of searcher's IN [133], which ultimately affects the user expectations and satisfaction criteria. Particularly crucial in this regard is to increase the informativeness about the cognitive underpinnings of the realisation of INs (e.g., knowledge context). In particular, to understand 1) IN and the variants of INs and 2) the user's perception of the IR information product that is needed to satisfy the IN and its match to what the user already knows.**

Current Behavioural Studies

The current mechanisms on top of which the mainstream search engines are built, do not implement the recognition of the query's intent influencing the expected output. Contextual-adaptation is an emerging area of IR [77, 78, 92]. Its advantage is using large quantities of available (or semi-available) data and metadata related to online search used to derive the IN context. Benetka et al. [26] questioned if specific geo-locations (based on geo-location tags of search queries) trigger specific INs, i.e. anticipatory INs. The study found a significant amount of independent questions (context-free), and the needs varied across single locations. However, the nature of these studies utilises indirect engagement with the users and the retrospective analysis where INs are described by the metadata of the input query. The direct examination of the user's individual's prior knowledge as a source of IN is represented by emerging research influenced by cognitive psychology and neuroscience.

As we pointed out, the meaning of IN highly depends on the perspective we look at. According to the system side, IN is represented as a query or request to retrieve the information from the underlying database of documents. Systems respond based on how well the system is designed and programmed to understand the query and match it to a relevant document. From the user point of view, this can be a more complicated journey [133]. The strategy of seeking, e.g. exploratory, IN depends upon how well the user can explain his needs concerning their existing knowledge.

Search is stimulated by the user's prior knowledge about the topic the sought information would fit in and the searcher's intent that specifies how the information in question will be used. For instance, the searcher might want to expand the (topical) knowledge, re-find the information or confirm what they already know. So, to ask "What does the user not know?" in order to establish the user's IN is difficult since the users themselves have problems answering that, and often, they only know the intent. In accordance with [109], the question has to be flipped to reflect the positive evidence of knowing by asking "What does the user already know?" or from the position of the user's self-reflection, "What do we already know?".

Without any significant prior knowledge in cognitive sciences, it is an established notion that internal information is retrievable from our memory as a storage for the knowledge we gathered throughout our life [3, 8, 9]. The question "What do we already know" implies the spectrum of knowledge, from the state of "We do not know anything" to "We know", including a partial knowing or remembering. Many of us use search engines to look for specific information, e.g. beginning of the Thirty Years' War, as we possess only partial information, e.g. Thirty Years' War happened in the 17th century, and we cannot recall the supplement, e.g. 1618. This search strategy is defined as known-item retrieval [37]. The user knows exactly what they are looking for and what the answer should contain (e.g. format as number). The retrieved answer provides the information that fills for the lack of content, i.e. semantics. Information Needs can therefore arise from the temporal unavailability to recall the information from memory or the uncertainty of the correctness of the information we possess. This mental state is described by a term commonly used in metacognitive studies, "Feeling of Knowing" (FOK) or "Tip of Tongue" (TOT). Both represent an intermediate recall state [134]. It is a common phenomenon when the user perceives immediate inaccessibility of retrieval, and the instant retrieval depends on a small clue to recall the information. Acknowledging the lack of categorisation of searchers in this regard, one of the latest addition to the IR community was introduced by Arguello et al. [95]. They identified searchers in TOT states with their INs presented as TOT requests and the information search process the searchers undergo specified as "TOT known-item retrieval". Authors were explicitly interested in characteristics of TOT requests posted on online forums from a user who could not recall a specific movie title but were able to provide additional characteristics based on their past experiences with the movie. The results proved that users in TOT states expressed their needs using the recall of declarative memories system [135]. In particular, they used the semantic information (semantics memory) of the movie, e.g. name of the actor, director, and genre, as well as information retrieved from their episodic memory, such as year or location they watched the movie, description of scenes, and characters descriptions. The study brought out a new perspective on how the user might perceive their IN, which ultimately affects not only the articulation of the IN but also the user search behaviours. Users reported failed attempts using online search engines, which urged them to seek help from community users. **This acknowledgement furthermore opens up a new area of research supporting users in these states. In order to develop a support strategy, more research is needed to understand a broader spectrum of users' cognitive states by their origin.** The present studies strengthen the link between FOK, TOT and IN. First, from the theoretical perspective, the user's FOK implies temporal inaccessibility of internal information in question, which is by definition a premise of IN to be formed [97]. Second, supported by the empirical results, the types of FOK have been examined as a type of IN states [95].

A growing amount of research concerning the relationships between the searcher's internal memory systems (i.e., what the searcher knows) and the external information (i.e., what is "out there" available to know) [71]. The prospective position of FOK in IS&R literature was strengthened by utilising user rates of FOK in relation to Internet search. Access to available external information means for the user to subconsciously rely on this information, extending it as part of their scope of knowledge [110]. The study by Ferguson et al. [136] demonstrated that individuals relied on the Internet data to increase their knowledge prospects in a simulated Q/A scenario and even formed with the Internet so-called "Transactive memory systems". Here, the user acts as an inquirer and the information recipient, whilst the Internet is the provider. The study found that the user has significant reliability on the Internet results, which consequently increases the person's FOK. In this case, FOK is the personal feeling that with access to the Internet, the person is likely to be more successful in answering. The user, thus, in a sense, offloads the responsibility to answer onto the Internet. Establishing the link between FOK and IN earlier, the present findings can expand the notion of IN in search and characterise IN as a product of our internal knowledge with the sense of availability of external information. We recommend validating and further investigating this view.

We see the potential of the novel studies targetting mental states of knowledge representation growing in size. TOT has been recognised as an intermediary state that might lead to a rise of IN, which subsequently poses a question about the impact of these findings in the context of future development of search systems and engines towards improved support for users. More clarification is needed, especially on how these novel states are formed concerning the user's existing knowledge; how the information fits into what the user already knows and how these states affect the searcher's expectations and behaviours [137, 138].

2.2.2 Four-levels of Information Need by Taylor (1968)

One of the earliest papers presenting a mental aspect of IN named " Question-Negotiation and Information Seeking in Libraries" by Taylor [13] from 1968. The study provides a communication package for librarians in the early times of Library Information Systems (LIS) with limited functionality, where libraries served as main information resources. Different stages of IN only highlighted the importance of the necessity of a constructive dialogue created by librarians, acting as intermediaries, to provide relevant aid to people with their inquiries. This study brought out a new outlook on the nature of IN and structured it as a continuum with different user awareness levels. Taylor recognised that a primary form of IN can be characterised as “a vague feeling of dissatisfaction” [13, 1968, p.182]. This idea of using the person’s mental state underlying the definition of IN helped to diversify the view about IN from the user’s perspective.

This view was developed into the dynamic model of IN. The model’s central feature is the transformation of specificity and expressiveness in linguistic terms underlying the IN along its continuum of four stages, each built and dependent on the previous one. The first level Q1-*visceral need* conveys the user’s actual need denoted with the absence of expressive linguistic terms, even the absence of consciousness. The move onto the next stage happens when the user adds more information and starts to form a description of their need. At the next level, Q2-*conscious need*, the user still feels ambiguous in terms of the area of the need, yet they are conscious of forming a mental description of their need. Next, Q3-*formalised need* is a statement of the need with concrete terms followed by Q4-*compromised need*, which is a conversion of their specific need to a query input to an information source, i.e. LIS, whilst considering the file organisations.

Information Need is represented here as a question. In each stage, the configuration of the question changes. The higher the level of IN, the higher the level of i) specificity of the question that underlies IN, and ii) expressiveness of IN in linguistic terms. Also, IN becomes more focused at each stage as the user is capable of narrowing down the solution representations toward satisfying the current problematic situation. However, the boundaries between levels are hypothetical, and the differences are mainly described according to changes in linguistic terms. Thus, it is not a simple task to investigate these levels on a behavioural basis.

The important factor appears to be the inquirer’s “subject knowledge”. Taylor suggests a downstream communication, which is driven by librarians. They utilise the discussion via the reference questions to assist the inquirer in returning to the problem’s core. The formation of INs (questions) helps to narrow down the focus. Librarian is often responsible for interpreting the discussion with the inquirer and constructing the Q4 level. They consider the file organisation system to fit the records to that interpretation and perform an effective search. The inquirer’s a priori picture of the expected outcomes is altered throughout this process employed with feedback.

Furthermore, Taylor suggested considering additional information related to the inquirer that would help them to arrive at an improved understanding of their needs and the extent of the search subject. These relate to interrogations about the motivation behind the IN, objectives, inquirer's background information and anticipations. This very much reminds an early form of personalisation experiences with consideration of the context of search and creation of personal profiles in order to help to (re-)formulate their IN. The assessment of the communication and information was done by specialist librarians themselves. Such assessments are automatically handled in the current information systems, using the early configuration of accounts asking for personal preferences or questionnaires. In the present form, the recommendation systems with access to users' historical records and transactions can recommend complementary information (e.g., genre-matching books) and anticipate possible future INs of their users.

Even though the study dates back to the 1960s, it keeps on contributing and inspiring present theoretical and conceptual frameworks [8, 28, 139, 140] and proving its significance as a "a timeless article" [141, 2015, p.247]. It remains more difficult to investigate on an empirical basis due to the difficulties of capturing the early levels as they are visceral. An insightful investigation used a qualitative analysis of IN states extracted from the transcribed voice-based conversations [142] to identify the linguistic features of each IN level. Next, the online forums were considered a relevant representation of people's confession of their inner states [143] where the focus was to differentiate between Q2 and Q3 based on language and textual descriptions associated with these needs.

IR system based on a growing "Self-Help" Approach

Taylor already realised the need for LIS to evolve as a part of a growing complex of communication systems. Moreover, the librarians' work might be exhausted as they cannot handle the growing demand on their services. Therefore, the system should be adaptive and intuitive enough to allow the users to self-help as part of a bigger picture built upon their self-direction and self-assessment. Still, the system should reflect the nature of the question-negotiation process (termed a question-based system), even in the absence of an intermediary.

At first, the challenge is to account for the user's initial feeling of ambiguity termed as "an area of doubt" [13, 1968, p.182], which caused the user to take action of search in the first place. The term "area" intuitively depicts a broader scope of the problem and, therefore, the system should be required to work with several variants and alteration of the question. Synthesising Taylor's proposition, the question-based system should implement a feedback mechanism through which the user responds to the outcomes of the search process, such as relevance feedback. This design allows easier development of IN and alteration of initial questions. The system itself is adaptive with feedback to allow it to learn and restructure its static parts. The interface should be designed to promote the interrogation process and build an interrelationship between the user and recorded knowledge in the system corpus. This idea implies that a focus on underlying knowledge is, thus, crucial. Utilising knowledge indexing and categorisation might severely increase the ease of use and progression of INs. The efficiency of search is the main attribute of such a system that allows the opportunity for self-generated INs based on how new information fits the current knowledge. Functional organisation of knowledge might also severely contribute to the transparency of the retrieved outcomes. In addition, from the search beginning, the user needs to achieve clarity about the content of the retrieved documents and the associated paths and links with the particular document. A common problem in the online space is the hypertext, where the users likely feel overwhelmed and lose track of their current position, which negatively impacts them, e.g. with feelings of information overload [144].

Unsurprisingly, these early recommendations coincide with present-based functional and design principles for information systems. They remain a valid premise for effective and efficient communication from the user-centred systems perspective.

2.2.3 Anomalous State of Knowledge by Belkin (1982)

Belkin et al.[3] introduced a perspective on IN accentuating users' gaps in knowledge, defined here as "the anomaly", in order to understand the drivers of INs. The resulting

Anomalous State of Knowledge (ASK) has become one of the well-established works related to defining the concept of IN.

ASK's disposition is hypothesised on a situation when the user is unable to specify their needs (in the form of a query to a system); however, the user is aware of their anomaly in knowledge concerning the situation. It was created as a response to the prevalent best-match retrieval (see Section 2.1.1) and the missing realistic feel to an IR system, mainly the absence of user-specific aspects of uncertainty and doubts in the user's state of knowledge. These are, in paradox, seen as triggers of one's engagement in an information search scenario, so their involvement should be taken into account.

Out of the definition of ASK, we can derive the primary premise of ASK being the human-native self-awareness mechanism to allow the recognition of the anomaly, with IN being just a reaction upon such realisation. That brings us to the second premise, clarifying that the anomaly does not necessarily have to be named explicitly but is manifested commonly as a feeling of uncertainty or doubt. The person then actively uses the degree of anomaly (e.g., degree of uncertainty) to guide their actions. That is, the nature of anomaly in knowledge is multifaceted and multimodal.

In contrast to a known-item scenario [37] with a well-defined question (question), a person often faces other situations which require a more thorough search consisting of a series of updates of knowledge, INs and shifts of search focus. Resolution of ASK is, thus, performed in iterations. As a result, anomaly and the user's perception of the problem change with each instance of communication between the user and the system's mechanism implemented to satisfy it.

Second, from a cognitive viewpoint, the state of knowledge mediates the interactions between humans and, analogously, between the user and the system. This experience must have a progressive character for the user. In this case, the users feel that search activity helps them develop a more concise picture of the problem by modulating their initial state of knowing. In general, the interactions with the systems aim to resolve INs expressed by often imprecise queries based on ill-defined ASK [2], creating a premise for a variety of ASKs. An accurate resolution of ASK is then necessary to achieve the efficiency of IR to solve the user's IN.

We now map ASK to Wissbrock's formula of IN [12] as a join of radical and rational IN, presented in Section 2.2. The ASK is transformed during the IR process and the user interaction with the information, which is reflected explicitly as transformed rational INs (e.g., queries). At the same time, radical INs are impacted, reflecting an implicit transformation of ASK and the inherent anomaly. The more we engage in search to solve the recognised anomaly, the more we start to fill in the other gaps we were not even aware of (radical IN), causing our increased awareness in the area of doubt [97]. As Belkin et al. claimed, ASK is a multidimensional phenomenon. The interaction with the system and information helps the users to uncover the network of knowledge associations that positively impacts the user's comprehension of their actual INs. If documents represent "a coherent state of knowledge" [3, 1982, p.64], the query or a statement related to an anomalous situation represents the incoherent internal state of knowledge. Iterations of interactions taken during the search process and exposures to new information balance out the user's incomplete knowledge to gain internal coherence.

ASK IR System with Cognitive View of IR Situation

Despite all the technical and technological advances in the last decades, the introduction of an anomalous knowledge element is well rooted in the notions of IN. The other element in the study that withstands the effects of time is the proposition of so-called "second-generation IR systems" [3, 1982, p.63] which implement the representation of ASK, i.e. ASK-IR system. We now proceed to report on its main constructs.

Conceptual State of Knowledge Belkin et al. defined the key input and driver of the user-system information exchange termed as "Conceptual state of knowledge" [3, 1982, p.65] as an underlying organisation of information for both parties. The user's state is comprised of their own knowledge and other personal factors, such as beliefs, whilst the system's one is formed by a corpus of documents and their organisation and the representation of text and media. Straightforwardly, the conceptual state of knowledge is the logical storage of the internal information of their respective parties. The user's state of knowledge is updated in each iteration of IR, i.e. at the intersection of both “systems”. Meanwhile, the system’s state is manipulated, but the content remains intact. The common operation performed on top of both is the retrieval of the information with mutual influence. The system’s retrieval mechanism depends on the outcome of the user’s retrieval, i.e. anomaly, represented in an appropriate form. In spite of the fundamental role of the representation of ASK and the anomaly, this representation leads to problems since the user’s ASK is query-unspecifiable (i.e., the user cannot construct a query in the particular ASK). The requirement for the ASK-IR system is an adaptive mechanism that enables it to adapt the system’s state to the user’s state of knowledge. In particular, it would assist the user in specifying their uneasy ASK, interpreting it, adapting the retrieval to increase efficiency, and, at last, integrating the user’s feedback as part of the communication process.

Representation of anomalies in IR system According to the authors, the ASK-IR system calls for an interactive, adaptive functionality of the retrieval mechanism to variants of ASK whilst providing iterative evaluation and recognition of the anomaly. Belkin et al. assumed that there exist different types of ASK that would require different retrieval mechanisms. In order to implement the ASK-IR system, it requires the representation of the types of anomalies upon which IN could be specified. This requirement extends over the system design principles and highlights the iterative and interactive evaluation of the problem the user faces as the primary element of the system. Despite Belkin et al.’s recognition of types of ASK, they did not draw out any criteria for how to differentiate them. The answer was brought by Wissbrock [12], who defined two areas in representing the magnitude of the anomaly. Firstly, the anomaly outlined by the question, “How specific is the anomaly to the user?” represents the cognitive element of ASK and highlights the individuality of the user. The additional question asking, “How deep do we recognise the anomaly?” supports our assumption about the relationship of the anomaly with relational and radical IN, brought up earlier in the text. The second element of ASK relates to the linguistics side of the anomaly by asking “Can we create a narrative?”.

A suggestion by Belkin et al. on how to specify the anomaly was to use word associations as the means of representing individuals' states of knowledge about the subject whilst considering the user's larger-scale intentions and goals. For instance, to involve more context of the information scenario and the quality of defined information [2]. The formulation of the problem statement was aimed at constructing a representation of the ASK and achieving the query-less specification of IN. They introduced a formal five-degree ASK classification scheme with the class reflecting how well the user understands the problem situation. It ranged from well-formed to ill-formed, associated with the quality of the problem statement. The schema was used during the investigation of thirty-five narratives to identify the most prominent relevance criteria associated with each class [45], e.g. novelty, topicality, presentation. The differences in usage patterns of the criteria also drew out the differences in the evaluation of INs based on the problem statement.

Conclusion We conclude that in order for the ASK-IR system to work, it has to implement the following:

1. Methods of how to obtain problem statement from the user.
2. Anomaly representation and evaluation mechanism in order for the IR system to encode the problem statement, convert it to IN and make it ready to be processed by an IR system.
3. Document structure (corpus) with associative and modal structures.

We will reflect on these comments in the last Chapter 8 Section 8.3.3 using the findings of the present thesis.

2.2.4 On the analogy between Q1-Q4 Model (Taylor) and ASK (Belkin et al.)

At first, we start with analysing similarities between both studies at the high level before moving on to more specific parts later. ASK has been referred to as an extension to Taylor's model [28] with a high level of interrelation.

Both concepts bring to attention the level of personality, the user's individuality and the subjective nature of their respective INs. Further dynamicity is given by the interactions with the world (as the representation of the external objective information). These stem from the natural abilities of humans, such as curiosity or interest to fill out the missing pieces in a state of perceived incompleteness or inadequacy in the subjective picture of the world. Although, as Cole [28] suggested, the actual cover of all the involved structures is broader, which will be explained later.

Taylor's extension of MacKay's idea [145] of "State of Readiness" represents the user's state of anticipation and readiness as the input for the actions for the situation user is in, e.g. to interact with the search system. This anticipation is based on a user's picture of the work created of previous experiences and incidents with the information systems, and search incidents. Belkin et al. proposed the "Conceptual State of the Knowledge" which conforms to this definition with a higher emphasis on the element of prior knowledge as the co-creator of the user's internal picture and the connector between i) user's ASK and INs and ii) INs and the judgment of IR's outcome. According to Taylor, the searcher's inquiry is based on the underlying "area of doubt" [13, 1968, p.179], addressing the user's dissatisfaction as the early manifestations of INs. The term "area" intuitively implies an extensive space for INs to arise in and to be satisfied in. Therefore, it covers not only the information space, but also the range of manifestations and modalities of INs. These characteristics conform to the definition of ASK's realisation of anomaly accompanied by hard-to-express doubts and uncertainty. To address this loop, we look at the underlying processes producing these manifestations. The feeling of the anomaly is underpinned by the self-aware or self-exploratory mechanisms allowing the user "to look through his own files" [13, 1968, p.18]) to fill in the own context of knowledge abilities, i.e. user's state of knowledge as the information to determine IN.

Both studies share the perception of IN and the focus on what lies behind IN. The ASK is not an equal substitution of IN, but reflects the realisation of the anomaly and journey to (self-)clarify users' anomaly. Taylor puts at the forefront the "actual" need (Q1), which is also more of a mental state lying deep in the user's cognition and surpasses beyond IN and the query.

The remaining problem is the same on both ends, and that is the representation of the anomaly (ASK) and the lower levels of INs (from Q3 to Q1). Q4 might lead to a false direction during information search due to wrongly elicited output from the system. Although it might conform to Q4, paradoxically, it does not truly reflect the Q1 of the searcher [13]. The proposed way is to work downwards towards the lower levels to overcome searchers' false interpretation of their needs. Interactions and iterations enable incoming information to flow in the cognitive mechanisms and help the user to explore the underlying area of doubt and unfocused thoughts they did not admit before.

In a fact-finding scenario, the expected answer is easy to predict, and the optimal query for a skilled user is easy to construct (compromised Q4). However, in a situation requiring the engagement of exploratory skills, the accurate representation of IN is problematic. Therefore the thing that comes to question is to set a baseline. ASK and Q1-Q4 are 'measurements of the unbalance" [28, 2020, p.13]. In Belkin et al.'s approach, the knowledge anomaly can be measured between the user's subjective knowledge and the objective knowledge on a research topic or an area of interest given by the relevant documents corpus. Similarly, moving up the levels (Q1, Q2, Q3) of Taylor's model, the dissonance with the user's Q1 increases.

The relatedness between Taylor's model and ASK by Cole (2012 & 2020)

The recent relation between ASK and Q1 level was brought by Cole [28], which was highly influenced by his early attempt [8] to introduce a deeper understanding of IN, largely based on Minsky's Frame Theory for knowledge representation [17]. In brief, the frames are the user's "mental representations" of their past episodic interactions with the outside world. In the context of the current problematic situation, the user's internal cognitive mechanisms locate the relevant frames and examine them to guide the assessment of the current situation. For this reason, they are attributed as "expectations" frames. In the current Internet age, where Google became a synonym for search, used practically daily, it became more accessible for the searcher to predict how to optimally formulate queries (e.g., often short queries) and what output to expect. A new search is actually a re-occurring situation, with "new" only referring to a current time point. The searcher re-uses the frames to predict subsequent similar searches. The content of the frame indicates "a priori picture of what he [the user] expects" [13, 1968, p.187], bringing up the aspects of the past to the user's consciousness as an expectation frame.

The frame structure formalises the ASK's proposition of the Conceptual State of Knowledge. The frame is an object about a search topic existing in the user's memory and available to recall in a new situation. Frames evolve as the user's knowledge and experiences evolve and are re-used. They consist of three basic elements from top to bottom:

- Knowledge, accepted by the user as objective knowledge about the world. To specify, it is the user's subjective knowledge about the objective truth.
- Personal beliefs, representing user's own perspectives on the topic, opinions and hypotheses. Beliefs are uncertain, variable and dynamic. They become active as the searcher begins to engage in research to form their own opinions tied to the personal abilities of analysis and critical thinking of the searcher. Uncertainty attribute is incorporated into beliefs which subsequently creates a set of alternatives with probabilities assigned to them, i.e. expectation set. It plays an important part that directs further information seeking, which "may or may not establish the belief as knowledge" [28, 2020, p.6].
- Registry, storage for initial impressions and perceptions, so-called "floating aspects of knowledge facts" [28, 2020, p.7] picked up by the searcher in a preliminary scan to create a topic outline. Often, the user is unaware of them. They might later prove to be relevant to the topic frame and, similarly to beliefs, "potentially leading a new knowledge production" [28, 2020, p.7]. These are essential to the Q1 level.

This framework of objectification using topic expectation frames gives the baseline for facilitating both Taylor and ASK Model. "The stronger the frames, the more efficient they are because we see the world we live in with greater understanding" [28, 2020, p.9].

Misleading problem of expectation frame The user mechanically transfers the content of the frame, episodic memories into the keywords that constitute his query to the search engine, meaning the searcher's actions are detained in and limited by their expectation frame. The consequence of this problem, linked to the expectation frame, emerges as the cognitive dissonance between Q4 and Q1. That is, the output to a query is relevant on the outside but does not satisfy the searcher's visceral level (Q1), causing the searcher to be in the wrong IN mode. Having now the mechanical object linked to the input of the user's cognitive context, Cole proposed the model that resolves the user's Q1 via an updated expectation frame based on the ASK of the searcher.

Determining Q1 through "The Q1 actualising intervention model" The user's ASK is the necessary component for the model. However, as we learnt, ASK is challenging to specify for the users. Therefore, Cole approached the ASK not as a single statement format but rather as "an ASK set" that interconnects the particular beliefs and uncertainties underpinning the ASK. Based on this premise, Cole developed the model that facilitates this structure. This model relies on the intervention mechanism by asking the searcher to give four alternative reasons for this particular belief. The searcher has to start their statement as "I believe X to be true because ..." representing a particular belief the user has about an aspect of their search topic. The user then assigns the uncertainty distribution to each statement in order to create "an ASK expectation set". The final distribution informs about the probability of each alternative to be selected by the user for further investigation, and it actualises, meaning it strengthens the beliefs part of the frame about the topic (see the frame's structure in the earlier part of this section). As a result, the user's self-awareness and understanding of their personal contextual position (i.e., user's cognitive context) are positively affected.

The purpose of four alternatives is for the user to employ cognitive and introspective functions, as well as the reasoning to explain why they hold this particular belief about their search topic. Consequently, their ASK is updated by facilitating a broader internal search using relevant and interconnected frames. “The searcher in this conception of Taylor’s Q1-level information must have an organic, relational function with the world of information to produce new knowledge.” [28, 2020, p.11]. As a result, the user’s self-identity produces updated (strengthened) frames based on organic knowledge rather than floating, inorganic knowledge facts. Then, the alternative with the highest actualised uncertainty distribution becomes the Q1 representation in charge of further information seeking. “He is now asking questions about the topic that has meaning to him” [28, 2020, p.13]. The user is finally in a correct and strengthened state of readiness.

In summary, the user’s self-intervention is the core of the mechanism to resolve both Q1 and ASK. Furthermore, it signifies the need for the (user’s) introspective analysis and manipulation of the relational knowledge objects (frames), which provides an improved understanding of the context of their anomalies and ASK and the actual needs (Q1). The model’s outcome help the user to create rational and self-identified INs. The model’s applicability should, however, consider its contextual suitability and effectiveness before its implementation. If used unnecessary, the deep self-insight the user is trying to facilitate might be counterproductive and instead increase the cognitive overload of the user [146]. Thus, the effective strategy should be preceded by the information that determines the user’s position with respect to the search and the information gain. For instance, the information about the user’s availability or information urgency and other factors of efficiency, such as cost and time.

Essentially, the presented mechanism is a self-help user-based model that increases confidence via understanding the internal inter-related anomalies and reduces the discordance between the user’s posed Q4 and finding his real need (Q1). As such, it addresses the first requirement of the ASK-IR model related to the methods to determine the ASK (see Section LR-BelkinSystem). Since no behavioural studies implementing this method were found, evaluating this method’s outcomes and effectiveness is recommended.

Our thesis will not evaluate this particular scenario. **However, as outlined by**

our aim presented earlier, we will aim to investigate the activity of users' cognitive processes as a form of data potentially informative of the users' cognitive context in IR, in particular their ASK. We promote the evaluation of introspective metamememonic and mnemonic functions with respect to the user's anomalies and respective variants of ASK.

2.3 Establishing NeuraSearch Science

In the field of IS&R, a relatively new branch of cross-disciplinary research emerged, expanding the traditional behavioural studies with a new element, by simultaneous acquisition of the users' brain data. The concerns over the limitations of the tools employed in user studies, such as surveys, questionnaires or interviews, motivated the interest of researchers in diversifying the methodological approaches, qualitative and quantitative metrics, measurement tools and the data source itself. An early attempt by Moshfeghi and Jose [69] tested the reliability of human biological signals, i.e. affective (facial expressions) and physiological signals (heart rate, skin temperature, neural activity), as a potential complementary information source for the user relevance feedback. The results showed the improved predictive capability of signals derived from sensory channels when combined with behavioural signals, such as dwell time (i.e., time an IR user spent viewing an information document). If we look at this approach from the perspective of the user-centred design in IIR (see Section 2.1.1), the user's involvement has been accelerated. In the interdisciplinary research of *NeuraSearch*, the users' responses and external behaviour (e.g., user-system interactions, button clicks) are represented by the detected biological signals, most commonly brain signals. The novelty of NeuraSearch lies in its quest to answer questions such as, "Do brain data provide a reliable signal that informs about the user's cognitive context in relation to their search behaviour?". Moreover, "Can the user brain signal be employed to control the user's search experience?". Some of the questions cannot be answered at once or by a single study and require cascading research that gradually reveals pieces of relevant information. IR and IIR are complex processes involving separate components of user interaction, such as IN, query construction or relevance feedback. To better understand the whole process from the perspective of the associated user's neural manifestations, separate investigations are advised to be undertaken to gradually and confidently complete the picture. The selected NeuraSearch studies, which we are going to present later in the text, were designed with the aim to contribute to i) demonstrate the neural manifestation of user interactions, ii) validate the data applicability as a source of complementary and meaningful data input into IR models, and iii) increase the clarity about established phenomenons and, ultimately, to challenge their definitions.

From a long-term perspective, the NeuraSearch research provides essential data to build new architectures, models and prototypes [147] for neuro-adaptive IIR [132]. The utilisation of brain signals as a complementary source of information can intensify some of these models' attributes:

- Robustness. NeuraSearch as a concept has been introduced as a series of experimental studies. Multiple investigations of the same concept were done using varied scenarios or different neuroimaging tools. Understanding single concepts in this sense helps build a reliable and robust system capable of evolving with new studies.
- Adaptability. Neuro-adaptive IIR [132] accommodates perceived neurophysiological signals as the data input to evaluate.
- Pro-activeness and Autonomy. The system utilises human-like cognitive capabilities (e.g., learning) in order to act in the current situation and modify a set of actions based on current and predicted states. Higher order of pro-activeness means that the system represents, to some degree, a substitute for the user commands. A higher level of autonomy allows the system to act on behalf of the user.

Brain imaging techniques provide us with a unique tool to acquire information about human cognitive processing. Collected data represent the subject's engagement of the brain functionalities manifested as neural activity. The precision of acquired data, depending on the chosen neuroimaging technique and the aim of the particular investigation, is determined by two qualities: 1) spatial resolution, which allows obtaining insight into the spatial distribution of activity or ii) temporal resolution, to observe the dynamicity and transitions between the neural states. The latter is well captured by the technique of Electroencephalography (EEG) which provides us with information related to the fine temporal dynamicity of the neural activity. This functionality enables us to match the information search activity (e.g., implicit relevance judgement) with the properties of the brain manifestation (e.g., spatio-temporal properties or latency of the activity). For example, findings from a study [148] related to image relevance judgments showed such manifestations before the user makes an explicit response.

The NeuraSearch investigation is usually built on simplified block-design scenarios [11] which:

- Separate the task into coherent blocks causing the isolation of the relevant brain activity and subsequent associations with the investigated phenomenon;
- Minimises information and cognitive overload on the subjects.

. Simplification is delivered by adapting the traditional IR scenarios to fit the requirements of a specific technique.

A cross-disciplinary element of NeuraSearch combines the knowledge of and the advances in computer and information science with the knowledge in neuroscience and cognitive psychology. The research concerns the insight into user experience with the systems and the user's internal experiences during a search scenario explained by neurocognitive functions. Data collected during such scenarios is a crucial element of the research as they drive the discovery of underlying neurophysiological patterns. We do not have to go far to look for a highly successful example of a relatively new interdisciplinary field of Bioinformatics that originated from the same data-driven principles. Now, many universities offer undergraduate and postgraduate degrees in Bioinformatics.

The number of NeuraSearch studies since its introduction grew in size and in the variety of topics they covered. Success and rise in studies over the last decade brought attention to this research by Müller-Putz et al.[131]. Further awareness about NeuraSearch and its potential applicability in IR was delivered by Gwizdka et al. [132]

and by Moshfeghi [21] who established the name *NeuraSearch*.

NeuraSearch is still a relatively new area of IR. The crucial aim of NeuraSearch studies lies in detecting and understanding the neurophysiological underpinnings of the core processes related to the IR and IIR processes. Discovery of brain manifestations and cognitive associations, dissimilarities between different levels of cognitive processing and the clarity into what aspects of complex brain circuitry are essential to inform the user's behaviour and INs. Following these, the future systems can better facilitate the modification of the behaviour based on received signals and advance in the area of architectures of brain-inspired neural networks and computational models [87].

2.3.1 Neuroimaging Hardware

We now describe the two most frequently used techniques of neurophysiological data capturing we found to be present in NeuraSearch studies. Following is the Section 2.3.2 that presents selected NeuraSearch studies and their accomplishments in enhancing our understanding of bringing new perspectives about fundamental concepts in IR.

MRI/fMRI

In general, an MRI scanner is a large tube-like scanner in which the examined person lies down face upward, whilst magnetic fields and radio waves produce the images of the intended body parts, such as the brain, bones and joints or internal organs.

NeuraSearch studies focus on investigations related to brain mechanisms. MRI scanner was used on several occasions, such as the investigation of neural correlates of relevance [149] or IN [11]. The main advantage of this technique is its high spatial resolution which allows to precisely localise brain activity within millimetres on the whole brain coverage and produce images of functional brain activity in a matter of every few seconds (2s time window reported in [149]). The fMRI images are important when the task scenario includes comparisons of brain activity due to contrasting independent variables. The fMRI measurements are based on the simultaneous monitoring of BOLD signal (Blood Oxygenation Level Dependent) whose levels depend on the amount of deoxyhemoglobin in blood, which is believed to then increase the neural activity [69].

The technique comes at the cost of lower temporal resolution, i.e. relatively slower data acquisition rate, compared to other techniques, such as EEG. However, this does not have to be an immediate obstacle if one aims to obtain highly precise spatial images of brain anatomical structures activated during the investigated task without the need for the detailed temporal aspect of data. Furthermore, the multidimensionality allows for the re-usability of data throughout several studies supported by data analysis sourcing from different angles, including applications of sophisticated machine learning methods, as reported in [23]. The physical limitations of this technique are one of the drawbacks preventing their wider adoption into IR. The robustness of the MRI and the physicality principles under which it operates only allow for limited and reduced simulation capabilities of real-life scenarios with very limited interaction from the participant. Furthermore, incompatibility with MRI machines and standard electrical devices (e.g., computers, monitors, interaction devices) used across traditional IR task-based behavioural studies leave the NeuraSearch researchers with limited control over the experimental task and design. One example of a restricted information presentation represents an initial investigation of image relevance judgments [149] where participants watched a reflection of the projected images (from a data projector) on an angled mirror in the MRI scanner.

Another critical part of the decision is whether to employ the MRI in a study is their cost of usage and lack of flexibility and mobility as the MRI machines are drawn to clinical environments. In addition, research governance is of central importance as the process of obtaining ethical approval for the study is meticulous. Moreover, a radiographer trained in carrying out the procedure must be employed and always present during the examination.

EEG

Electroencephalography (EEG) is built on the knowledge that the brain generates small electrical activity in the order of a few millionths of a volt. EEG represents a procedure to capture this activity in real-time using EEG's main advantage of high temporal resolution of data collection. Time frequency (or sampling rate) is the measure of data sampling. For instance, EEG with a frequency of 500 samples per 1 s collects data evenly every 2 ms. The sensor attached to a specific location of the skull surface to capture the cortical electrical activity is called an electrode and is usually made of sintered Ag/AgCl material. A common approach is to use an "EEG cap" made of elastic light-weight fabric, which serves as the recording interface, with multiple electrodes attached, to get a signal originating from different brain areas. The electrode configuration on each cap follows the standardised systems of EEG electrode positions, e.g. "10:20 System of EEG Placement" [150]. These allow for comparable results of spatial activity between subjects within a study and between the studies. The cap's density denotes the amount of electrodes a single cap holds. Commonly we encounter EEG caps with 32, 64 or 128 electrodes or also referred to as channels.

An event-related potential is the measured brain response as an effect of a specific sensory, cognitive, or motor event. More formally, it is any stereotyped electrophysiological response to a stimulus.

Brain signal is an electrophysiological response to a stimulus as a direct result of a specific operation in the brain. We acquire Event-Related Potentials (ERP) during the brain signal measurements. It is a common approach to analysing EEG data based on averaging EEG response waveforms, usually time-locked to the stimuli onset (start) and offset (end), across people and trials (see Table 2.1 with a glossary of EEG-related terms).

EEG is a painless, non-invasive technique (in contrast to "intracranial" EEG, which requires a surgery to place the electrodes underneath the surface layer of the brain). After undertaking supervised training sessions, the researchers themselves can conduct the EEG examination. The advantage of EEG over MRI is EEG's flexibility as it is not bound to any particular location. The only necessities are the tools and devices to conduct the research. The location where an interactive (user-system) EEG study is planned to take place must be equipped with i) an EEG cap, ii) a recording computer with software that records the signal sourcing from the electrodes in real-time, as well as checks for optimal signal quality (in terms of impedances), iii) an amplifier that connects the cap with the computer and iv) a computer with a screen that runs the task and stimuli and collects the behavioural information (timestamps, button press) related to stimuli information. The overall expenditure for this equipment makes the EEG relatively low-cost compared to the MRI machine.

Although the strict EEG environment conditions are there to ensure the highest data quality of the examination, they also pose higher demands on the participants' attention, focus and stillness. For instance, they are asked to maintain a consistent position and minimise eye blinks and other body movements, which may cause discomfort in cognitive performance. Therefore, introducing pauses between the task steps and breaks between trials can help reduce potential limb stiffness and discomfort. New attempts have been reported to develop mobile portable EEG sets working as a headset applied in both clinical [151] and non-clinical settings [152]. For instance, an experiment based in a museum where EEG data of over four hundred people were collected during an art exhibition [153]. However, portable devices are not yet widely produced and are currently in the stage of further evaluation of their quality and usability.

One of EEG data's challenges is ensuring an appropriate level of data quality. Raw scalp-recorded electrical activity is known to be contaminated with external background noise and sources originating from inside the body, such as heart activity, eye blinks, eye movements, facial and other muscle movements. They are known as "the artefacts" amplifying the signal in the order of tens of times greater than those produced by the brain [154, 155]. Once the EEG data are collected, increasing the Signal-to-Noise ratio imposes a significant and challenging task in front of every researcher to separate these artefacts from the signal emitted by the brain itself. The data challenges we encountered in the study featured in this thesis and the explanation of the data cleaning process is reported in Section 3.5.1.

In the context of NeuraSearch, numerous studies have been performed using EEG [22, 148, 156, 157], which are further described in Section 2.3.2. In addition, Table 2.1 provides a glossary of terms commonly used in EEG literature and will be used throughout the later text.

Table 2.1: Terms associated with EEG and their description

Term	Description
Stimuli	In general, an object of any nature (text, audio, visual) that is primarily used in a study in order to evoke a response from the participant and whose response is measured concerning this stimulus. In the EEG context, this response is the participant's brain activity.
Event	Event is anything that can be manifested as something that has occurred, such as stimulus onset or a keyboard button press. It is common to time-lock EEG to the event to identify the occurrence of the event within the EEG timeline.
Topological Map	Generally accepted model of the brain structures with the defined spatial areas.
Electrode	An instrument that serves to record the signal from the human brain, placed along the scalp of the person. Each electrode has a unique ID and spatial property, which allows the signal to be associated with an approximate location on the topological map. The relative proximity of the electrodes can be associated with these regions.
EEG cap	A device that is placed on the human scalp, containing a set of electrodes to capture human brain signals from multiple scalp locations simultaneously. The placement of electrodes is not arbitrary but follows the defined standards, such as the 10:20 System.
EEG Signature	Significant spatial and temporal properties of the EEG data. Data captured from a single participant are in 3D format - Electrodes x Time Points x Signal (i.e., elicited potential in μV).
EEG Data Epoch	Extracting EEG data in time intervals in which the brain response is observed. For example, suppose a stimulus was presented for 1 000 ms. In that case, it is common to epoch the data to observe this duration as an event during which the relevant brain activity is expected to emerge.

Time Window	Further split of the data epoch. It allows for a deeper investigation of particular time intervals within the data epoch, e.g. to observe the activity of N1 component between 50 - 150ms poststimulus, i.e. after the stimuli have been presented on the presentation device.
EEG Waveform	EEG waveform is a visual representation of the EEG data epochs.
ROI (Region of Interest)	Identification of a spatial property of the EEG signature, i.e. regions from a topographical brain map which according to used metrics carry significance in a particular analysis.
ERP (Event-Related Potential) Component	Identification of a temporal property of the EEG signature. It represents a particular deflection of the EEG waveform evoked by neural operations. The standard convention for labelling ERP components is: "Letter" describing the deflection in terms of the ERP amplitude's polarity: Positive (P) or negative (N), and "Number" refers to the time point on the series where this deflection reaches its local extreme, e.g. N1, as a particular instance of ERP components, means negative deflection peaking at 100 ms poststimulus.
Onset Latency	Property of the ERP component. Occurrence of the investigated ERP in relation to the onset of stimuli presentation, i.e. default baseline is equal to the moment of stimuli presentation (assigned as 0 ms).

2.3.2 Selected NeuraSearch Studies

One of the first concepts submitted to NeuraSearch was relevance. Several investigations [148, 149, 157] have been conducted in this area, using images or textual information as stimuli, with the latest outlook on a cognitive perception of relevance [22]. One of the earliest investigations introduced by Moshfeghi et al. [149] applied the fMRI machine. Topical image relevance judgment was selected as a task to capture brain activity. Significant variation when participants assessed relevant and non-relevant images was found in three regions located along the right hemisphere of the brain (their functional specialisation is given in brackets): superior frontal gyrus (memory, cognitive control and inferential reasoning), inferior parietal lobe (multisensory representations and visuomotor control), the posterior region of the inferior temporal gyrus (visual processing). Identifying these regions' distribution helped map relevance onto functional brain networks. The authors identified two segments: 1) executive functions to encode the instructions of the tasks and maintain attention and ii) function of relevance assessment by encoding the visual features of stimuli and determining the relevance using visual working memory.

Later, Allegreti et al. [148] first hypothesised that EEG signals can be exploited to identify significant brain activities while assessing the relevance of images according to a topic. Contrasting EEG signal captured within the first 800 ms of relevance judgment provided the answer to the questions "How the signal evolves over time, and how does it differ for implicitly judged non-relevant and relevant images?" The signal was split into time ranges to calculate differences in consecutive intervals. The time course of a greater activity associated with processing relevant images suggested a gradual involvement of frontal regions, moving into central and centro-parietal regions, whose electrodes carried the highest significance in differentiating the two conditions. In conclusion, 800 ms is sufficient to observe activity related to implicit relevance feedback of a visually presented stimulus. Kim and Kim [158] continued the theme of evaluation of topical relevance judgments, inferred from EEG data of 23 participants, on a set of video segments aiming to create key relevant shots as an efficient meta-tool in video browsing, video indexing and navigation. The study found two discriminative ERP patterns of relevance judgment, namely N400 (higher association to non-relevant shots) and P600 (higher association to relevant shots) components. The study by Gwizdka et al. [157] contributed to relevance understanding with a new stimuli modality by employing a task which used textual presentation of stimuli instead of previously used images. The task employed a block-design with 21 factual questions and started with a question followed by a sequence of three snippets of new stories. These were classified as either i) relevant, ii) non-relevant, or iii) partially relevant. The participants could only provide responses on a binary scale. Furthermore, this study employed natural-like reading, which allows for individual variations in reading time, contrary to a more common fixed time for reading. Therefore, as the time course of activity related to reading each snippet varied in length, the authors decided to split it into three time epochs of 1,000 ms and 2,000 ms positioned at the beginning, in the middle, and at the end of a trial relative to reading time. In general, readings of relevant text exhibited greater values in relation to reading non-relevant text. Nevertheless, the performance also depended on the position of the found relevant term in the text. The authors also experimented with the length of the epoch with the conclusion that shorter epochs match better with the timespan of distinct cognitive processes than longer epochs which contain more overlapping brain activity.

Relevance remains an enticing topic. One of the latest EEG investigations by Pinkosova et al. [22] diverted the focus from the "traditional" binary notion of relevance and introduced relevance as a three-graded variable (high, low, non-relevant). In contrast to the previous study [157], which encoded three types of relevance into a binary representation of relevance, this work acknowledged partial relevance as a single (and new) representation of relevance. The study applied a component-driven, i.e. by pre-selecting i) ERP components previously found to exhibit during judgments of relevance (N300, P400, N600) and ii) the associated time windows. Findings showed that the strength of ERP components varied as a function of different grades of perceived relevance. These differences in distinct neural activity suggest that various cognitive processes are relied upon to different degrees during relevance feedback.

Studies that researched the involvement of brain networks in the realisation of IN are described in separate Section 2.3.4, as their analysis informs the objectives for the present thesis.

Furthermore, Moshfeghi et al. [159] created an fMRI study focusing on the searcher's transitioning between the stages of the search process. Participants' brain activity was measured via fMRI in a scenario consisting of the main stages of a conceptual search process: (1) IN, (2) Query Formulation, (3) Query Submission, (4) Relevance Judgment, and (5) Satisfaction Judgment with four adjacent transitions between them. The attention was put on transitions highlighting the changes in neural states of the users as they proceeded through the search to reveal the interplay between brain regions seemingly subserving different cognitive functions involved in user search behaviour. Identified significant clusters of brain regions informed about the allocation of neural resources to particular functions (motor-related activity was excluded). Each of the stages was matched with brain activity, such as activity seemingly subserving attention to visual processing (1), preparatory functions (2), and speech production sound processing (3). This was followed by language, greater visual and cognitive processing related to reading and information encoding (4) until the final stage (5), exhibiting greater visual processing during the user's document scanning and traces of decision-making. Diverse activity patterns within different brain networks provided an important step into mapping the sequence of information search behaviour onto underlying cognitive functions.

The scope of most NeuraSearch investigations concerns the fundamental and implicit concepts of IR, but it is not limited to them. Such as a recent EEG study by Kangassalo et al. [156] reporting temporal association of neural responses with words as potential query terms (keywords) that differed by term specificity, which, concerning the query representation, had been previously reported as a factor of retrieval effectiveness. The participants reacted to a sequence of words presented for 700 ms that constituted a document text. The results conformed to a hypothesis about term specificity being associated with amplified brain activity. Furthermore, neural correlates of specific and neural correlates of non-specific terms yielded significant differences between 200ms to 800ms after the term was presented. In conclusion, the finding evidences the user's natural ability to discriminate between terms with different specificity. The following study could expand the link between term specificity and the actual query formulation and further validate the link between term specificity and IN realisation.

2.3.3 Integration of NeuraSearch into IR

The interdisciplinary approach under which NeuraSearch is built should strengthen the confidence that the users of IR systems are understood and that IR systems are developed. For IR to benefit from the outcomes of NeuraSearch, it is crucial to operationalise the findings for IR and IIR. The scope of the current investigations can be characterised as a theory-driven and being of exploratory basis, in terms of used technology and techniques, with the current aim to test the capabilities and informativeness of this interdisciplinary area. In order to avoid the stagnation of this area, there is a need for a distributed project-based approach with inter-related studies designed to contribute to a mutual goal, such as the series of the fMRI investigations concerning the concept of IN (see Section 2.3.4). The future movement would also benefit from a more proactive approach from the IR community. We believe NeuraSearch's scope will be expanding in the following years. However, cooperation and more understanding are needed from the IR community to help better plan future NeuraSearch projects. The integration lies in introducing novel concepts and prototypes of models of IR similar to the Brain-Computer Interfaces (BCI) [152]. These can perform simple tasks (e.g., mouse control [160]) on behalf of the user based on the classification of associated brain data features (e.g., mouse click, page scrolling [160]). The idea behind the extension of these models is to include a new neural component responsible for real-time monitoring and evaluation of the users' brain activity that would substitute the original component in the model. For instance, evaluation of a dwell time and user's post-click search behaviour that demonstrates relevant documents [161] is replaced by brain-detected document relevance. A practical example is the first, to us known, proof-of-concept IR system introduced by Eugster et al. [147]. It performed automatic information filtering and recommendation of new documents based on monitored brain activity alone, which detects relevant and non-relevant words while the user was reading. Noteworthy is a recent approach to BCI by Torre-Ortiz et al. [152] in order to test the feasibility of BCI feedback as a generator for task-relevant images. BCI combined generative adversarial neural network (GAN) with an EEG classifier that infers brain signal features representing relevance judgements, i.e. "EEG of relevance". The signal was used iteratively to adjust the GAN model output, and through learning from the user's brain reactions, the model increased its predictions of the next produced image. The final results proved to be highly efficient, with the BCI feedback reaching accuracy over 82%

and, notably, performed not significantly lower than the explicit feedback (accuracy over 93%) that was gathered in a separate offline study. This result proves the validity of the generation process controlled by neurophysiological data alone. Furthermore, it promotes the further applicability of interactive BCI models to represent potential alternatives to standard generative image systems. Another example we take from the area of Music Information Retrieval, which we can look at as a branch of IR as it conforms to the basic principles of IR. Utilising EEG signals such as the recognition of user's mental processes evoked by listening to pieces of music was conceptualised in a model proposed in [162].

Regarding scenarios submitted to NeuraSearch, past studies concentrated on measuring the activity whilst performing a particular task, e.g. relevance judgment, and differentiation between several mental states evoked by different classes of stimuli, e.g. non-relevant documents and relevant documents. Also, an IR scenario can be seen as a sequence of actions between the user and the system, both operating with their decision sets and logic, linked by their interactions and mutual understanding. Correspondingly, multistage tasks could represent a more robust form of measuring the user's mental processes evoked by different components and stages of the IR mechanism. In like manner, the study [159] developed a prototypical IR task with basic stages of user-system interaction.

User information behaviour is endorsed by natural transitions involving the person's internal storage of information and received information. Due to human cognitive thinking and perception abilities, users evaluate the information and integrate it with prior knowledge [8]. The power of information can potentially cause a significant change in users. In one way or the other, it represents the user's gain. Therefore measurements of these "gains", such as knowledge generation and memorability of information [76, 163] would be beneficial to understand the extended effects of the system on the user. These could be based on an extensive set of neuro-psychological studies involving memory tests and experimenting with different sets and orders of user stimuli [164, 165, 166, 167, 168].

Supporting our claim drawn out in the previous Section 2.3.2, the scope of the

NeuraSearch should be expanded to allow for wider recognition and acceptance of the field.

2.3.4 Information Need within the context of NeuraSearch

A first user study that submitted the idea of IN realisation for the investigation using neuroimaging technique, precisely fMRI, was brought by Moshfeghi et al. [11]. The work subsequently resulted in the entire series followed by a study concerning predictive capabilities of neurophysiological data in relation to IN by Moshfeghi et al. [23] and culminated in the formulation of the Model of IN by Moshfeghi and Pollick [24].

The first work of the series [11] started with the investigation of brain manifestations underlying the rise of IN. The initial research intents were very straightforward as to understand how IN emerges with a focus on locating actively involved brain regions, using fMRI's fine spatial resolution capabilities, and the subsequent differentiation of signal between two cognitive categories: the rise of IN (IN) and no-rise of IN (noIN). The research relied on a developed Q/A task of general knowledge with multiple answer choices where participants of the experiment would likely experience both categories. As captured by fMRI, the brain activity of 24 participants was recorded whilst they responded to the presented information classified according to their subjective response, whether they experienced IN or not. In order to allow the users to respond when they experience a potential IN state, the fixed answer choice "need to search" was introduced. The response other than this option was automatically evaluated as noIN. In conclusion, IN was reduced to a binary concept, represented "a state of the knowledge" [11, 2016, p.335] in which users felt a higher probability of not knowing the answer than knowing the correct answer (or than making a guess call of the correct answer). No deeper investigation concerning and potentially diversifying the user's "state of knowledge" was done. However, as the task involved the user's access to knowledge, the authors anticipated that rise of IN was connected to a feeling of anomaly and, thus, connected IN to ASK (see Section 2.2.3). Two scenarios were implemented using this concept, applying within-participant design. Scenario 1 implemented acknowledging the ASK with no further action, meaning realisation of the anomaly and potential IN is a final state for the user. In contrast, Scenario 2 allowed a further action, representing a simplified search, where users were asked to issue a query to their IN by recording it into an MRI-compatible microphone device.

Study 1 The study delivered promising initial findings. Increased activity for noIN responses was found in a network of regions commonly responsible for successful memory retrieval, working memory and decision-making. Such functions are expected to see when one can provide an (explicit) response supported by available and accessible (recallable) memory. This increase was found prominent in Scenario 1. On the other hand, evaluating IN responses showed consistent findings of a significantly greater activity across both scenarios, namely in region *posterior cingulate*. Notably, the identified *ventral posterior cingulate* in Scenario 1 is believed to be allocated to increased attention to assessing internal information. Comparatively, prominent in Scenario 2 was *dorsal posterior cingulate*, believed to employ broader attention. In narrative terms, when the memory assessment is performed, the information about the unavailability of the internal knowledge (i.e., IN) is passed on to the user's awareness (Scenario 1). As a result, the user transitions to direct the attention toward external sources to seek information (Scenario 2). The differential pattern of activity found in *Posterior cingulate* region suggests its significant contribution in this transition. Specifically, it acts as i) a switch between this internal and external processing and ii) a hub that coordinates the cognitive activity and brain resources, making it a significant region in identifying IN components.

Study 2 The pattern of activity related to IN realisation was established in the first study. Building upon these findings, the authors decided to pursue a new aim to test the predictive capabilities of brain signals in IN realisation without expressing the query. To find Regions of Interest (ROIs) as a feature set that seemingly determines IN realisation was, thus, crucial. The researchers used a set of techniques specifically implemented to support the analysis of fMRI data, such as Multi-voxel Pattern Analysis (MVPA) in identifying activity patterns within groups of voxels and the ROI-SVM classification method. Two predictive models were devised, each with a different outtake on ROIs and the user. First, the Generalised Model (GM) with a pre-defined set of ROIs common for all participants (as identified in [11]). Second, the Personalised Model (PM) that considers the individual realisation of IN of participants with the feature set of voxels derived for each participant.

In order to determine the unique ROIs for PM and, thus, to compare the ROIs contained in two models, a topological probability map was constructed, showing the overlap of the voxels for each participant. The final map with the criterion of approximately one voxel present in at least 1/3 of the participant's sample resulted in coverage of 0.6% of all voxels in brain volume. In total, ten unique regions were revealed for the PM model, where the brain exhibited higher activity for IN responses. These were distributed across the brain, with a majority from *frontal gyrus*, involving the functions of high-level cognition, low perceptual and textual processing. Input to both models was then a different set of ROIs due to different methods of identifying these ROIs, i.e. GM based on the General Linear Model and PM based on MVPA and probability map. The comparison of the final set revealed one particular ROI, *left inferior frontal gyrus*, being mutual in both sets and consisting of a high volume of voxels.

The results of the prediction performance revealed that GM performed above chance levels, i.e. 50%. On the other hand, PM with unique signatures of IN outperformed GM, reaching an accuracy of almost 80%. As was mentioned previously, the input to both models was different, which led to the conclusion that the prediction accuracy depended upon the choice of brain regions used to build the model.

In light of the results, confusion might arise when contrasting different significant ROIs from Study 1 and Study 2. However, the difference in sets of ROIs was caused by the nature of the methods and the measures they used to find these significant ROIs. In Study 1, GLM was used to answer differences in mean activation between noIN and IN, employing univariate analysis. On the contrary, MVPA, as used in Study 2, relied on considering synergy and connectivity within a group of voxels with lesser power individually. In conclusion, *left inferior frontal gyrus* region found by both methods indicates that this region both changes its mean activation (evidence by GLM) and its spatial distribution (evidence by MVPA) of activity for IN responses.

In conclusion, analysing brain data is a significantly challenging task due to their complex anatomical and physiological nature consisting of highly distributed networks of neurons. The brain analysis discovers only the pieces of the "truth" gradually in order to reveal the integrated networks under which the brain operates. Different methods can, therefore, yield different outcomes even with the same data. In order to accurately interpret the outcomes of the analyses, it is crucial to have clear hypotheses and prepare the analytical framework that fits the study's aim and that governs the clarity of the used methods.

Study 3 The outcomes of the past two studies resulted in promising findings, which prompted the authors to dive deeper into a network analysis of active regions (as identified in Study 1) and examine their possible interaction. The results were subsequently conceptualised as *Neuropsychological Model of the realisation of information need* [24].

Task-related functional connectivity and network analysis were performed in order to obtain the links between ROIs identified in the task scenario (Study 1). The authors used pairwise correlations between eight identified ROIs (acting as nodes in the network), seemingly sensitive to IN, to measure their connectivity. The larger the correlation coefficient was, the stronger the link was. The outcomes of network analysis resulted in the model which arranged this distributed network related to IN into three main interrelated components:

1. Component 1 - **A Memory Retrieval Component**, consisting of *left thalamus, left caudate body, right caudate head, left inferior frontal gyrus.* These are seemingly involved in correct memory retrieval (MR), which supports the findings of higher activity for the noIN condition. Further functions relate to working memory and decision-making, factual search and language semantics processing. Moreover, a subregion of *left inferior frontal gyrus, left dorsolateral prefrontal cortex*, was in the past studied (analysed by the authors) in the context of FOK judgments (explained in Section 2.2.1) and differing levels of FOK judgments.

2. Component 2 - **An Information Flow Regulation Component** comprising *left cuneus, left dorsal posterior cingulate, left ventral posterior cingulate. Poste-*

rior cingulate supported by significant evidence concerning IN in Study 1 earlier, is described as a hub for balancing the activity between what the user already knows and what they need from external sources. Specifically, its ventral region is linked to a narrow internal focus, whilst the dorsal region is linked to a broad external focus, as evidenced by the increased functional connectivity between these two. Furthermore, the activity in *posterior cingulate* was found to be associated with the metamnemonic FOK. Alike the findings for Component 1, the re-occurrence of the FOK phenomenon only reinforces the possible relationship between IN and FOK. **We expand on this notion with a further examination of FOK in the context of IN presented in Chapter 5 of our study.**

3. Component 3 - **A high-level Perception Component** which consist of *right fusiform gyrus.* As the literature proposes, this region is engaged in a diverse range of domains. Particularly relevant appear to be its involvement in processing visual inputs to create cognitive and conscious representations of viewed objects and their properties. Therefore, the evidence from the task with image stimuli in Study 1, where this region was found, is not surprising. Due to the increased functional connectivity with Component 2, the mechanism behind visual cognition can also be drawn as top-down feedback, i.e. receiving input from higher brain areas (Component 2) aids the interpretation of visual stimuli. One such possibility is the involvement of memory retrieval, Component 2, to represent visual properties based on the extracted information.

The question now remains, on how to proceed with future investigations. It all depends on the aim of the intended work. As recognised and advised by the authors, investigating spatio-temporal properties of the development of IN realisation is one way. This proposal implies the application of a different neuroimaging tool, such as EEG, to capture the fine temporal series of brain data. In addition, a combination of fMRI and EEG data outcomes would likely help synergise both outcomes and increase the certainty and understanding of the cognitive activity related to INs due to the different data perspectives both techniques offer. Future work might also target the already identified ROIs or specific cognitive operations and, in particular, observe how these respond under different conditions, e.g. expand on the context of the Q/A scenario.

2.3.5 Motivation for the development of our study

The just reviewed fMRI series answered the questions “1) What neural manifestations are detectable in the user’s brain responsible for IN realisation, and 2) Where in the brain are they present?”.

The Model [24] conceptualised the components involved in IN realisation based on the evidence of spatial brain activity discriminating between two user states: IN and noIN. However, we see it is missing a temporal element as to when these components are triggered and to understand their interaction and connectivity better. The question, therefore, remains “When (in time) does the brain start exhibiting detectable activity related to IN experience?”. The answer can bring the application of other neuroimaging techniques with fine temporal resolution, such as EEG, which has been successfully applied in other NeuraSearch studies [22, 148], recent or past. The spatio-temporal activity resulting from EEG application might create a temporal picture of the cognitive development of within-brain development of IN and, thus, expand on the outcomes of the current studies.

To expand the study in the conceptual area, specifically concerning cognitive functionalities behind IN, we refer to the Model again. The Model’s components represent the functional areas, as evidence suggests, contributing to the user’s realisation of IN. As the authors assumed, the present scenario created a state of knowledge analogous to ASK [3], underpinning their IN response. The knowledge anomaly is the crucial element in ASK, with differing levels of anomalies assumed to supply variants of ASK. Expanding the knowledge context of IN [6] from the empirical perspective might not only contribute to the empirical knowledge about IN and ASK but also evidence of the involvement of user’s (anomalous) states of knowledge as the preamble to IN. In particular, we refer to mechanisms of memory (i.e., mnemonic), as identified by the Model, that enables access to and the retrieval of the person’s internal knowledge, which is used to inform the user's decision and behaviours. In addition, the Model found several associations with cognitive investigations of FOK, introspective state of knowing we mentioned earlier in Section 2.2.1, which now opens up a question about a potential link between FOK state and IN. Gathering the evidence from the user's brain activity in the context of knowledge and memory might significantly clarify the role of the user's state of knowledge as a driver for their INs.

Section 2.4 delineates the specific goals we will pursue to address with the present thesis.

2.3.6 Conclusions and Present Challenges of NeuraSearch

We see two current challenges that NeuraSearch projects face. First, and likely of the highest priority, is related to a careful design of the experiments and tasks submitted to the NeuraSearch. Common user studies in IR are often impossible to reproduce to the same extent. They must often be modified to uphold challenging settings and conditions of the neuroimaging techniques. The experimental design and the stimuli choice must be discussed between the researchers on every side of the problem spectrum, i.e. IR researchers, information scientists, neuroscientists and even collaborators from the industry. Collaboration is a key that allows to co-create the IR scenarios to fit the requirements of all involved disciplines. Furthermore, as part of the project planning, it is essential to understand all aspects of the intended study, including those related to costs, resources, and recruitment of the participants, whilst adhering to the ethics standards. Future studies would likely prosper from the increased volumes of representative samples to improve the statistical induction.

Second, depending on the fact that we are dealing with an interdisciplinary type of project, deepening the internalisation of these projects within the IR community is crucial. The lack of acceptance of the research based on lack of comprehension is a pessimistic sign for the future of this research. Therefore, the discussion opens up for NeuraSearch is undeniably in education and knowledge sharing within the involved communities. A higher level of readers' comprehension allows the authors to improve the interpretability of their findings with attention to greater detail and inclusion of references and focus on establishing a solid premise for each study.

NeuraSearch is a progressive new route with promising results, however, it is not yet fully established within IR and IIR. In order to scale up the studies, a change must happen from the inside, within the community (e.g., by introducing new frameworks). The progression would positively impact any future projects, and the potential authors would feel encouraged to take on a new project.

2.4 Research Goal (The Conceptual Research Framework)

The current thesis aims to provide an empirical bridge to the theory concerning the origins of IN from the cognitive viewpoint discussed in Sections 2.1 - 2.2. The literature review informed the selection of the main aspects of our aim. Motivated by the perspectives of NeuraSearch studies, particularly the studies concerning IN, we will aim to delve into functional processes accountable for a cognitive realisation of IN in the context of knowledge and memory. Informed by the analysis of the series of fMRI studies (Section 2.3.4), we delineated the significant elements left to be investigated (Section 2.3.5) and which motivated the primary aim of this thesis and the featured studies. We now expand these into Research Goals:

2.4.1 Investigation of User's state of knowledge in connection to epistemic feelings of knowing as the driver behind IN

From the cognitive perspective of IR, the user's state of knowledge contextualises the IN [6] from the point of what the user knows in a (problematic) situation, i.e. in which IN arose. User's cognitive context [7] encapsulates the user's understanding of their current knowledge capabilities and readiness in a given situation [8]. It guides the users in their information-seeking behaviours strategies in order to obtain the information expected to satisfy their IN.

Nature of FOK linked to Information Need Works by Moshfeghi et al. [11, 23], and by Moshfeghi and Pollick [24] that concerned the process of IN realisation revealed functional networks commonly associated with processes supporting metamemory, FOK and factual memory search. Their results supported the activity of internal processes engaged in epistemic (knowledge) retrieval highlighting FOK, an introspective state of knowing [169]. FOK is a metamnemonic state that reflects the assessment of one's extent of knowing that at present one cannot recall [71]. FOK is an insight into the user's internal knowledge and its availability, is generally a relatively accurate measure [168, 169] and is speculated to be part of a rapid automatic process to assess an incoming stimulus [170]. Moreover, FOK judgments tend to scale with factors such as familiarity cues, e.g. higher FOK are associated with familiar stimuli [170, 171]. Its potential prospect for a search context was accentuated in studies [71, 110, 136]. Also, a study [95] acknowledged a broader spectrum of users' states by defining TOT requests of INs, with TOT being a subtype of FOK (see Section 2.2.1).

Having FOK, the searcher feels the current unavailability of memory information [172]. According to the theoretical notions of the user's ASK [2, 3], this unavailability is a premise for IN to arise. Following the notion that INs reflects what the user knows [109], FOK represents an estimate of what the searchers think they know or believe to know. It can also predict whether the searcher will or will not know/remember the information queried at a later stage of IN realisation [169]. Its prospective character implies present uncertainty, user's estimation and, as such, under- or overconfidence in the estimation outputs [173]. However, being an estimate implies its inherent nature of uncertainty and broadly supports the variable cognitive feelings the searcher experiences during a search process [5, 18]. This uncertain nature of metacognitive feelings then quite naturally impacts their accuracy. A decrease in accuracy happens to correlate with phenomenons such as Illusion of Knowing [174] when the users cannot recall the memory when they are supposed to. The Illusion of Knowing was found to occur in all kinds of metacognitive feelings, but more evidently in judgments of a prospective character, such as FOK [171, 172, 173]. The Illusion of Knowing informs us about a mismatch between what we thought we knew (FOK) and what we actually know. Accuracy of FOK can, thus, be an indicator of a (delayed) knowledge anomaly, and later in the process could manifest as IN [10].

The accuracy of epistemic feelings, including FOK, is thus not guaranteed as the user's thoughts of uncertainty influence it. In addition to EEG data analysis, we will explore the accuracy of epistemic feelings, including FOK in Chapter 4, as informed by the results of behavioural data we gathered. Coupled with the brain data analysis, we aim to bring a bigger picture of the role of epistemic feelings in user search behaviour.

2.4.2 Investigation of further IN states based on Memory Retrieval outcomes

Ingwersen [15] analysed the cognitive aspects of IN and stressed the roles of the user's memory recall and recognition capabilities to support the process of IN realisation. Kuhlthau referred to the topical knowledge of the user as a "personal frame of reference" [5, 1991,p.361] playing a vital part in the constructive process of problem solution-finding. Memory Retrieval (MR) has been mentioned in several other studies of IS&R [8, 28] and has been attributed as a component in the Model of IN realisation [24] orchestrating the activity between internal (memory) and external search.

As has been established, metamemory is founded on the notion of "knowing about knowing". In contrast, MR uses the structure of episodic (past experiences) and semantic (facts) specifics [175] in order to recall information from memory. Therefore, it requires a deeper memory search [135]. Moreover, the strength of memories is a variable [27] that causes different MR outcomes. Hence, to address the role of MR in the context of the user's state of knowledge, we want to obtain an insight into brain activity associated with different MR outcomes. We will ask if a failure to retrieve information from memory, attributed as a gap in knowledge [8, 99] in IR, ultimately leads to the rise of INs or not. Furthermore, we will investigate what factors might affect the transition from a gap in knowledge to IN, e.g. user's information preferences [6]. This Research Goal is addressed in Chapter 6.

2.4.3 Perception of Confidence as an attribute of Memory Retrieval outcome

In the context of the quality of the epistemic states, recognition of the insufficient knowledge co-manifests with feelings of uncertainty [5], feelings of disagreements with user's beliefs [3], feelings of unease [8] and feeling of dissatisfaction [97]. Searcher was found to naturally exhibit the uncertainty with a varied intensity as the search progresses through the phases of the information search process[5] and as the user's understanding of the problematic situation changes. The strength of one's memories modulates memory retrieval (MR) and affects the perceptions of uncertainty [176, 177].

According to Taylor [13] searcher's inquiry is based on the underlying "area of doubt", implying the absence of confidence and increased uncertainty. Similarly formulated, in ASK Model [3], the realisation of anomaly is often accompanied by feelings of doubts and uncertainty, which are hard to express but, paradoxically, seem to act as triggers of one's engagement in a search scenario. Thus, affective feelings could be perceived as a sign of pre-manifestation of INs triggered by facing a new problematic situation. Our study will approach the confidence judgments from the perspective of "what the user knows" (or believes to know), derived from a notion that INs are expressed with respect to the user's available knowledge [109].

We are particularly interested in the correlation between confidence and MR to explore if different confidence levels are tied to specific users' states of knowledge determined by the previous goals and how confidence can inform us about the changes in user behaviour. This Research Goal is co-addressed with the previous Goal in Chapter 6.

2.4.4 Interaction between Metamemory and Memory Retrieval

Further exploration of how epistemic feelings are transitioned and altered during the IR process will provide insight into the accuracy of these predictions. This exploration would support uncovering the potential disassociation (What we think we know is not true) between epistemic feelings (Meta) and the actual knowledge retrieval (MR) and further inform the area of the user's cognitive context. For instance, we can expand on the FOK level. FOK as an exhibited level of the user's temporary unavailability of information implies uncertainty based on the estimation of the user's future prospect to remember and is only relative [173]. Questioning this estimation's accuracy might help put ASK in a broader context, such as by analysing the consequences of the user's misattributed FOK regarding their search behaviour. A broader acceptance of FOK will require a better definition and categorisation within IR. The present goal will help us specify to what extent FOK impacts the MR output and, in general, the user's cognitive context. This Research Goal is addressed in Chapter 7.

2.5 Chapter Summary

The current chapter provided the review of theoretical literature and the empirical research supporting the concept of IN within the context of IS&R as the main objective of the current thesis. It sets the topic within its historical context of IS&R and provides a review of the current empirical research. Finally, it dedicates attention to introducing the NeuraSearch research branch as the primary motivator behind the methodological design of the present study. Specifically, this chapter presents:

- The research area of IS&R, as an umbrella field to which the topic of this thesis belongs.

- The concept of IN within the context of IS&R and helps to establish it as a multi-faceted concept. It describes the core models and frameworks influencing the follow-up and current research into IN.

- NeuraSearch branch of IR research, which integrates neuroimaging data acquisition techniques within an IR user study. It describes the advantages and the drawbacks associated with a NeuraSearch study and highlights the benefits for the IR community.

- Research Goals derived from the literature review.

Chapter 3

Methodology

In this Chapter, we describe the methodology related to the i) user study, ii) data collection, and iii) data analysis. We present the procedural model of the study and describe the task the participants were subjected to and how each sequence of the task relates to our Research Goals (see Section 2.4 for reference). We clarify the design choices behind the study, describe the input-output model and present the implementation process of the study with the tools and techniques we used. Furthermore, we present a pre-processing data pipeline we constructed and a set of data analysis methods and tools we applied.

Our study is a user study employing human subjects to participate in a designated task we had constructed with the intent to collect behavioural data. We will use the terms participants or subjects interchangeably. We refer to the information presented to the human subject as "the stimulus", which is aimed to evoke a specific response from the subjects. This response is of interest to our study. Since we use the EEG terminology throughout the text, please, refer to Table 2.1 with EEG glossary in Section 2.3.1 for the explanation.

3.1 Participants

Participants were recruited via university mailing lists and flyers posted at the campus of the University of Strathclyde and via SONA, the recruitment system of the School of Psychological Sciences and Health at the University of Strathclyde.

Data were collected between June and October 2019. The participants received no monetary payments but were eligible for academic credits. Participants' demographics information were collected via a pre-task questionnaire (see Appendix B.1). In total, 24 healthy volunteers enrolled to participate in the study. There were 17 females (71%) and 7 males (29%) within the age range between 18 and 39 years and the mean age of 24 years (sd 6). Undergraduate students accounted for up to 66.70% of all the participants, followed by 25% of PhD students and 8.30% of Masters degree students. Just over half of the participants (54%) studied for Psychology or Psychology combined degree, followed by 25% of Computer Science students, students of Mathematics (8.30%) and Speech & Language Pathology (8.30%). One participant (4.2%) studied Biochemistry and Microbiology.

A majority (over 66.50%) of participants were British, with the rest of the participants being of nationalities, each contributing by 4.17% to the overall distribution - Irish, Greek, French, Polish, Chinese, Nigerian, Thai and Omani. Participant demographic information (gender, nationality, education level) was not balanced as our hypotheses were not relevant to the impact of these demographics as an independent variable. Participants completed the task on average in 44 min (sd=4.62, med=43.40), excluding the time of two breaks each participant was required to take during the task. The questionnaire further revealed a diverse range of interests the participants possessed. Among the most common we found were: Films and Videos (87.5%), Music (79%), Performance and Crafts involving singing, playing a musical instrument or any creative activities (67%), Science and Technology (54%) and Literature (50%). Lower proportions of participants reported personal interests in Languages (46%), History (38%), Sport (29%), Politics (25%) and Quiz shows (17%).

3.2 Study Design Framework

The experimental task consisted of 120 general knowledge questions (i.e., stimuli) the participants were presented with, followed by a series of additional queries related to each stimulus. The stimuli were presented in a textual format on a desktop computer monitor. The task was computerised as a Question-Answering (Q/A) system. The participants performed the task via interaction with the system that automatically recorded their responses. A detailed description of the task is reported in Sections 3.3.1 and 3.3.2. The task followed the methodological framework, fitting the purpose of our Research Goals, which we now proceed to describe.

We employed a modified version of a well-established Recall-Judgment-Recognition (RJR) paradigm [166] combined with the Retrospective Confidence Judgments (RCJ) paradigm [178]. The typical procedure of RJR starts with presenting subjects with a stimuli cue (that triggers the memory remembering processes) and asking them to recall the target information from memory. If they cannot do so, they are asked to make a FOK judgment, i.e. how likely they feel to recognise the information at a later time. Following is the recognition test that utilises mnemonic cues in order to enhance memory recall. RCJ extends the memory test by asking the participants to rate their confidence that they correctly remembered the target information. Both of these paradigms are widely used in studies delving into memory monitoring employing a recognition memory task [166, 178].

Our study combines RJR and RCJ in the Q/A Task of general knowledge to empirically investigate our Research Goals. Refer to Section 2.4 that provides a theoretical description of the underlying concepts and reasoning for their investigation in the context of INs. The task implements:

- Cognitive states of knowing evoked by metamemory processes with a special interest in investigation of FOK as the cognitive feeling of future remembering to address the cognitive nature of IN - linked to Research Goal 1.
- Factual MR that involves the engagement of episodic and factual declarative memories to recall a piece of information from memory. IN is seen as a product of a failed MR - linked to Research Goal 2.
- User's Confidence as a cognitive attribute associated with accuracy and correctness of a produced MR output - linked to Research Goal 3.
- The interaction between MR and prior metamnemonic cognitive states of knowing

in order to assess the validity of these prior "estimates" - linked to Research Goal 4.

Now we proceed to describe how were our Research Goals translated and applied in the Task.

3.2.1 Metamemory and inclusion of FOK

The general knowledge questions naturally evoke human epistemic (knowledge) perceptions, simply by asking ourselves, "Do we know this?". Human metacognitive abilities supply the user with an introspective insight into their knowledge abilities and aid them in their behaviours and decisions.

Metamnemonic introspective feelings could identify early recognition of IN based on early recognition of a gap in knowledge or an anomaly according to the ASK Model [3]. Employment of FOK reflects the searcher's temporary unavailability of knowing, a phenomenon not yet studied in the context of IR literature. Its nature fits the IN premise, and thus, the study of FOK can provide more insight into the differentiation of drivers of IN and the user's cognitive context. We constructed three states corresponding to three different metamnemonic outcomes the participant could perceive: 1) Participant recalled the answer; 2) Participant not recalling the answer but possessing a Feeling-of-Knowing (FOK), a temporal inability to recollect with the prospect of future recollection; 3) Participant does not know the answer. This segment of the task addresses Research Goal 1. In Section 4.3.2, we explore the behavioural data connected to metamemory with Chapter 5 expanding on the evidence obtained from EEG-related data analysis. Moreover, it provides detailed information connecting the metacognitive processes with cognitive states of knowing and IN. It reports the outcomes of the discovered underlying active brain areas behind these states. Finally, it helps us to lay down a new perspective on the fundamental IR concepts, such as ASK and expand on the notion of ASK variants [3].

3.2.2 Factual Memory Retrieval Employing Mnemonic Cue Recognition

In our study, the participants are accessing the declarative memory [135] in order to answer a question of general knowledge requiring a factual memory search. Declarative memory stores facts and events [167, 175] that were found to be crucial for the searchers to express their Tip-of-Tongue (TOT) states of INs [95]. Following the RJR paradigm employed in past studies [166], the Recognition tests often utilise the presentation of mnemonic cues, i.e., information stimuli. They tend to stimulate the user's brain activity related to memory recall [178]. In particular, they tend to either enhance correct memory retrieval or act oppositely through the employed distractors (incorrect answer choices). Depending on the outcome, we can deduce the strength of one's memories and support the user in reducing knowledge misconceptions and assumptions [179]. In our study, the participants' performance determined the outcome of the trial of the recognition test where the participant could either 1) choose a correct answer choice to the question; 2) attribute incorrect answer choice as the correct one or 3) acknowledge that they did not know the answer.

This segment addresses Research Goal 2. First, Chapter 4 reports on the results of the analyses of behavioural data. Then, Chapter 6.1.1 makes the conclusions based on the findings from the EEG data analysis.

3.2.3 Interaction between Meta and MR

The sequential format of the task implements the investigations of the separate parts of the task, as well as their combined effects, such as the interaction between Meta and MR. Specifically, in the Recognition (MR) segment of the task, we asked the participants to provide factual answers compared to the preceded Recall (Meta) segment. The initial epistemic feelings (Meta) interpret the participant's knowledge perception and prospects related to the stimulus (question) and, in a sense, represent the person's estimate. In interaction with the recognition part (MR), we can evaluate the accuracy of the user's states of knowing, present and future. It might furthermore help to identify INs occurring later in the search process. In particular, we discuss the misattribution of the perception of knowing ("What we think we know is wrong"), known as the phenomenon Illusion of Knowing [174], from the point of drivers of INs and user search behaviour.

As we mentioned, the Recognition part of the study employed mnemonic cues to stimulate participants' MR. Mnemonic cues are represented as answer choices, traditionally used in Q/A format studies [180] or quiz shows in media. The output of IR, such as document snippets on the Search Engine Result Page (SERP), could also be translated as mnemonic cues. These are usually the first IR input for the users to judge their relevance and usefulness in a given situation. For instance, they can trigger information familiarity [181] and stimulate mnemonic processes of remembering or recollection. Therefore, information quality appears to be a valid factor in exploring its effects on the efficiency of IR and overall user satisfaction. For instance, the efficiency of IR is measured based on the quality to deliver a quick and relevant memory cue to solve the user's memory failure.

First, the initial data insight provides the analysis of behavioural data in Chapter 4. We then continued investigating EEG-related data in separate Chapter 7 and elaborated on their impacts for IS&R.

3.2.4 Confidence in Knowing

Deriving from the certainty notion about INs in IR, the user's expressions of INs reference what the user knows [109]. In this sense, our study approaches the confidence judgments as the attribute of what the user knows (or believes to know), i.e. epistemic certainty [176]. Memory retrieval occurs as knowledge information recall, whose outcome is usually regarded as graded [134], e.g. only partial information is recalled, similarly as found in [95]. Each recall state could, thus, rest on different confidence magnitudes. We believe this can inform our understanding of memory strengths, users' states of knowledge and INs attributed to their perceived confidence. We constructed two levels of confidence judgments: 1) Low Confidence and 2) High Confidence that extended the participant's assessment of their MR (Recognition test). This segment is co-addressed with Goal 2 in Chapter 6 and extends the assessment of the neurophysiological data featured in this study.

Lower Information Needs

We gathered the evidence to account for differences in users' information preferences if they acknowledged a knowledge gap. In the IR context, not-knowing is automatically evaluated as the premise for IN and the IR output affecting user satisfaction. Several papers investigated the discourse between the anticipated needs (from the information provider point of view) and the users' actual INs; prevalent in the area of medical and health information for patients [182], or patient supports [183]. The users' lack of information was exhibited as a symptom of INs, but not every transitioned into INs, i.e. lower INs were created [184]. The causes might differ, depending on the context of the situation (e.g., urgency), attribute of the information (e.g., value) or others, such as interest.

The design of our study acknowledges that a recognised gap in knowledge might be further modulated according to participants' preferences, implementing the view that the knowledge gap does not have to ultimately manifest as IN. We gave participants two choices on how to proceed with the task. They could either resolve their gap by choosing the option 1) "I want to know" or, instead, choosing the option 2) "I do not want to know" (meaning, the participant does not want to know correct answer). The initial insight into the participants' preferences produced the analysis of collected behavioural data in Chapter 4. In the light of these outcomes, we made the conclusions related to the analysis of the corresponding EEG segment (co-addressed with Goals 2 and 3 in Chapter 6.1.1).

3.2.5 Factorial Hierarchy

We used a within-subject (or often termed as "repeated-measures") experimental design, meaning each participant was subjected to perform a task (refer to Section 3.3.1) containing the same and all the conditions. Our experiment accounted for a 3-factor hierarchy of independent variables constructed to address our research objectives. By limiting the space of available levels in each factor, we had control over the categorisation of users. Each behavioural response was assigned one level from each factor from the hierarchy. The dependent variable was 1) behavioural data, such as factor-dependent responses, the response time (presented in the next Chapter 4) and 2) the EEG signal of the brain (Chapters 5 - 7); both acquired from the participants while they performed the Q/A task. Section 3.3.1 explains the experimental task in phases and their corresponding variables. Chapters 5 - 7 investigate in detail a specific section of this hierarchy (brackets contain the corresponding acronym):

1. METAMEMORY (META Levels)
    1. I recall (KNOW)
    2. I might recognise later (Feeling-of-Knowing) (FOK)
    3. I do not know (NKNOW)

    1.A MEMORY RETRIEVAL (MR Levels)
    1. Correct (MR-C)
    2. Incorrect (MR-I)
    3. I do not know (MR-N)

    1.A1 CONFIDENCE JUDGMENT Levels
    1. Low (L)
    2. High (H)

    1.A2 SEARCH DECISION Levels
    1. I want to know (SEARCH)
    2. I do not want to know (NOSEARCH)

3.3 Experimental Procedures

Ethical permission no. 954 and 1017 (an extension to include a recruitment portal SONA of the School of Psychological Sciences and Health of the University of Strathclyde) was obtained from the Computer and Information Science Ethics Committee at the University of Strathclyde. Each participant obtained a unique numerical participant

ID to ensure the participant's anonymity. We did not store any sensitive information about the participants, keeping, thus, the identity of the participant confidential. All the data were stored securely on a dedicated university network storage with authorised access to ensure a high level of data protection. Detailed information (concerning data collection, metadata, data storage, and data preservation) was provided in the Research Data Management Plan submitted as part of the ethics review and application process.

The formal meeting with the participants took place in a laboratory setting. All participants fulfilled the inclusion criteria to take part in the study. We set the criteria as: healthy people (i.e., without any prior or current psychiatric or neurological conditions that could influence EEG signal) between 18 – 55 years and fluent in English. Each participant received an Information Sheet explaining the experiment procedure, and then, they were asked to provide informed consent (see Appendix A for reference). The participants became aware of their rights, including the right to withdraw from the experiment at any point. The assessment started with two questionnaires requesting their demographic information (see Appendix B.1) and their habits with information searching and search engines (see Appendix B.2). The participants were then informed about the task and entered the practice session. To ensure that all the participants had a general understanding of the procedure, they underwent a practice session, which resembled the main experimental task, described in Section 3.3.1, to familiarise them with the task structure. After the main session, there was a debriefing session. Finally, the participants were required to complete a final post-task questionnaire related to their subjective perception of the task (see Appendix B.3). The practice session consisted of 5 questions, was not limited by time, and participants could repeat it if required until they felt comfortable to proceed to the main session (i.e., to participate in the Q/A task). No time limit was introduced to provide responses, which were entered by the participants via button clicks using three keys previously allocated to each option. Question order, as well as answer options on the screen, were randomised across participants. Randomisation ensured that the stimulus order did not affect the recorded signals and behaviours. During the main session, two breaks were introduced without any time limit (after completing 1/3 and 2/3 of the questions) to avoid fatigue. Participants were asked to remain still and minimise body movements, particularly blinking. The stimuli were displayed in a black-coloured text font running on a white screen. Participants rested their chin and forehead on a support area to steady the head and, thus, minimise the head movements.

A pilot study was conducted to ensure that the experimental procedure and related software worked correctly and ran smoothly. Before starting formal data collection, we ran two pilot studies. Feedback from the participants in the pilot study was used to improve the procedure and determine the parameters of the experiments, such as stimuli presentation time.

3.3.1 Overview of the Experimental Pipeline

In the following section, we provide an overview of the flow of the experimental task. Then, we present the methodological framework constructed for the Task and further justify specific decisions related to stimuli presentation and EEG technique constraints that influenced the task design.

Main Session - Q/A Task

Figure 3.1 illustrates the task sequence. Each participant was subjected to 120 trials (i.e., 120 questions from Q/A Dataset described in Section 3.3.2).

Every trial followed the same order of steps:

- RJR Part: Fixation Cross, Step 1 *Question Presentation*, Step 2 *Prospective Judgments*, Step 3 *Memory Retrieval* performed as Recognition test employing a set of mnemonic cues individual for each question from Q/A Dataset.
- RCJ Part: Depending on the response recorded in Step 3, participant could either move to Step 4.1 *Confidence judgment* or Step 4.2 *Search*.

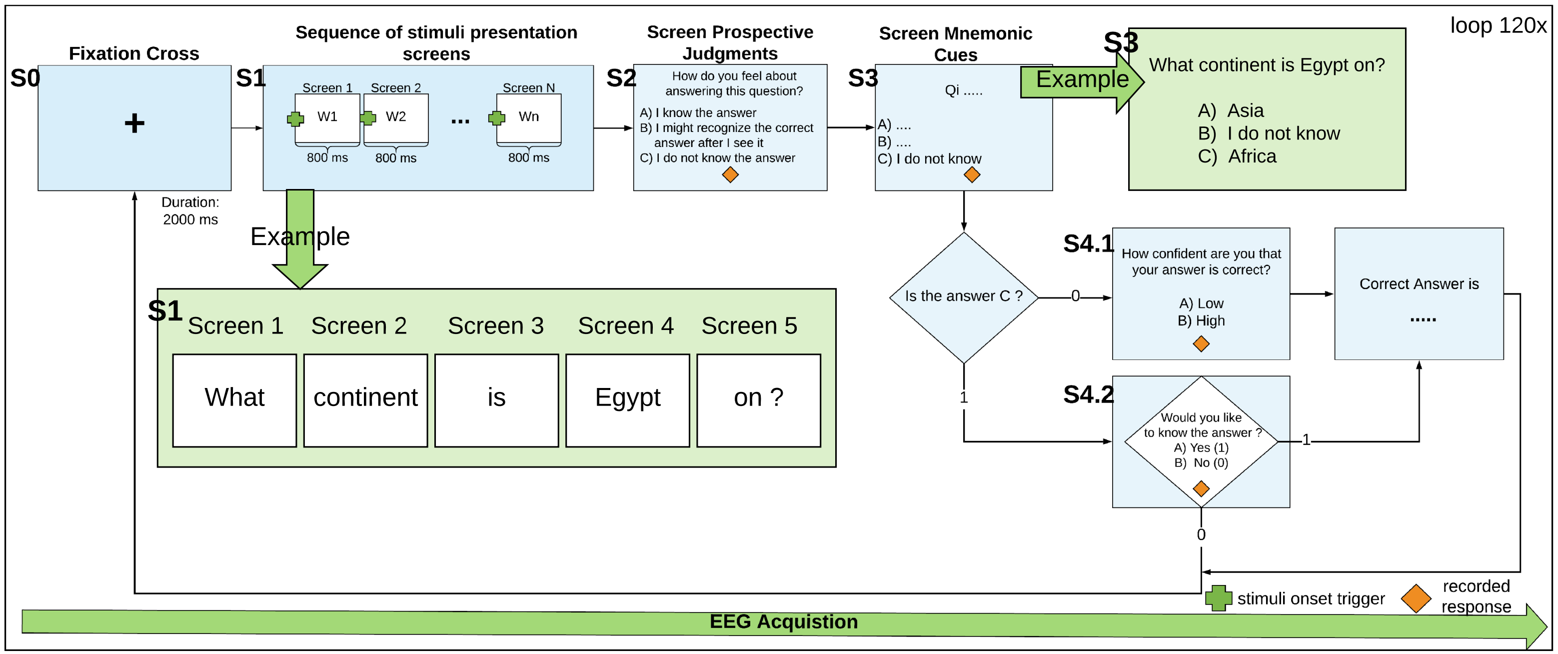


Figure 3.1: Diagram of the task structure with the stimuli examples.

The brain activity was captured during the entire course of the trial, but the core section of the captured data represents the data captured in Step 1 (S1). Here we captured the participants' brain activity during the sequential (word-by-word) question reading. The collected data will be further analysed to explore the engagement of our investigated concepts in the context of our Research Goals. The following sections (S2 - S4.2) are no less important, as they record the participants' responses to encode the data into the levels from the factorial hierarchy. The brain responses evoked by the textual stimulation in S1 will be analysed in order to observe what is the temporal pattern of the brain responses when a person faces a new situation/problem. In our case, the problem is represented as a series of general knowledge questions the participant is required to answer. The Q/A type of stimuli is a standard format of related user-based investigations [11, 166]. Per our research, we are concerned with the neurocognitive processes engaged during the subject's realisation of the cognitive states of knowing. The S1 represents the information processing. The following steps of the task (S2 - S4.2) encoded the EEG segments (S1) according to the factorial hierarchy (presented at the beginning of this chapter in Section 3.2.5):

- Meta levels (recorded in Step S2): KNOW, FOK, NKNOW.
- MR levels (recorded in Step S3) MR-C, MR-I, MR-N.
- Another level of hierarchy was added using the responses of i) Step 4.1, which

represents Confident Judgments (L, H), and ii) Step 4.2 marking Interest in Search (SEARCH, NOSEARCH).

Each segment of the study, addressing a separate Research Goal, has a dedicated chapter explaining in detail the motivations, data encoding levels, and, finally, presents and discusses the outcomes of the data analyses (see Chapters 5 - 7.)

Trial

The trial started with viewing a fixation cross in the middle of the screen for 2000 ms that indicated the location of the subsequent stimuli on the screen and was a way to minimise eye movements on the screen. Next, participants viewed a word-by-word presentation of a question randomly selected from the data set.

Stimuli Presentation Format Sequential presentation of a stimulus has been applied in ERP studies examining neurological correlates of reading [185], as well as in IR-related studies of relevance [22] and query construction [156]. It aims to control free-viewing and minimise the presence of any confounding artefacts (i.e. saccades). As a result, the ERPs were time-locked to the word onset presentation. The participants were instructed to read individual words that formed a question. The words on the screen were presented using a Fixed Rapid Serial Visual Presentation (fixed-RSVP) of 800 ms for each word. As previous studies of sentence processing [186, 187] pointed out, a ratio above 700 ms applies engagement of higher cognitive abilities. These are important for us as we want to capture the human information processing and extract EEG signals associated with particular words, i.e. events. The duration of the word presentation was tested in a pilot study, and the outcomes determined the final ratio of 800 ms. It was found sufficient for fluent reading and to avoid the overlapping effect of two consecutive words on the ERPs [147]. An alternative approach, i.e. self-paced reading methodologies, allows for a more natural-like reading [187], which considers the fact that the longer or more difficult words require more time to process by the human brain. We, however, justify our reasons for using fixed-RSVP, and the reasons were the following: 1) to time-lock the stimuli presentation to get an equally long-lasting signal from processing each stimulus separately and 2) to reduce the effect of processing time differences.

Trial Flow After the last word of a question run, participants were instructed to make the first response (Step S2 in Figure 3.1). They were required to respond by selecting one of these options: A. *I recall the answer* (KNOW), B. *I might recognise the answer after I see it* (FOK), C. *I do not know the answer* (NKNOW) presented in random order. Here we captured responses related to participants' metamemory recall outcomes incorporating the option related to Feeling-of-Knowing (FOK) as the prospective judgment of future knowing (see Chapter 5).

After the participants responded, Step S3 followed. Here the participants were requested to choose an answer to the question from three on-screen presented mnemonic cues, which in random order represented i) the correct answer to the question (MR-C), ii) the incorrect answer (MR-I) and iii) the default option to acknowledge when they did not know the answer to the question, respectively could not recognise a correct answer (MR-N). The subsequent flow of the task depended on the response participants provided in S3 and could be either Confidence level judgments (S4.1) or Search Phase (S4.2) to learn the correct answer. Participants' confidence levels represent retrospective judgments in terms of confidence related to their performance (i.e., confidence that provided answer was correct) in two levels: low confident (L) and high confident (H). If the participant's response in S3 was NKNOW, they proceeded to S4.2. Step S4.2 stands here to simulate a real-life fact-finding search scenario. In case of the negative response (i.e., I do not want to know, NOSEARCH), the experiment moved on to another question from the Q/A dataset; in case of a positive response (i.e., I do not want to know, SEARCH), the correct answer appeared on the screen. The term "Search" is simplified here, as the participant did not perform any online or offline search. The purpose of this part is to account for not known (S2) and not recognised (S3) responses attributed to a gap in general knowledge and to see if they ultimately trigger INs (SEARCH) or not (NOSEARCH). A "real" search would introduce into the study multiple levels of body movement activity, especially regarding entering a query (depending on a mode level, such as typing or speaking up). This scenario would contaminate EEG data with motor-related brain artefacts. Therefore, due to these EEG constraints and the overall study time constraints, we decided to provide a correct answer straightaway to satisfy the participant's interest in knowing the answer.

3.3.2 Q/A System

The interactive Q/A system which ran the Task (Section 3.3.1) was programmed in a behavioural research software e-Prime2 from March to June 2019. The EEG recording was done in the following manner: The laboratory room, where the subject study took place, was equipped with two computers and one EEG amplifier connected to the EEG cap placed on the participant's head. The first computer served to run the task and collect the behavioural data. The participant used a standard computer keyboard with the instruction set to interact with the system (i.e., send the responses via button press). The second computer was directly connected to the EEG amplifier allowing it to monitor the EEG channels connectivity and the time waveforms of the brain activity in real-time.

Q/A Dataset

For our Q/A system, we constructed a raw dataset consisting of 180 general knowledge questions. The questions were taken from following sources: (1) TREC-8 and TREC-2001[1] (50% contribution to whole data set) and (2) B-KNorms Database[2] (remaining 50% of questions). The former is widely applied in studies in information retrieval [22, 69], and the latter has been used in cognition and learning studies [166].

The questions were of the open domain and closed-ended answers. Each question had assigned a correct answer (MR-C) and an incorrect answer (MR-I) taken from the aforementioned sources. An example of such a question: "When is St. Patrick's Day?" with the correct answer: "March 17th" and the incorrect answer: "March 23rd". Two study-independent assessors assessed the difficulty of each question in the data set. The

[1] https://trec.nist.gov/data/qamain.html
[2] https://www.mangelslab.org/bknorms

assessors were independent, meaning, they were not invested in the concept of our study nor the outcomes of our study to ensure the objective assessment. They were supposed to judge if the question was generally easy or difficult to recall the answer straight away. The assessors were not given the answer choices for each question. The Cohen's Kappa measure of inter-rater reliability reached 0.61. We selected 120 questions as our final set (provided in Appendix C) where the annotators' judgments matched. The questions were equally distributed between easy (60) and difficult (60). Additional five questions we used as the input for the practice session.

We used the Difficulty attribute to manipulate the distribution of the first set of responses concerning the metamnemonic states of knowledge (Meta). We expected that different perceptions of knowledge were going to be triggered by different levels of difficulties. For instance, easy questions are likely to trigger more recalled responses (KNOW), and difficult ones trigger more not-recalled (NKNOW) responses. FOK level is more challenging to predict. As FOK was found to be sensitive to input difficulty levels [166, 180], we expected that higher levels of FOK would be observed at the intersection of the two levels of difficulty, for instance, when a strong feeling of a later recollection at the users prevails. Here is an example of a Difficult question from the dataset: "What is the length of the coastline of the state of Alaska?" and an Easy question "What primary colours do you mix to make orange?". The mnemonic cues (answer choices) in the Recognition part were only used to enhance the retrieval and were not applied to control the distribution of the MR factor. We recognise that in each pair of the MR-C and MR-I answer choices, one of the choices might have felt more obvious than the other and influenced the increase of MR-C by guess. The current study design does not account for this separation, so it can be considered an extension in the future. Investigation of the effects of difficulty level on neural activity was not related to our hypotheses, therefore, not used as an independent variable in the investigation of EEG data. However, the following Chapter 4, specifically Section 4.4.2, provides the analysis of collected behavioural responses distributed by their assigned Question Difficulty.

Additionally, we ensured that the selected questions were not ambiguous and still appropriate by manually validating each answer using a search engine. The order of the questions and the answer choices in Steps S2 - S4.2 were randomised for each participant.

The questions covered a diverse range of topics: History, Science and Technology, Geography, Culture and Art. The questions were not balanced across the topics as we did not investigate the effects of this variable on the neural signatures, similarly as in the case of the question difficulty. The question length was measured by the number of words the question consisted of. The question length ranged from 3 words to 13 words (see Table 3.1). Some questions from source (2) were syntactically modified to fit the question length limit. Question length was, similarly, as question difficulty analysed as a potential factor impacting the Meta levels (see Section 4.4.1).

Table 3.1: Distribution of Questions according to their Length in Q/A Dataset

Question Length (Word Count)	3	4	5	6	7	8	9	10	11	12	13
Question Count	13	7	8	9	9	15	17	10	8	14	10

3.4 Data Acquisition

3.4.1 Apparatus and Equipment

The main experimental task was synchronised with an EEG system. A 40-electrodes NeuroScan Ltd. system with a 10/20 configuration cap was used for data acquisition. EEG data were recorded with a sampling frequency of 500Hz. Impedances were kept below 10 kΩ and the signals were filtered online within the band of 0.1 - 80Hz. EEG recordings were subsequently pre-processed offline using toolbox EEGLAB version 14.1.2 [188] executed with Matlab R2018a. The pre-processing pipeline is described in Section 3.5.1. A further stage of statistical analyses was done in RStudio with R version 3.6.1. The data analytical methods are described in Section 3.5.2.

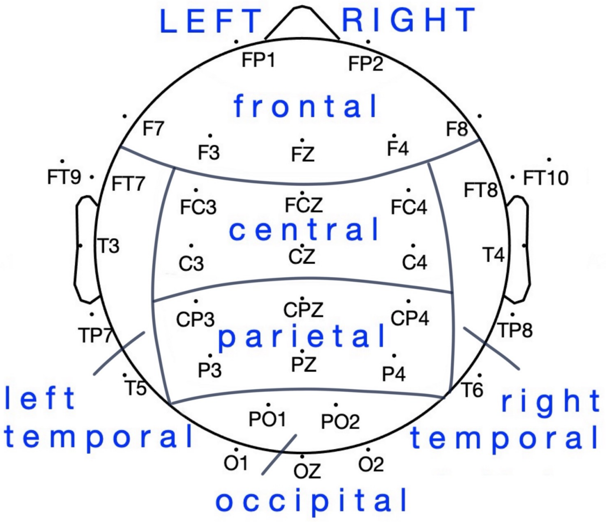


Figure 3.2: Placement of the electrodes according to 10/20 System and their regional brain assignment.

3.4.2 Synchronisation of EEG data and Behavioural data

EEG brain signal was measured for the duration of the entire task. EEG signals were time-locked to the word presentation, as shown in S1 in Figure 3.1.

The result of each participant session were two files: 1) one that captured real-time raw EEG data (i.e., voltage measures in a given time-frequency per each electrode) and 2) one that recorded the chronological activity of the presentation screen (e.g., the question number) and the participant interactions (e.g., button press or ID of the participant). Both files were synchronised using triggers. Triggers represent unique markers depicting a particular activity of our interest, e.g., trigger #2 marked the recorded FOK response; trigger #7 marked a low confident response or the start of the presentation screen with mnemonic cues was indicated by the trigger #12. At the onset of each stimulus, a trigger with a timestamp and a unique ID (#) was sent onto a behavioural data file (as depicted by a green cross icon in Figure 3.1). Another trigger was sent when the button press indicated the response (orange diamond icon in Figure 3.1). The response trigger encoded the entire sequence of stimuli according to a factorial hierarchy (described in Section 3.2.5). These triggers are of high importance as they allow us to mine and navigate within the EEG recordings.

By design, we eliminated the signal contamination by neural correlates corresponding to motor responses (i.e. hand movement to make a button click) as these generate a separate signal (often called noise) affecting the underlying brain signal. The user was instructed to read the textual stimuli on the screen that followed the order of the words of the currently presented question (screen S1). During this run, as the EEG data of the participants' information processing was simultaneously recorded, the participants were not instructed to press the response button. They only did it when answering the questions depicted on screens S2 - S4.2. Furthermore, randomisation allowed to eliminate any order bias and response tendencies.

Behavioural data - Logs

After completing the experimental session, a log file containing behavioural data was generated for each participant. Each file contained the chronologically represented data as they appeared on the presentation screen. These included sequences of triggers (explained in Section 3.4.2) and timestamps. The same information, but in a different format, was generated as metadata of the EEG data files (the brain signal). The advantage of the metadata files was their readability by the EEGLAB toolbox in Matlab software we used for the data processing and data epoching. It allowed us to mine the relevant data, such as the mean duration of the FOK responses. A sample metadata structure is in Appendix D.

3.5 Data Evaluation and Assessment

This section will present the data analytical framework covering part of pre- + post-processing techniques. Creating a coherent and cohesive framework applicable to all study segments (presented in Chapters 5 - 7) was intentional. At first, following a systematic approach of data pre-processing results in i) enhanced data quality across all subjects of the study and ii) data equality to allow for comparability across subjects. Second, consistency in data analysis methods allows for qualitative data comparison across levels of the factorial hierarchy, which is our main target.

3.5.1 Data Pre-processing and Cleaning Pipeline

Individual participant data were pre-processed using the pipeline in Table 3.2 constructed according to the guidelines for the standardisation of processing steps for large-scale EEG data [189]. The table presents the order of steps that resulted in the data refined for the next phase, i.e. data analysis. All the steps were mandatory, except for Steps 5 and 8, which were only performed when needed.

Step 1 was applied as the electrical recordings often tend to be contaminated by residual power-line interference, which lowers their quality (i.e., measured by the Signal-to-Noise ratio). The cut point at 50Hz conforms to the United Kingdom's standard 50 Hz current, where the study was conducted.

Next, the EEG waveform of an average healthy person still contains physiological variability. In order to keep those frequencies commonly associated with performing cognitive tasks [190], we applied filtering, a standard pre-processing procedure, in Steps 2 and 3.

Step 4 was used to reduce data volume while still maintaining enough data granularity and quality. We downgraded the original 500Hz recordings to 250 samples per second.

Step 5 is the first step in reconstructing a low-quality EEG signal. This step was applied only on selected electrode/-s whose recordings were found to be very noisy (therefore of low quality) or their recording was interrupted (e.g., disrupting contact with the scalp during recording). If not treated, a missing channel represents a significant portion of underlying cortical activity that would not be accounted for, which might adversely affect the further stages of the data analyses. In order to reconstruct the poor electrode's signal, we interpolated its signal combining the produced signal from the electrodes in spatial proximity to the interpolated electrode. We used the spherical interpolation method to measure the distances between the EEG channels to decide on the electrodes.

The next common technique applied in the pre-processing of EEG data is re-referencing. It provides an approximation of zero microvolts for the reference at each time point) The mastoid (electrode A1) sensor was initially used as the reference electrode. In Step 6, we used average re-referencing, which creates an average of all scalp channels and subsequently subtracts the resulting signal from each channel. Average re-referencing is suggested as an appropriate approach [191] in a case of data-driven exploratory analyses of ERP components and ROIs given by the novelty of the task where associated neural activity is unknown [192], such as ours. The idea behind re-referencing is to express the voltage at the EEG scalp channels with respect to another - new reference. After re-referencing, the overall electrical activity (amplitude) across all channels will sum up to zero at each time point. Amplitudes are reduced overall when using this reference, but each channel contributes equally to the new reference.

We then moved on to Step 7, where we performed Independent Component Analysis (ICA) in order to detect and adjust noise-introducing artefacts associated with ocular, cardiac artefacts and muscular movements based on their power spectrum and time course. Step 8 was applied only when such EEG markers were present. It was done by manually checking the list of markers recorded during each session. Completing Step 8 resulted in an artefact-free signal that could be epoched (Step 9), i.e. selecting the events of interest. We epoched data from 200ms prestimulus presentation to 800 ms poststimulus.

Finally, Step 10 performed a baseline correction using the -200 to 0 ms window applied to each epoch. We achieved this by subtracting the mean of the points from the baseline period prior to the onset of the first word of a question (Screen 1 in Figure 3.1) from each point of the corresponding waveform. It was used to remove DC-offset or, in other words, to compensate for signal drifts in electrophysiological recordings [193].

After that, we averaged all epochs which belonged to the same level from the factorial hierarchy (see 3.2.5) for every participant. For each condition, we thus obtained a file generated for each participant with a grand average data epoch (waveform) for every channel. As the last step, the grand mean of each channel was subtracted from the value at each time point of the corresponding waveform to remove the linear trend [194]. These data entered the further stages of data and statistical analysis.

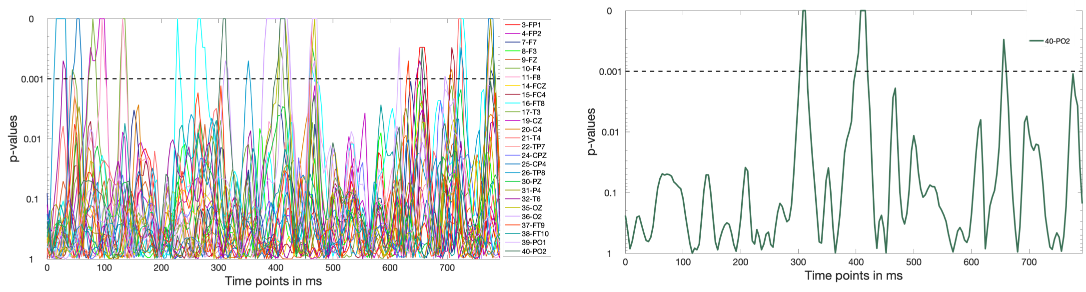
Table 3.2: Data pre-Processing Pipeline with mandatory (N) and optional steps (Y) fitted to our experimental study

Steps	Optional
1. Remove power line noise at 50Hz	N
2. High-pass filter at 0.5Hz	N
3. Low-pass filter at 30Hz	N
4. Down-sampling to 250Hz	N
5. Interpolation of noisy electrodes	Y
6. Average re-referencing	N
7. ICA decomposition and removal of artefacts	N
8. Removal of random noisy EEG markers	Y
9. Data Epoching (window -200 to 800 ms)	N
10. Baseline correction (window -200ms to 0 ms)	N
11. Epochs averaging	N
12. Removal of the mean for each channel	N

3.5.2 Data Analysis

Refer to Table 2.1 in Section 2.3.1 containing a glossary of EEG terms used in the text. Initial visual inspection of the EEG data and the power spectra of the ERP waveforms showed a clear manifestation of periodic deflections of the baseline, which can be interpreted as the occurrence of ERP components. Thus, we decided to apply a combination of an exploratory and component-driven approach, focusing on evaluating the ERP deflection within specific time windows where such deflection occurs.

In contrast, a pure component-driven approach reflects the researchers' interest in studying specific ERP components that are believed to be associated with a particular phenomenon. For instance, a study of Pinkosova et al. [22] applied this approach to the investigation of the cortical activity of graded relevance (high relevance, low relevance, no relevance), and, thus, building upon previous evidence [148, 157] which associated relevance with the emergence of the components: N300, P400 and N600. The study then took these components and the time windows in which they are believed to occur and exploited these components in a new setting. Moreover, the split of time series in the component-driven approach usually refers to a prior similar investigation and use the expected times where the ERP components should be present. As such, it is a more



(a) The list of significant electrodes (b) Selected electrode PO2

Figure 3.3: Visual output of a bootstrap test contrasting MR-C and MR-I level depicting the sequence of p-values for significant electrodes.

artificial approach and does not reflect the differences between studies. On the other hand, our approach involves the present data on a larger scale to create more natural boundaries for components determined by the onset and offset of the ERP deflections specific to our investigation.

Since the concept of IN was not directly tested using EEG before, we did not have evidence of specific ERP components expected to occur. It motivated the idea of the component-free approach, which conforms to the suggestion by Kappenman and Luck [192] for new tasks or tasks that have not been previously subjected to ERP studies. We identified ERP components evoked during our investigation of IN and associated them with their spatio-temporal aspects of ERP activity linked to the task, avoiding, thus, selection bias and Type I error. As we mentioned, EEG activity is a spatio-temporal activity; therefore, two fragments need to be determined: time and space (i.e., regions on the scalp) with meaningful activity. Spatio-temporal investigation of neural activity requires i) unbiased selection of the relevant spatial regions where the activity is significant and ii) splitting the overall timeline into smaller time windows. We framed a procedure that allows us to achieve unbiased results. Its details are provided in the next Sections 3.5.2 and 3.5.2.

Identifying Regions of Interest (ROI)

Kappenman and Luck [192] suggested dealing with both the selection of time windows and ROIs by separating statistical tests for each time point at each electrode, combined with correction for multiple comparisons. Following this approach, we searched for significant differences across factorial hierarchy with a combination of the 2-sample paired Monte Carlo permutation test and non-parametric bootstrapping running 10,000 permutations (further refer as "bootstrap test").

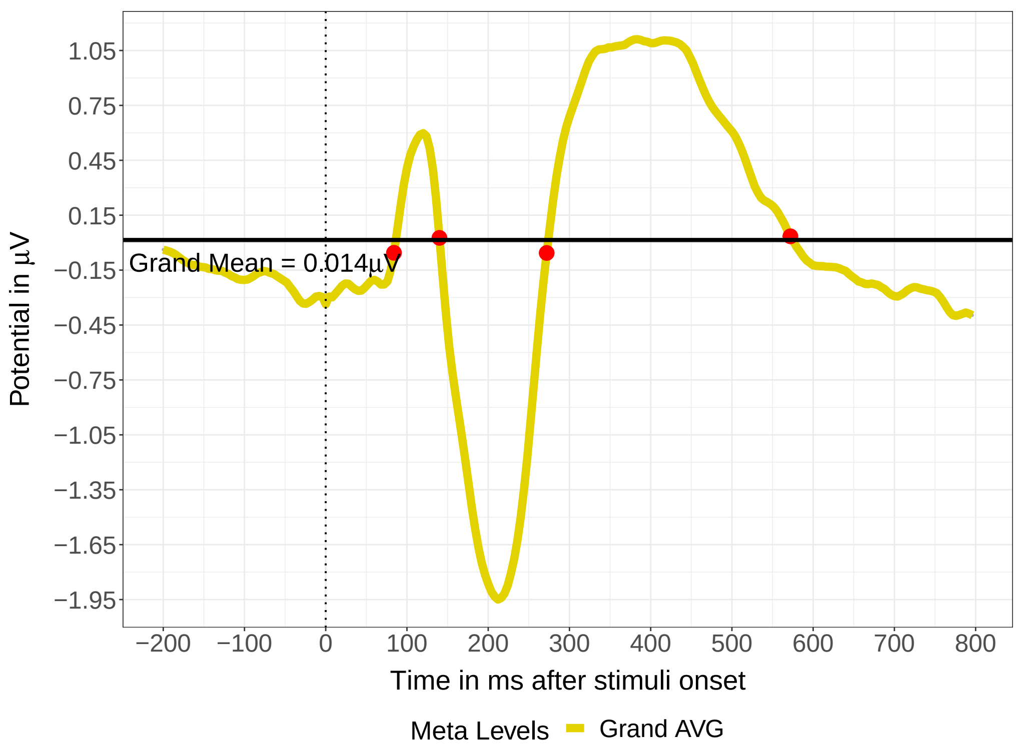
For instance, we ran three pairwise tests to investigate 3-level factor MR levels: MR-C vs MR-I, MR-I vs MR-N and MR-N vs MR-I. The outcome of each pairwise comparison was a set of significant ($p<0.001$) electrodes and their assigned time point where the activity significantly differed. The sequence of p-values on the data epoch timeline contrasting MR-C vs MR-I level is plotted in Figure 3.3. The Figure 3.3a shows all the electrodes identified as significant whilst the Figure 3.3b only depicts the p-value line for PO2 electrode. We notice that the activity is significant in three places, i.e. where the p-value is lower than our threshold ($p<0.001$).

An electrode found in all pairwise tests represents a common modulation of brain activity in a particular sequence of the timeline. We categorised the time points with the significant activity to the time sequences as: the onset (0-200ms), the beginning (200-400ms), the middle(400-600ms), and the end (600-800ms). This segmentation serves only as an arbitrary placeholder for future (and non-arbitrary) time windows (described in Section 3.5.2). At last, as electrodes can be part of hubs, where it was possible, we assigned electrodes into a cluster (ROI). These were created based on their spatio-temporal properties, i.e. local proximity (according to Figure 3.2) and commonly exhibited significance within a specific time sequence. In summary, this first step helped us to reduce the number of electrodes and analyse the time points where the significant activity was happening.

(ERP-fitted) Time Windows

As we mentioned earlier, capturing a majority activity of a single deflection helps us to get a sufficient amount of information describing the dynamicity of neural activity to identify ERP components and, thus, contrast the investigated concepts. To ensure the decision to set the boundaries of time frames was not arbitrary or biased, we used a simple data-driven approach we now describe.

(a) Right Frontal/Front-Central ROI



(b) Temporo-parietal ROI

Figure 3.4: Identifying time windows based on grand mean baseline

We use the set of ROIs identified in the previous section as the input. By default, the EEG uses the baseline set at y=0. In order to capture the actual values of activity recorded for each electrode, we need to adjust the baseline to a generated grand mean. First, we start with generating ROI's mean values for each participant and each experimental condition separately (Result: Electrode's mean value per participant in each condition). Afterwards, we average data across the participants. As a result, we obtain the mean value representing ROI's mean potential value in each investigated level (Result: X values for each electrode where X is the number of conditions). At last, we calculate the grand average for each ROI. The final value represents the actual baseline for each ROI. We apply this value to the corresponding grand average waveform for each ROI. The time point where the waveform reaches the baseline represents a point where EEG deflection departs from the baseline respectively returns to a baseline (i.e. conforming to the definition of an ERP component in Table 2.1).

Figure 3.4 depicts the grand average waveform of the right frontal/front-central ROI (3.4a) and temporo-parietal ROI (3.4b). For help with the localisation of ROIs, refer to Figure 3.2. The horizontal black line represents ROI's temporal grand average which we used as a baseline reference. Red points are generated boundaries for splitting the timeline into smaller time frames, each containing a certain deflection of the same polarity, i.e. ERP component.

Next is the decision to translate these identified boundaries as the time windows, one of the major elements for further analysis. One of the criteria for the ERP component is that it underlies a cognitive function which translates as the objective we try to capture. Time windows can be, thus, created as either:

- One set of time windows and fit them to all significant regions (ROIs) regardless of different latency of the components at different parts of the brain.
- Different sets of time windows to adjust for the latency of components at different brain locations, for example, the identified P200 component spans between 160 ms to 250 ms poststimulus in the frontal area, but it spans up to 280 ms poststimulus in posterior regions. Therefore we create 2 "versions" of the P200 time window, one for the frontal region and another one for the posterior.

We decided to apply the first approach and generate one set of time windows to capture the majority of a single ERP activity regardless of the regional differences in the onset and offset of the ERP components. For instance, in the early onset of the timeline, two time intervals were generated i) in the front-central area 72 -150 ms, and ii) in parieto-occipital 90 - 156 ms. In alignment with the procedure, we set the boundary as "90-150 ms" as the first time window. We similarly proceeded to approximate the next three windows: 150 -270m, 270-570ms and 570-800ms, each of which described an underlying ERP component. The systematic approach using one set of parameters whilst having multiple investigations of different but related phenomenons (i.e., Meta, MR, Confidence in the context of the searchers' IN) also contributes to a coherent comparative analysis. For instance, to observe the similarities or disassociation between the outcomes of two investigations.

In summary, both of the procedures behind the determination of ROIs and time windows helped to associate time with a relevant space and, thus, reduce the 2D dimension (time points in ms x electrodes) only to significant time and space, which were then moved to statistical analysis.

Interpretation of ERP

We follow a systematic approach while interpreting the waveforms in an EEG recording. We intend to perform ERP analysis extracting the amplitude of the ERP component to contrast the neurological behaviours associated with the levels from the factorial hierarchy 3.2.5. In general, the amplitude of an ERP component reflects the voltage elicited by the neural activity giving rise to an ERP component. The higher the voltage, the higher the ERP amplitude, which indicates that a greater amount of neural resources (activity) are recruited to support the specific computational operation performed. When an ERP component measured during two experimental conditions (i.e., hypotheses) is compared, the resulting differences can inform about the spatio-temporal properties of the neural activity subserving the investigated hypotheses.

Another aspect that might appear confusing for an audience with no prior knowledge of human signal data is the dipolar nature of ERP components. It means that every component is positive over some part of the head and negative over others within the same time windows, summing to zero over the entirety of the head [154]. We can demonstrate this aspect by looking at both plots in Figure 3.4. In Figure 3.4a we see the component N100 with negative deflection measured over anterior (frontal) area within the time frame 90 -150 ms poststimulus (see Table 2.1 in Chapter 2 for standard naming of ERP components). On the other side, within the same time window, this component has positive polarity over the posterior area (Figure 3.4b). Therefore, one can argue that in this particular case, the N1 component should be more accurately described as P100, where "P" stands for Positive, as we presented in Table 2.1. However, in the EEG and ERP literature, such a separation is not always the case as the polarity is not considered the most relevant aspect of the ERP [154], but rather the underlying cognitive functions of the ERP components described. The separation of an ERP component is sometimes done via the specification of a brain region or an electrode where it occurred [195], for instance, the component N100p where "p" stands for a posterior region or component P400cz found in [196] describing P400 component centred over the Cz electrode. We will use a standard convention to name the ERP components consisting of the polarity and time latency indicators, as described in Table 2.1. The text will always specify where the ERP component occurred and describe its properties.

Regarding the shape of an ERP amplitude, the standard approach is to observe the amplitude's absolute local maximum (i.e., regardless of the amplitude's polarity). The absolute value of the maximum is the indicator of the variability of the amount of employed resources from a specific ROI. In general, the higher the elicited amplitude, the more resources were engaged to support the cognitive processing mechanisms [192]. Brain regions form the functional networks to support the neural processes subserving the stimuli evaluation, e.g. visual stimulus encoding to support selective retrieval of contextual information associated with the stimulus [197]. The investigation of the spatial properties of activity, i.e. brain regions where the activity is significant, allows for a functional comparison across the investigated levels.

3.5.3 Sample Size Processing for EEG Data

As we introduced earlier, we will evaluate two portions of the data collection - behavioural and corresponding EEG data. Behavioural data comprise the participant responses classified according to the factorial hierarchy. They are essential to inform us about the general distribution of responses, report on any significant effects, and uncover the relationships between the factors, specifically between their levels. We will analyse the whole set of behavioural data. A different approach will be taken to evaluate EEG data. Here, we expect to have for every individual analysis different portions of subject samples as the subset of the entire data collection. As we will report in the next Chapter 4, our data showed high variability among the participants in terms of the number of responses across the levels of factors as well as between the subjects themselves. As our exploratory analyses rely on within subject-data design, they require a sufficient amount of records across all factors. All the more critical for ERP analysis, as it relies on grand averages of within-subject levels. The more individual data samples we have, the more pronounced and refined ERP components begin to emerge. Our first data insight showed data skewness following the distribution of responses labelled according to the levels from the factorial hierarchy. The differences are even more pronounced on the levels of the interaction of the factors and their specific levels. For instance, we found that we do not have almost any samples for some specific interaction levels, i.e. MR-N+NOSEARCH.

If we overlook this aspect, we introduce the ERP analysis using data contaminated by a low amount of records samples which appears as a type of noise. If not treated properly, the analysis can result in significant findings caused by such noise and not by the differences in actual underlying neural operation. For this purpose, we reviewed individual data before every investigation. We automatically excluded participants with zero responses (as there would be nothing to average) and those who did not fulfil the condition of the least amount of samples. This condition was calculated based on mean values for each factor and is the cause of different sample sizes presented in Chapters 5 - 7. The procedure, as well as the output, are reported in each of the chapters.

3.5.4 Statistical Methods

The quantitative analysis consists of methods to statistically evaluate the neural activity connected to different levels of the factors from the hierarchy (Section 3.2.5) as well as to discriminate the significant activity across these levels. This approach will allow us to reveal the spatio-temporal drivers behind each investigated level and understand, from a cognitive perspective, users' states of knowledge behind the IN realisation.

Our main comparative measure is the mean signal, calculated as the mean of the ERP activity, precisely the amplitude that describes the ERP activity, which occurred within a particular time window (see 3.5.2) and a significant ROI (see 3.5.2).

Mixed Linear Model See Section 3.2.5 for the reference of the factorial hierarchy used in the statistical models. We created a separate mixed linear model for every investigation, i.e. every segment of the study. We used the mixed linear model, which does not assume independence of observations, fitting to our within-participant design. One of the important aspects of mixed models is that they allow for different sources of random variation in data. They are often used in studies involving human subjects [198]. The neural activity of the human subjects is prescribed to between-individual variations, which are subjected to different factors. For instance, brain ageing (i.e., brain morphology changes with the subject's age [199, 200]) or motor-controlled activities (e.g., production of facial expressions [201]). We eliminated the brain ageing effect by limiting the age range of our subjects. Furthermore, they shared a common characteristic of being all university students without any past or current neurological impairments that might influence the EEG signal. The "perfect removal" of the motor-related activity is not possible, and the data, thus, will be affected by individual differences to some extent. Random effects in the constructed data models are, thus, considered an additional source of variations explained by data. Our model structure contained information about 1) independent variables, i.e. the classification of the data, 2) participant factor (i.e. participant ID) as the random effects variable, and 3) dependent variable was the mean potential calculated for the significant electrodes and the ROIs (determined in 3.5.2). The model was applied for each time window we defined in 3.5.2.

ANOVA In order to test if and how much the participants' neurocognitive response (i.e. dependent variable) varied within the investigated factor levels, we applied Analysis of Variance (ANOVA) repeated measures test over the model. The results of ANOVA answer the question: "Is the variance between the means of the given within-subject condition significantly different?". Our null hypothesis (H0) is for a specific independent factor constructed as: All the within-subject means (levels of the factor) are equal and there is no significant difference between the means. The alternative (H1) hypothesis stands as: Not all of the means are equal.

The H0 states that the obtained results are due to chance and are not significant in terms of the support for the idea we are investigating, i.e. different levels of the factor. The H1 states that the independent variable did affect the dependent variable, and the results are not due to chance.

Data were assessed if they fit the ANOVA's assumptions of normality and sphericity in order not to compromise the results' veracity. First, the condition of data normality assumes the normal distribution of variances between the factor levels. To test this condition, we used Shapiro-test of normality. The second assumption of sphericity expects that the variances of the differences between all possible pairs of within-subject levels (i.e., levels of the independent variable) are equal. We used a commonly used Mauchly test that is implemented as part of the R package STATS. Finally, we used the Greenhouse-Geisser correction when the dependent variable did not meet the sphericity criterium.

We performed both One-way and Two-way ANOVAs. **One-way ANOVA** was used with the model containing only one independent variable to study if the participant score differed between the levels of a factor, i.e. one independent variable. For instance, Chapter 4 used the One-way ANOVA to statistically assess if there was a significant difference in the number of responses classified into three Meta levels the participants recorded during the experiment. The corresponding EEG analysis in Chapter 5 investigated the effect of Meta levels on the neural activity (mean potential elicited) recorded at a specific ROI to see if there are any differences between the neural activity for KNOW, FOK, and NKNOW.

Two-way ANOVA considers the interaction of the factors. For instance, Chapter 6 studies if there is a significant effect on elicited EEG potential, sourcing from not only the main effect of the MR factor, the main effects of Confidence but also their interaction.

In order to consider ROI as significant, i.e. to accept the H1 hypothesis and reject the H0, we generated a probability value (p-value) for each ROI. P-value is the probability of getting a result at least as extreme as the one that was actually observed, given that the H0 is true[3]. We considered three levels of statistical significance expressed as the probability threshold and contrasted the observed p-value: i) p-value<0.05, ii) p-value<0.01, iii) p-value<0.001. The smaller the p-value obtained, the stronger the evidence against H0. For instance, the p-value<0.05 indicates there is less than a 5% of probability that the H0 is correct.

For ROIs identified as significant following the previously described approach, we ran pairwise post-hoc tests with Bonferroni correction for multiple comparison corrections to specify the individual pairs that drive the significant effect. For example, in the time window, 90 - 150ms, the difference in right centro-parietal ROI was driven by the significant difference between the FOK signal and the KNOW signal, with the latter being significantly greater.

Each of the following Chapters 4 - 7 specifies the model parameters and reports on the findings resulting from the applications of these statistical methods.

3.5.5 Topography similarity and temporal dynamics of brain signals

The analytical framework described so far will help to explore the significant differences in the mean amplitude of ERP components across the investigated phenomenons and their interactions. Mean signal means that we converted the elicited signal within a time frame into one single number. In general, contrasting mean signal across conditions brings information if there are differences in the elicited activity but does not give

[3] https://www.simplypsychology.org/p-value.html

sufficient information about the progress of the signal. For illustration, a specific time frame is characterised by oscillations of positive and negative cycles, which would result in the mean signal being close to zero. Such a result, however, does not truly reflect the dynamics of the observed activity.

The purpose of the application of machine learning methods suits the aim to discover dynamical interrelations and patterns between the brain signals. In general, clustering seems to be a good and efficient approach to assign the electrodes based on their pattern similarities and dissimilarities using the advantage of simple data manipulation and operations. The flexibility of the clustering allows the investigations of multiple layers/data dimensions - time frames within conditions and interaction of conditions (e.g., Meta and MR). The potential outcome could lead to discoveries of patterns behind significant neurophysiological patterns using the local information input to answer questions such as, "Is there a typical activity that precedes the occurrence of the P2 ERP component?".

Therefore, as part of comprehensive data further research to target temporal dynamics of brain signals, we developed an application based on a hierarchical clustering algorithm, Derivative Dynamic Time Warping Algorithm (dDTW) [202] and local derivations to find similarly shaped signals within data. The initial output seems promising to localise electrodes sharing similar topography of activity. Moreover, to observe the synchronicity of activations of specific ERP components and create a more precise topological map of the neural co-activity.

The description of the solution and the report of its performance is described as part of Chapter 7.

3.6 Chapter Summary

The current chapter described in detail the methodological framework behind the design and implementation of the experimental study and the data analytical framework used in the current thesis. In particular, it provided:

- Overview of the conceptual framework used in the study and described how each part of the framework is involved in addressing our Research Goals.
- Overview of the procedures to conduct the study and how the study adhered to ethical standards for studies involving human participants.
- Illustration of the task of the study, explanation of the Q/A input and the definition of the factorial hierarchy.
- Explanation of the EEG Data pre-processing pipeline and the data-driven analytical framework to retrieve relevant information to further serve as the parameters for the statistical analysis.
- Description of the statistical methods as part of the analytical framework and the brief introduction to a dDTW machine learning solution used in the final part of the data analysis.

Part II

Investigations

Chapter 4

Analysis of Behavioural Data

In the present Chapter, we will report on the findings informed by i) the data gathered in the questionnaires that were distributed to the participants of the study and ii) the behavioural responses collected during participants' performance in the task (described in the previous chapter in Section 3.3.1). The data evidence we found informs further investigations (Chapters 5 - 7). We discuss several implications for broader research in IS&R, including the factors of query quality as potential indicators of the level of knowledge and user uncertainty reduction in the domain of the user's cognitive context and contextual task difficulty.

4.1 Participant Questionnaires

In this section, we will report on the findings informed by a targeted pre-task questionnaire (see Appendix B.2 for reference), where we gathered data about participants' search habits and simulated a Q/A task. The participant demographics information, such as age or education, were reported earlier in Section 3.1.

4.1.1 Search Habits

In addition to the demographic information, the pre-task questionnaires gathered information about the participants' search habits. A majority (88.75%) of participants responded that they search for information multiple times per day. Two participants used search once per day or not at all, respectively. One participant reported they use search frequently. For a fact-finding type of search, almost 96% of participants agreed that they use online search engines. In contrast, exploratory type of search, e.g. write a class essay, revealed a variance between answers: 41.7% of participants use libraries and library catalogues, the same proportion (41.7%) use online sources and the remaining 16.6% use a combination of both. We further enquired about participants' search habits related to search sessions, with participants having an option to select multiple answers. Over 71% of participants often run multiple simultaneous searches. Out of these, 17% of participants often feel information overload and 41% reported that one search leads them directly to another one. Contrasting search habit, i.e. completing one search before starting a new one, was found in 25% of all participants. In 21% of these cases, the participants tend to feel information overload.

4.1.2 Discriminative terms and Prospective feelings of knowing

In the last part of the questionnaires, we asked the participants to read five general knowledge questions sequentially (word-by-word) and mark a specific term or terms when they started feeling they might know or might not know the answer. Sequential reading reflects a process of accumulation of information until the searcher feels they possess enough information to make a decision. In the case of our investigation, we named these terms "discriminative" and participants' feelings of (not) knowing as "prospective".

We found a high level of agreement among the participants - in the selection of discriminative terms and their association with the reported state of prospective knowing (i.e., either "might know" or "might now know"). In addition, the participants were asked to compare their prospective feelings after they read the whole sentence, which gave us an indication of the prospective accuracy.

What country features a maple leaf on its flag? The agreement of the participant on the selection of discriminative terms reached 83%. The results showed that they were either "maple", "leaf" or their combination "maple leaf". These represent the point up to which the participants accumulated enough information to feel they might know the answer. These terms seemingly triggered information processes towards a successful recall of the answer as these were associated with positive prospects. Their prediction was 100% accurate as they knew the answer after reading the whole sentence. In terms of the sentence syntax, the first part of the question already determined two important descriptors, "country" and "maple leaf" and, thus, likely gave away the indication that the question was going to ask about a flag and increased the participant's awareness about their knowing prospect.

Name the play by Shakespeare that features a brooding Danish prince. Altogether, 42% of participants chose either the single terms "brooding", "Danish" or their combination "brooding Danish" as the discriminative terms. Sixty percent (60%) of the participants were associated with negative prospects of knowing as they felt they might not know the answer. Their feelings were absolutely (100%) accurate. The remaining 40% were associated with positive prospects of knowing, and as was revealed, they were 100% accurate as well. The second most common term was "Shakespeare", which was chosen by 38% of participants. The majority of these participants (67%) perceived feelings of not-knowing the answer with their prospective accuracy of 83%. The remaining 33% of participants had feelings of positive prospects. However, here the accuracy reached only 33%.

The writer's name seems to be a relatively strong attribute to trigger the knowledge prospect. Due to differing accuracy levels, more precise information, such as a play or character description, is likely needed. When the participants continued reading, the later terms providing more detailed input information helped to narrow down the memory search space and impact the participants' prospective accuracy.

What band featured Sting, Steward Copeland and Andy Summers? In this case, 75% of the participants chose the name "Sting" as the discriminative term. Half of this sample felt up to this point that they might not know the answer, which proved to be 100% accurate. The remaining half had an opposite prospective feeling, i.e. they might know the answer, out of which 79% of participants were accurate in their prediction. Here, the name of the band singer provided a relatively strong association with knowing or not knowing.

What vegetable in the mustard family is named for an European capital city? Over half of the participants (58%) agreed on the discriminative terms "mustard", "family", or their combination "mustard family". All of these participants felt they might not know the answer and were highly accurate (93%), with only one participant knowing the answer after reading the whole sentence. Low proportions of participants chose other terms such as "vegetable" or "European capital". The final discriminate term "mustard family" in the context of the previous term "vegetable", can be seen as a specific knowledge (related to a food study) which caused a high level of not-know answers.

What is the translation of this Morse code: ... - - - ...? Over 71% of participants felt they accumulated enough information up to reading the term "Morse". The majority of these, 76%, associated this term with not-knowing, whilst the remaining 24% of participants felt they would know the answer. In both of these scenarios, the participants' prospects were 100% accurate. In this case, high accuracy was expected. Once the language/code method (such as Morse code) is known, a person can quickly respond driven by knowing their own translation abilities.

4.2 Task Perception

Task perception represents the participants' subjective judgments of the selected task attributes. The data were gathered in post-questionnaires each participant received after completing the task. We did not ask the subjects to separate their perceptions per EEG and per the Q/A task itself. We realise, then, that some of the attributes, e.g. level of challenge, would likely be influenced by the general settings of an EEG study. For instance, the level of commitment, effort and concentration this method demands from the participants (e.g., minimise eye blinking and movements; see more in Procedures in Section 3.3).

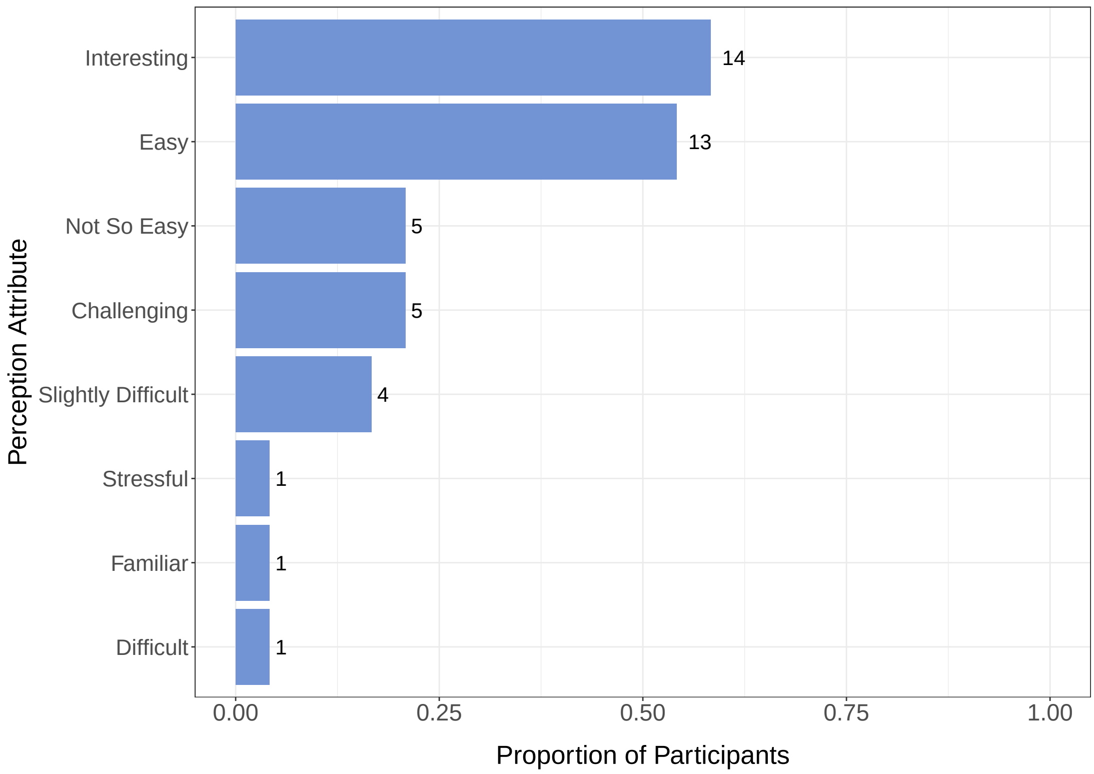


Figure 4.1: Agreement on Task Perception (number next to each bar is the absolute number of participants)

Participants perceived the task mostly as Interesting (58%). In terms of the difficulty, the task was perceived as relatively Easy (54%), followed by perceptions of some degree of difficulty (Not so Easy 21%, Slightly Difficult 17%). One participant (4%) perceived it as Difficult. Those who perceived some degree of difficulty also found the task to some degree Challenging (21%). In general, the task was not perceived as Stressful (4%) nor Familiar (4%). Table 4.1 shows the proportion of participants agreeing on perceptual attributes they associated with the task.

Overall, the participants agreed that the Q/A dataset was an appropriate mix of easy and more difficult questions of general knowledge. We select a few additional participants' comments which expand on their perceptions with the Q/A input set and confirm our conclusions:

- *"Topics varied widely, which was very interesting as there was quite a mix of things I knew and things I did not."*

- *"Varied, some answers I thought I knew and I was wrong and vice versa."*
- *"A good mix of things which were easy and hard; even if I got the wrong answer, I could tell it was a question of a low/high calibre."*
- *"Some were hard, some were easy. I knew the answer to a couple after the answer was given."*

4.3 Behavioural Responses

As was mentioned in the previous Chapter 3 Section 3.2, the task framework consisted of two functional paradigms: Recall-Judgment-Recognition (RJR) and Retrospective Confidence Judgment (RCJ). This framework was constructed to investigate our research objectives by gathering the evidence of underlying processes of knowledge awareness to inform the context of IN realisation. Please, refer to the Section 3.2 describing the individual steps of the task from a theoretical perspective and explaining their involvement in our study targeting cognitive perspectives of IN context. The following sections report on the empirical evidence of the relationships between different stages of the task, which represent the transitions between cognitive feelings of knowing and their attributes (e.g. confidence) used as the variables in our study. For the labels of the variables, refer to Section 3.2.5.

4.3.1 Aim of the exploratory analysis of behavioural data

The preliminary investigations of the behavioural data aimed to discover the patterns of interactions between the investigated levels. We analysed the behavioural responses, such as response distributions or response time, to complement and inform the EEG data analyses (Chapters 5 - 7), i.e. the analyses of the simultaneously captured neurophysiological data. It provides us with a comprehensive insight that contributes to our research goals. Specifically,

- Metamemory-evoked processes providing the user with an introspective insight into their current and prospective knowledge (cognitive states of knowing) reflecting the stimuli, i.e. in our study, the questions of general knowledge;

- Factual Memory Recognition to confirm or contradict prior metamnemonic outcome with IN seen as a product of a failed memory retrieval (MR), i.e. gap in recalling and remembering;
- Confidence as the variable of MR and memory strength reflecting the user's estimate that their retrieved memory information was correct and accurate;
- The route between the realisation of a gap in knowledge and IN indicating the user's information preferences;
- Question attributes as part of the situational context modalities.

Although we devised the data analysis on an exploratory basis, we had Research Questions (RQs) in mind to support our Research Goals. The functional paradigms of RJR and RCJ implemented in our study are indicative of the subject's knowledge awareness, their transitions and attributes in the process and, therefore, we ask:

1. **RQ1:** 1) Is introspective (Recall) judgment an accurate predictor of the user's ability to know the information in question at a later time (Recognition test)?; 2) How does the participant in Feeling-of-Knowing (FOK) state perform in this scenario; and how do the findings reflect the variants of INs?
2. **RQ2:** Does the participant's confidence scale with different knowledge states?
3. **RQ3:** Do stimuli attributes (question difficulty and length) affect what knowledge state is evoked?

The main findings of each section will be presented at the end of each section. Following is the summary and discussion of the outcomes supported by relevant works in IS&R and cognitive neuroscience at the end of the chapter (see Section 4.5).

The aim of the analysis presented in the following sections is to:

- Provide an overview of the behavioural data as a result of the Q/A scenario.

- Closer inspection of the patterns associated with FOK as the cognitive state of intermediate recall [19].
- Identification of significant trends and relationships that will serve as the basis for the subsequent analyses of associated EEG data.

4.3.2 Responses Distribution

Detailed data in Table 4.1 presents the distribution of responses according to factorial hierarchy established in Section 3.2.5. The statistical methods are described in Section 3.5.2. Starting with the 1st level of the hierarchy, Meta levels, participants on average recorded the most responses of FOK, 43% (sd 12), followed by 29% (sd 11) of responses of NKNOW. The lowest amount of responses represented KNOW responses, 28% (sd 15). We visually inspected the histogram of Meta levels distribution (Figure 4.2) and noted that whilst FOK and NKNOW levels seem to be normally distributed, the shape of KNOW follows a bimodal distribution. As a reliable measure, we used the normality test, Shapiro test, prior to deciding upon a test of a significant difference. The output of all three tests implied that the data distribution is not significantly different from the normal distribution, meaning that the ANOVA test can be used.

We ran ANOVA repeated measures over the individual participants' data in order to statistically evaluate if there was a significant difference between participant mean volume responses in each Meta level. The results proved to be significant ($F[2,46]=6.62$, $p\text{-value}<0.01$). Based on the results of the post-hoc tests, we can summarise the effects as follows: Participants responded significantly higher amount of FOK responses in comparison to KNOW ($p\text{-value}<0.01$) and NKNOW ($p\text{-value}<0.01$) responses.

The Majority of FOK was the most commonly followed by correct retrieval responses, MR-C (60%), with over half of them (57%) associated with low (L) confidence. MR-I responses accounted for 30% of FOK responses. Out of these, the majority (76%) was of L confidence. The remaining 10% of FOK responses were not recalled, MR-N, with a majority of 89% responses where participants wanted to know the answer (SEARCH), in contrast to the remaining 11% where participants were not interested in knowing the answer (NOSEARCH).

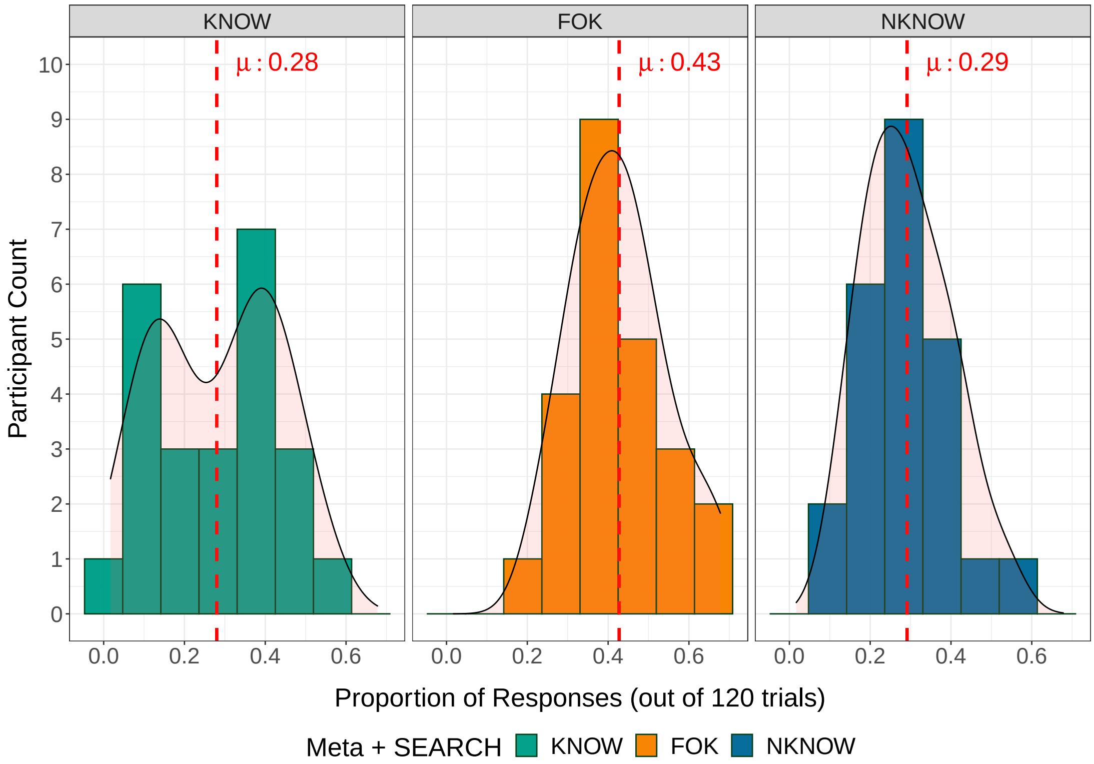


Figure 4.2: Histogram of Meta levels

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KNOW responses provided a similar pattern of a follow-up distribution of MR levels as FOK but with a higher variance amongst the levels. The majority, 82% of KNOW responses, was followed by MR-C commonly associated with high (H) confidence. MR-I responses accounted for up to 17% of KNOW with a relatively equal split between L and H confidence. The remaining 1% of the share represented MR-N responses.

In total, 44% of NKNOW responses were followed by MR-N level with a significant majority, 84%, of SEARCH responses. Following is the 31% share of MR-C responses, commonly (79%) associated with participants' L confidence, similarly as in 25% of MR-I responses where L confidence responses accounted for up to 89%.

Table 4.2 provides data in a relation to MR and Confidence levels. We can conclude that on average more than half of the provided responses were of MR-C, i.e. in more than half of the questions participants were subjected to, their MR was accurate. Next, a quarter of responses represented incorrectly retrieved responses, i.e. MR-I.

Table 4.1: Distribution of responses (average per participant) per 1st hierarchy level)

META Level	*% of Overall Responses*	*MR Level*	*% of Relative Responses*	*Confidence/ Search*	*% of Relative Responses*
KNOW	28	MR-C	82	L	14
				H	86
		MR-I	17	L	52
				H	48
		MR-N	1	SEARCH	70
				NOSEARCH	30
FOK	43	MR-C	60	L	57
				H	43
		MR-I	30	L	76
				H	24
		MR-N	10	SEARCH	89
				NOSEARCH	11
NKNOW	29	MR-C	31	L	79
				H	21
		MR-I	25	L	89
				H	11
		MR-N	44	SEARCH	84
				NOSEARCH	16

Table 4.2: Distribution of responses (average per participant) per 2nd hierarchy level)

MR Level	*% of Overall Responses*	*Confidence/Search*	*% of Relative Responses*
MR-C	56	L	45
		H	55
MR-I	25	L	73
		H	27
MR-N	19	SEARCH	81
		NOSEARCH	19

Table 4.3: Distribution of responses (average per participant) per 3rd hierarchy level)

% of Overall Responses			
Confidence		*Search*	
L	*H*	*SEARCH*	*NOSEARCH*
43	38	15	4

Data further indicate that with incorrect responses (MR-I) increasing, the confidence decreases, i.e. demonstrated by the relatively higher amount of L responses (73% of L relative to 27% of H responses). This result could seemingly suggest the association of L confidence and false impressions, which MR-I responses in their sense might suggest. The lowest number of responses (19%) where participants did not know the answer (MR-N).

The comparison of the proportions between SEARCH and NOSEARCH responses (see Tables 4.1 - 4.3) points to a strong preference of participants wanting to resolve their knowledge gap. The exit questionnaires provide a partial explanation for the low proportions of relative and absolute responses of participants not interested in knowing the answer (i.e., NOSEARCH). We retrospectively learnt that the questions mostly evoked curiosity and interest in learning the correct answer. We select a few of such responses that conform to this conclusion:

"I responded positively to every [question] because I found it an opportunity to learn."

"I like to know the answers to things that I do not know."

"I like finding out new information. Having that option was really good; it kept you interested even when you did not know the answer."

"Genuine interest. The information may be useful in future."

We now proceed to expand on the outcomes of Table 4.1 using the correlation analysis.

Associations

In the previous section, we observed some expected associations, such as recalled responses on the metamnemonic level (KNOW) attracted the recognition of the correct memory cue (MR-C) and seemed to be correlated with high (H) confidence. We, however, found some less anticipated links, such as over 30% of all not-recalled responses (NKNOW) were correctly recognised (MR-C). In order to test the statistical significance of the associations, we conducted Pearson's Chi-squared test to test the correlations between paired samples and calculated the significance level (p-value) of the correlation and the correlation coefficients.

We only report on the pairs with significant correlation and with at least "moderate" correlation (0.40< $|R|$ <0.59). "Strong" correlation is when $|R|$ is at least 0.65 and "very strong" when $|R|$ is over 0.80. As anticipated, the results showed a strong positive correlation (R=0.70, p-value<0.001) between KNOW and MR-C responses, meaning more KNOW responses increase the recognition of the correct memory cue. An opposite effect of a moderate negative correlation (R=-0.42, p-value<0.05) was found when an increase of KNOW was associated with fewer responses of MR-N. In addition, KNOW responses were found to have a very strong positive relationship with H confidence (R=0.85, p-value<0.001).

Responses with the feeling of temporary unavailability of recalling the answer (FOK) were moderately positively correlated with L confidence (R=0.50, p-value<0.01) and moderately negatively correlated with H confidence (R=-0.52, p-value<0.01).

Furthermore, as expected, the pair of NKNOW responses and MR-C responses proved to be significantly negatively correlated (R=-0.68, p-value<0.001), meaning more NKNOW responses would likely result in less correctly recognised responses, MR-C. On the opposite side, we found a less strong positive correlation between NKNOW and MR-N responses (R=0.61, p-value<0.01), meaning an increase of initial NKNOW responses was associated with an increase in MR-N responses, meaning no recognition. NKNOW were also negatively correlated with H confidence (R=-0.58, p-value<0.01), meaning not knowing the answer would be less likely to be associated with H confidence concerning memory retrieval.

Furthermore, we observed a strong positive correlation (R=0.72, p-value<0.001) for the pair of MR-C and H confidence responses, meaning a response triggering correct memory retrieval would likely be associated with H confidence. For MR-I responses, we found a strong positive correlation with L responses (R=0.71, p-value<0.001).

A very strong positive correlation was found for the pair of MR-N and SEARCH responses (R=0.87, p-value<0.001), meaning participants who did not know the answer would likely choose to search, i.e. to learn the correct answer.

Summary We can summarise the results into two areas. First, participants were most accurate when providing KNOW or NKNOW answers as the two definite recall states [19]. As expected, participants initially knowing (positively recalling) the answer (KNOW) or not knowing (not recalling) the answer (NKNOW) were more accurate, as proved by the results of the association analysis. In the case of KNOW, the participants' initial KNOW recall awareness matched the recognition of the correct answer. The found strong correlation between KNOW + MR-C + H can be interpreted as a sequence: "We know the answer (NKNOW) - We recognise the correct answer (MR-C) - We are highly confident my answer is correct (H)". In the case of NKNOW, participants more likely did not recognise the correct answer, demonstrated by the strong correlation between NKNOW and not recalled (MR-N) answer. This situation explains the sequence: "We do not recall the answer - We do not know (recognise) the answer (MR-N)". The accuracy suggests that KNOW and NKNOW are good indicators of the current and the predictors of future knowing and not-knowing, respectively. From the perspective of NKNOW, this might also explain why the searchers engage in a search as they believe they do not know something and are likely to be correct. Their intuition, as given by the Meta levels, is likely to be accurate.

Second, we address the outcomes related to FOK as the intermediate state of recall [19], which implies the temporary unavailability to recall the information with a prospect to recollect. Here, we did not confirm any, at least a moderate correlation, with MR levels. These outcomes support only a relatively accurate character of FOK measure [110] possibly associated with weak memories [27], which at the time of the recognition test emerged and resulted in a negative prospect of FOK. It reinforces the notion of a conservative approach to knowledge awareness because having FOK was not predictive of MR. In addition to MR, the associations between FOK and confidence did not indicate any strong linear relationship. The associations were only moderate and found for both pairs (i.e., FOK+L and FOK+H), which might suggest that FOK can be followed likely by H as well as by L confidence retrieval, which further indicates that FOK is not predictive of users' rates of confidence.

We now proceed to expand on the findings to test the statistical significance of differences between the participants' responses to test the interaction effects between pairs of Meta and MR.

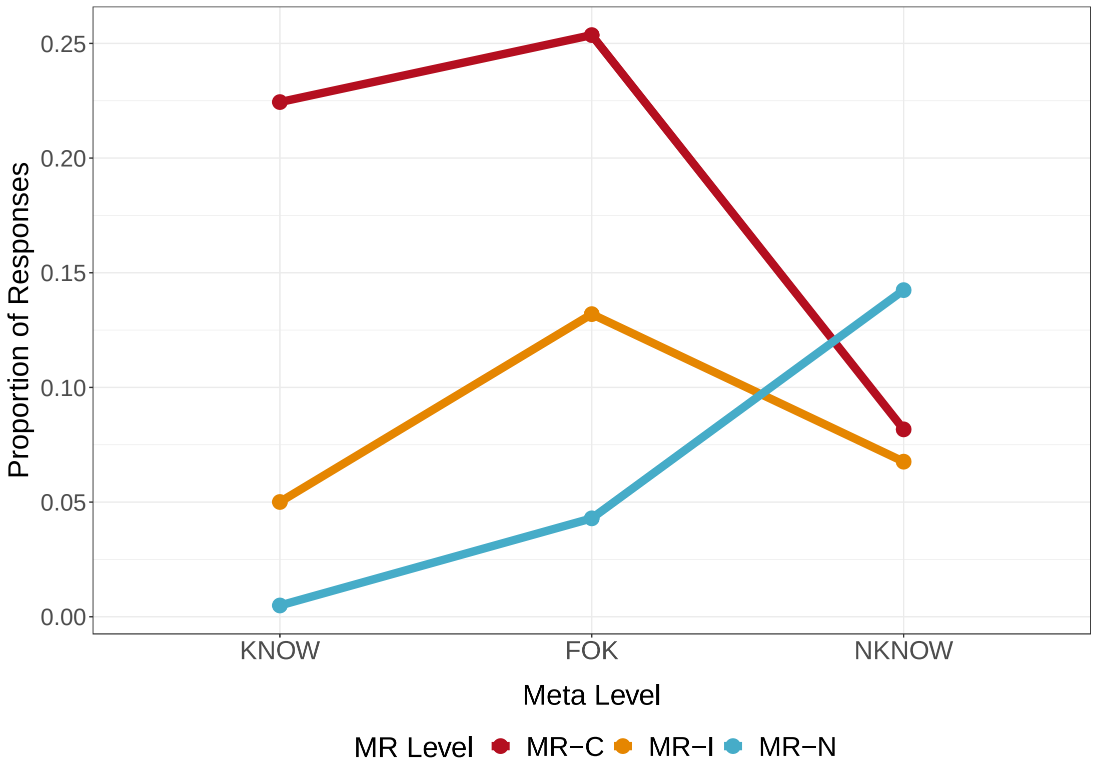
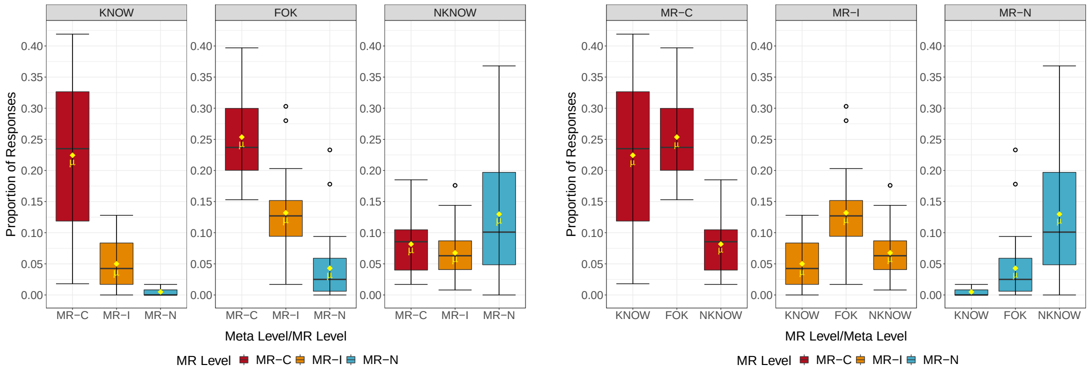


Figure 4.3: Interaction Plot between Meta levels and their corresponding MR levels



(a) View by Meta levels

(b) View by MR levels

Figure 4.4: Distribution of responses by their assigned Meta and MR level

Interactions of Meta and MR as an indicator of the Accuracy of Initial Knowledge Awareness

To answer our RQ of the accuracy of Meta levels and FOK, we conducted ANOVA repeated measures (described in Section 3.5.2) to test out the linear model involving the interaction effects between Meta levels and MR levels. In contrast with the previous correlation outcomes, ANOVA, in general, is based on a linear model with the statistical control for other independent variables in the model and focuses on the unique variation in the dependent variable explained by the independent variable[1]. In our study, it is the proportion of responses explained by the independent variables (i.e., the categorisation of Meta and MR levels) and their interactions. It provides more specificity, mainly when used with post-hoc tests, to disclose the drivers of significant changes in the data. Therefore, we expect to explore the detected relationships further and possibly uncover new ones.

ANOVA, like the regression analysis, uses correlation. However, it controls statistically for other independent variables in the model by focusing on the unique variation in the dependent variable, as explained by the independent variable.

Figure 4.3 shows the interaction plot contrasting the mean proportions of MR responses for each Meta level. Additional insight provides Figure 4.4a.

First, we report on the main effects of two independent variables separately. The

[1] https://irumehar.medium.com/anova-as-an-extension-of-linear-regression-ab8b0b32610a

results revealed a significant main effect of Meta levels (F[2,207]=10.48, p-value$<$0.001) with post-hoc pairwise contrasts specified that the mean proportion of FOK responses was significantly higher than of NKNOW (p-value$<$0.001) and of KNOW (p-value$<$0.001). Next, the main effect of MR levels was found to be highly significant (F[2,207]=60.23, p-value$<$0.001). Post-hoc analysis specified that the mean proportion of MR-C was significantly higher in both pairwise contrasts, i.e. with MR-I (p-value$<$0.001) and with MR-N (p-value$<$0.001).

We found the interactions of Meta levels and MR levels causing significant differences (F[2,2,4,207]=30.02, p-value$<$0.001) of mean proportions with pairwise post-hoc tests specifying the direction.

- First, there was a significant interaction effect within KNOW level between 1) the pair of MR-C and MR-I which resulted in a significantly higher (p-value$<$0.001) proportion of responses of MR-C (μ=0.22) in contrast to MR-I (μ=0.05) and 2) the same effect (p-value$<$0.001) between MR-C and MR-N (μ=0.005).

- For FOK level, we found all pairwise contrasts of the subsequent MR levels to be significant. First, the significant difference between the pair of MR-C (μ=0.25) and MR-I (μ=0.13) is driven by the significantly higher proportion of responses of MR-C (p-value$<$0.001). Second, the same effect (p-value$<$0.001) between MR-C and MR-N (μ=0.04) mean responses. The third significant difference was revealed during the contrast of MR-I and MR-N responses, where the mean of MR-N was found to be significantly lower (p-value$<$0.001) than the mean of MR-I.

- Finally, for NKNOW, we found two significant pairwise contrasts. First, between MR-C (μ=0.08) and MR-N (μ=0.14) where the proportion of responses of MR-N was significantly higher (p-value$<$0.01). Second, the significant difference between the pair of MR-I and MR-N is driven by the significantly (p-value$<$0.001) lower proportion of MR-I (μ=0.06) in contrast to the proportion of MR-N.

Summary The outcomes support the earlier conclusions made for KNOW and NKNOW. The frequency of KNOW followed by MR-C is significantly higher than the rest of MR levels, meaning, the participants who thought they knew the answer were likely to recognise the correct answer. The accuracy also holds for the pair of NKNOW and MR-N, whose proportion was found to be significantly higher than the pairwise contrast of NKNOW with the remaining MR levels. It means that people who initially had a negative recall of the answer (NKNOW) were accurate, as the Recognition test confirmed that they did not know the answer (MR-N).

In the previous section investigating the associations, FOK was left unmatched with any MR level. The findings of the post-hoc tests, however, uncovered significant effects driven by the interaction of FOK and MR. A significantly higher proportion of responses of type MR-C linked to FOK indicates a relatively good accuracy of FOK in predicting the recognition of the correct answer, MR-C.

A complementary view provides a perspective from the point of MR levels (see Figure 4.4b). At the recognition level, the majority of all MR-C responses were preceded by FOK level (μ=0.25) and KNOW level (μ=0.22), without a significant pairwise difference (p-value=0.5). This result could suggest that correct retrieval, MR-C, can be initiated equally likely by FOK or KNOW. With respect to FOK, this confirms that FOK can be a predictor of knowing. The difference occurs at the contrast of Meta levels that resulted in MR-I level. Here, the mean of KNOW responses (μ=0.05) as well as the mean of NKNOW responses (μ=0.06) was significantly lower (p-value$<$0.001), respectively (p-value$<$0.01), in contrast to the mean proportion of FOK responses (μ=0.13). FOK, then, more likely results in Illusions of Knowing [174] reflecting the user's uncertainty with their FOK.

4.3.3 Response Times

In addition to our main analyses, we investigated whether there were any significant effects between the investigated phenomenons and their associated response times. To be reminded, the participants were not restricted by the time limits to provide the answers after each question. There were no significant effects found between the levels of Meta (F[2,46]=0.015, p-value=0.985). The average response time was for 1) KNOW 1.89 seconds (s), 2) FOK 1.91 s, and 3) NKNOW 1.90 s.

For a second category, MR levels, we revealed highly significant differences between their respective response times ($F[2,46]=8.60$, p-value<0.001). The pairwise tests with Bonferroni correction specified that the significance was driven by the highest average response time for MR-I of 3.88s. The highest pairwise significant difference (p-value<0.001) was found contrasting the average NKNOW response time (3.04s), followed by a minor significant difference (p-value<0.05) contrasting the average response time for MR-C (3.31s). These effects could suggest a longer stimuli processing time required for the MR-I level.

4.4 Preliminary Effects of Stimuli Attributes

In Section 3.3.2, we presented our dataset input. As noted, we manipulated the input (questions) attributes, namely the difficulty, to evoke different cognitive states of knowing. Although the contextual factors were not our primary concern in studying the EEG data, we can explore if the input attributes moderated any significant effects on the behavioural data. From the IS&R perspective, the interplay of specific cognitive states of knowledge and contextual challenges can provide valuable insight into the contextual drivers of search behaviours.

In this section, we look at the distribution of behavioural data associated with the input attributes: Question length and Question Difficulty. We will present the outcomes concerning Meta levels as the top level of the factorial hierarchy as it was the first user-triggered perceptions with the questions. We are notably interested in two areas: i) if the variability of question length affects the distribution of Meta level responses significantly and ii) if the difficulty is a significant factor affecting the data distribution.

4.4.1 Question Length

Q/A Dataset was not balanced according to Question Length (see Table 3.1 in Section 3.3.2 for reference). To balance out the different length distributions and avoid countereffects of different question counts for different question lengths.

We divided the individual's mean number of responses in each question length category by their respective question count number (see Table 3.1).

Figure 4.5 presents the final distribution. In order to test the significance of the interaction between question length and Meta levels, we, similarly as in previous scenarios, repeated the ANOVA test for the factors: question length, Meta levels as the independent variables and the response amount as the dependent variable. It, however, did not reveal any significant effects (F=1.822, p-value=0.12) of the question length attribute. In addition, Pearson's Chi-squared test was conducted to test the potential association of Meta levels with Question lengths, e.g. to see if shorter questions would attract more KNOW responses. The results were not significant ($\chi^2 = 24.8$, df $= 30$, p-value=0.7).

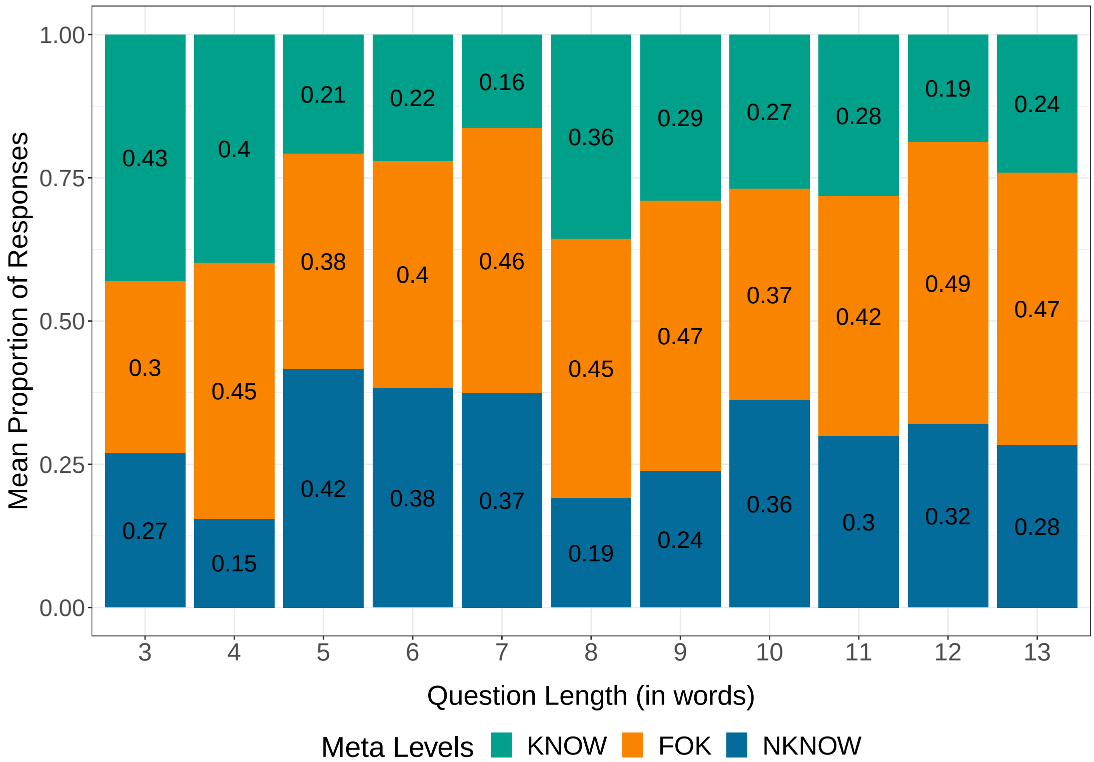


Figure 4.5: Proportion of responses in each Meta level according to Question Length attribute

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4.4.2 Difficulty

In our context, the question difficulty is considered an element of task difficulty, a common modulator of the information search. The searcher is responsive to task difficulty, for example, manifested by varying factors of the query quality entered in the system [84, 85], such as linguistic expressions, query syntax or semantics[203]. Furthermore, a link between the difficulty and metamemory performance was indicated in several studies [166, 198, 204]. FOK itself was a target in several Q/A tasks [166, 172] with a question difficulty used as a modality to explore the effects of varying difficulty in relation to rates of FOK they produced [166], and thus, providing reasoning behind the following investigation.

In our study, questions were equally distributed into Easy and Difficult, hence, no data pre-processing was necessary. Figure 4.6 shows the box plot of participants' responses in each Meta level and their associated question difficulty levels (E - Easy, D - Difficult) in a session (i.e., 120 trials as the total number of questions participants were subjected to).

In the model, we included the main effects of factors Meta levels and Difficulty and their interaction effects. ANOVA repeated measures found several effects with a variable significance within this data. First, there was not found any significant difference triggered by the main effects of Difficulty levels (F=1.01,p-value=0.32). Second, similarly, as in previous analyses, we found the recurring effects of Meta levels ($F[2,138]=16.8$, p-value<0.001). Questions from our Q/A Dataset attracted significantly more (p-value<0.001) responses of FOK (μ=0.21) than the remaining two levels, KNOW (μ=0.14) and NKNOW (μ=0.15).

In addition, we have found a significant interaction between Meta level and difficulty level (F=12.95, p-value<0.001). The pairwise contrasts of the interaction revealed these outcomes:

- Significant differences between the proportions of Easy questions of KNOW (μ=0.19) and Easy questions of NKNOW (μ=0.12), with the mean of the former being significantly higher (p-value<0.05).

- Significant difference between a pair of Easy questions of FOK (μ=0.21) and Easy questions of NKNOW (μ=0.12), with the mean proportion of FOK being significantly lower (p-value<0.001).
- Significant difference between the proportions of Difficult questions of KNOW (μ=0.10) and NKNOW of the same difficulty (μ=0.17), with the latter being significantly higher (p-value<0.01).
- Significant difference between a pair of Difficult questions of FOK (μ=0.22) and Difficult questions of KNOW (μ=0.10), with the mean proportion of the former being significantly higher (p-value=0.001).
- Significant difference (p-value<0.001) where Easy questions triggered a significantly higher proportion of KNOW responses (μ=0.19) than Difficult questions (μ=0.10) of the same Meta level.
- At last, no significant differences (p-value=0.8) between a proportion of Easy (μ=0.21) and Difficult questions (μ=0.22), which both resulted in FOK as well as no significant difference (p-value=0.3) between a proportion of Easy (μ=0.12) and Difficult questions (μ=0.17) which both resulted in NKNOW level.

Conclusion The results provide evidence of our initial resolution to create a balanced Q/A dataset in terms of question Difficulty (see Section 3.3.2). The findings affirmed our expectations: 1) Easy questions were associated with higher volumes of participants knowing the answer (KNOW) or feelings they might know the answer (FOK), and 2) Difficult questions were associated with a higher volume of not recalled answers. No significant differences emerged between levels of FOK and NKNOW differentiated by Difficulty. This outcome could suggest that the contextual difficulty seems less relevant if the searcher is uncertain (FOK) or predicts the lack of knowledge (NKNOW).

In addition to FOK, we found that the frequency of FOK is higher than of KNOW for difficult questions, whereas, for easy questions, the frequency of FOK is higher than that of NKNOW responses. First, the contrast of FOK and KNOW for difficult

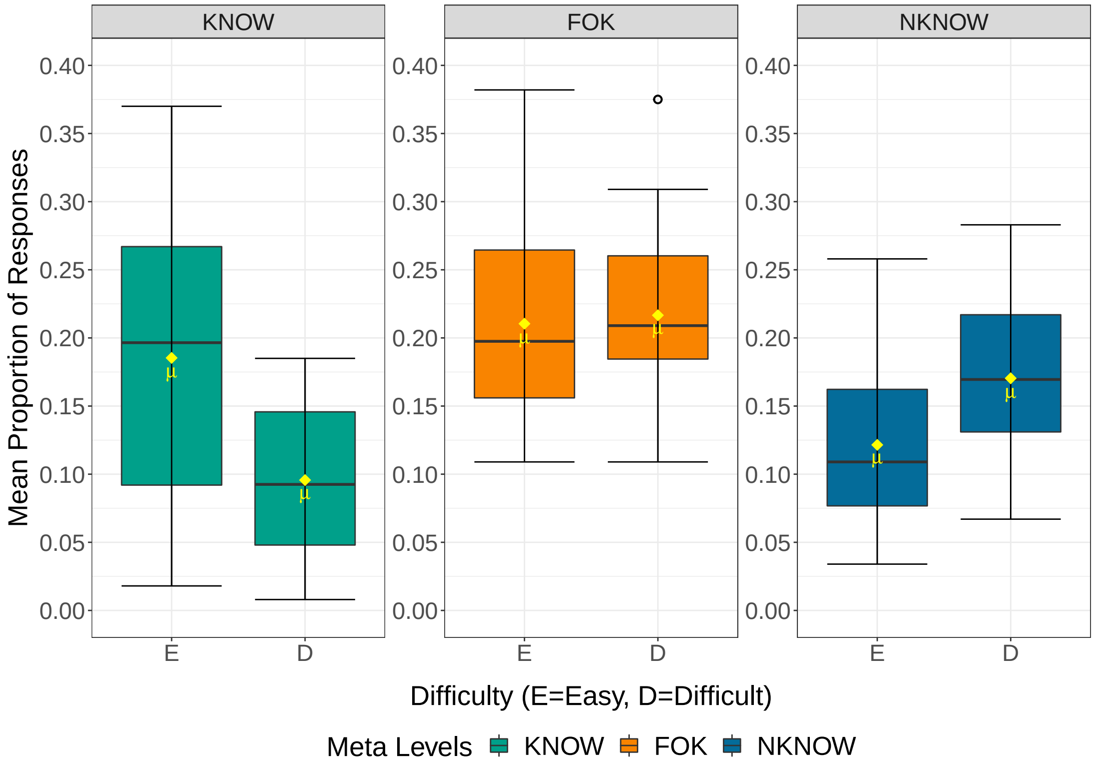


Figure 4.6: Proportion of responses in each Meta level according to Question Difficulty attribute

questions suggests that participants were less confident in their knowledge. Coupled with the increased user uncertainty, the number of FOK responses significantly prevails over the amount of KNOW (FOK > KNOW). Participants made the FOK decision, believing that a further stage, i.e. recognition (MR), confirms this feeling, i.e. they will recollect the answer and, thus, reduce the uncertainty. Second, having easy stimuli, participants chose to be more optimistic. Even though they felt not-knowing the answer right away (NKNOW), they felt positive and confident about the future recognition (FOK > NKNOW). IR research can expand on investigating the query quality in the context of task difficulty and the user's cognitive context. For instance, to study the query quality as an indicator of the underlying context of "what does the user not know". From the system side, the results would be beneficial to model a better representation of "what should the user know". For instance, improved query reformulation support in order to increase the user's positive sense of knowing, i.e. positive FOK

[205].

4.5 Discussion and Conclusions

The present chapter supplies 1) our research with the information applicable in the following investigations of EEG-associated data (Chapters 5 - 7), and 2) the IR research with a functional framework to study the underlying processes of the user's realisation of the state of knowledge used to determine the knowledge anomaly [3] and IN. We now proceed to conclude the major findings and elaborate on their impact on the IR field, specifically

- Causes of disassociation between Feelings of knowing (Meta) and the actual knowledge retrieval (MR) as potential manifestations for false memories [27] or Illusions of Knowing [174] (i.e., What we think we know is not true).
- Improved support for the user in different states of knowledge and different demonstrations of INs, e.g. delayed IN.
- Memory cues as part of the IR output to enhance knowledge retrieval, understanding and confidence.
- Effects of Contextual attributes on differences in produced states of knowledge.

4.5.1 Findings addressing the Research Goals

First, we were interested in the relationship between initial epistemic states of knowledge (Meta levels) and the factual MR. A study of the transitions between the users' thoughts of knowing, i.e. "What do we think we know" vs "What do we truly know" can provide a beneficial insight into searcher's information behaviour based on perceived states of granular knowledge. We further expand on the interpretations of the mnemonic cues, cognitive feelings of confidence and information preferences in searcher's behaviour to determine different states of knowing and anomalies in knowing, i.e. the circumstances of users' INs.

Resolution of Metamemory and FOK

Our data suggest that KNOW and NKOW are good predictors of their anticipated MR (for detailed results see Section 4.3.2). Positive knowing reflected as KNOW followed by correct recognition, MR-C, was also found to trigger H confidence in participants. The level NKNOW was found to accurately predict not-knowing (MR-N) and, additionally, to be associated with SEARCH, meaning, the participants preferred to satisfy their knowledge gap and learn the correct answer to the question.

Concerning the FOK level, we found that FOK can also be a relatively good predictor of the correct retrieval. Knowing (MR-C) was equally likely evoked by KNOW and FOK levels. Moreover, we found that 30% of FOK responses were followed by MR-I, which suggests the Illusion of Knowing effect [174], i.e. participants' perceived FOK failed them. This scenario could potentially increase the chance for (delayed or subconsciously deferred [108]) INs to arise in the future, i.e. to fix the misconception of the searcher's actual knowledge. This idea opens up a discussion for IR research on how to incorporate the novel cognitive states [95], e.g. TOT-type of IN, FOK-type of IN, into the user-system model and to address improved support for the users in these states. IR system should support propagating a strong positive sense of FOK in users [205] and increase the confidence. In addition, the effects of metamemory and cognitive states of knowledge can further help to expand on the idea of variants of anomalies in ASK [3]. The magnitude of FOK rates [206] can be considered an extension of this task concerning INs and, thus, develop a more granular spectrum of states of knowledge awareness.

Complex EEG-related data analysis and the discussion are presented in Chapter 5.

Resolution of Memory Retrieval on Recognition

To note, we cannot conclude that the effect of mnemonic cues to enhance the MR was significant, as we miss the baseline to compare it with, i.e. to observe the effects without the mnemonic cues. We only make our conclusions regarding Meta levels, precisely how the presentation of mnemonic cues altered participants' initial Meta perceptions.

The effect of mnemonic cues caused a disassociation with the initial epistemic

(Meta) feelings. These effects were significant for NKNOW, where mnemonic cues enhanced factual recognition (56% of the cases). According to the results from the Recognition test, the participants were able to transform their initial NKNOW and recognise the answer from the set of mnemonic cues, instead of failed MR. This outcome supports the results of 56% of all NKNOW responses followed by either MR-I (31%) or MR-C (25%). Likewise, for FOK responses, where 10% and 30% of these were not recognised (MR-N), respectively, recognised wrongly (MR-I). The performance in the Recognition test (MR levels), thus, did not match the participant's positive FOK feelings. Our findings also revealed that the significantly highest amounts of correct responses (MR-C) were preceded by either FOK or KNOW.

In the IR context, the mnemonic cues can represent the retrieved documents, such as keywords, excerpts on SERP or metadata, as the information the user is expected to interact with. On the user side, an issued query can provide insight into what the user knows. The quality of these elements is a factor that impacts the IS&R context [35, 207]. For instance, the query represents the underlying user's cognitive context, and its quality reflects another context, such as task difficulty [84, 85]. IR process should utilise this information in the retrieval process to enhance the retrieval output's efficiency and recognise "what the user needs". Mnemonics cues or other forms of mnemonics aids help to enhance the user's knowledge retrieval, remembering and education [208]. The IR process could, thus, contribute to several areas of the user's information search experience. First, support the factual MR of IR users where the retrieved information contributes to building a coherent knowledge base of its users [5] and in order to build a coherent knowledge base. Second, in the area of active learning [209], focusing on the user's document-interaction journey to generate new knowledge and reduce the user effort to find the relevant documents whilst increasing the retrieval accuracy [210, 211]. Third, avoid misattribution of information that negatively impacts the users' knowledge generation, e.g. data veracity checks and document annotations validations.

Comprehensive EEG-related data analysis is reported in Chapter 6.

Resolution of Confidence

We have found associations between different levels of confidence and the prior Meta or MR judgments. In the case of NKNOW judgments, we first found that the confidence associated with the factual MR (Recognition test) was significantly low.

High confidence was more likely to be triggered in a scenario of successful recall (KNOW) followed by correct recall (MR-C), i.e. high accuracy (see Section 4.3.2). The evidence provides indications of the role of confidence modulated by the strength of the MR outcome. IR subconsciously affects the user, including their affective and cognitive feelings [5]. Uncertainty and associated confidence can be seen as cognitively manifested aspects of disassociation between Meta and MR and which is potentially associated with phenomenons, such as Illusions of Knowing (MR-I), reported earlier. Orientation to reducing uncertainty and increasing users' confidence in the IR process should be further investigated as part of the users' cognitive indicators of INs and IR performance.

Complex analysis using EEG data is reported in Chapter 6.

Resolution of Lower INs

As we explained in the previous chapter (see Section 3.2), the NOSEARCH level that we applied as a factor in our data supports the phenomenon of lower INs [184]. According to general participants' perceptions, participants mostly felt an interest and curiosity in learning the correct answer to a question (as indicated by a higher proportion of SEARCH responses). Participants also considered information usefulness in any future event when deciding upon whether to skip a trial or learn the answer (see 4.3.2). In conclusion, lower INs participants experienced only rarely and the majority of participants preferred to learn the answer and, thus, satisfy their knowledge gap. We believe this decision is associated with the situational context the participants were subjected to, i.e. Q/A. In the future, it would be beneficial to validate this finding for other situational scenarios.

4.5.2 Task Difficulty

The past findings suggest that general knowledge questions, evaluated as objectively difficult, elicited higher FOKs compared to easy questions [166, 172]. Moreover, participants provided overconfident FOK answers to difficult questions [198]. Also, in terms of metamemory accuracy, the highest accuracy was reached for the easy questions and the lowest for the difficult questions [212].

We have found numerous significant differences in pairwise contrasts of Difficulty and Meta level, which were reported and discussed in Section 4.4.2. In conclusion, the searcher's knowledge awareness (Meta levels) seems to be affected by the Question Difficulty to a different extent, most prominent between KNOW and NKNOW, where Easy questions are likely to trigger KNOW, whilst objectively Difficult questions trigger more of NKNOW. Question Difficulty seems to be a driver of knowing and (un)certainty and, thus, to differentiate between the pairs of elicited perceptions of knowledge. For instance, the results for KNOW or FOK for difficult questions suggest that the participants' behaviour was more conservative (FOK > KNOW). For easy questions, the contrast of NKNOW and FOK showed that the participants were more optimistic (FOK > NKNOW). Concerning FOK level, we did not find any significant differences between the volumes of FOK separated by the Question Difficulty. Also to note, the proportions of FOK responses for both Easy and Difficult questions were the highest out of all Meta levels. The following study could, similarly, as other works [169, 212] expand on the grades of FOK (low - high) to observe the associations on a smaller scale.

4.5.3 Information for future analysis of EEG-related data

The identification of a highly unbalanced distribution between SEARCH and NOSEARCH uncovered a potential obstacle in performing within-design analysis over the associated EEG data as it requires balanced data in each investigated level (see Chapter 3 Section 3.5.2). A contrasting analysis between SEARCH and NOSEARCH would have provided us with insight into neurophysiological patterns of a person having a gap in knowledge modulated by their preference to know or not to know the answer, i.e. to satisfy their gap. The Chapter 6 Section 6.2.1 describes how we altered the analysis.

In addition to the findings between SEARCH and NOSEARCH, the relationships between Meta, MR and Confidence helped us to similarly identify the levels with low interactions, e.g. the pairs MR-I + H and KNOW + MR-N. The present analysis helped us to link the naturally occurring phenomenons with stronger and weaker associations and, on this basis, to select data for EEG investigations. Each of the following chapters, dedicated to analysing the EEG-related data, contains a section "Samples Size", which informs about any data issues and the data processing done before running the EEG analysis.

We also found the effect of Question Difficulty on the change in the proportion of evoked Meta levels. Thus, it seems valid to consider involving this modality in further data analysis.

4.6 Chapter Summary

The present chapter delivered information about behavioural data used in the current thesis. In particular, it provided:

- Insight into participant's demographics and their search habits (as part of the general questionnaires) as well as their perceptions of the task study (as part of the exit questionnaires).
- Discriminative terms in questions of general knowledge triggering feelings of knowing and not knowing.
- Descriptive statistics and statistical evaluation of behavioural data across the factorial hierarchy uncovered the associations and trends between the investigated phenomenons used to inform the IN context.
- Further statistical evaluation of behavioural data effected by stimuli attributes, namely Question Length and Question Difficulty.
- At last, we discussed how the present findings affect further stages of our investigations and the implications for IR research in the context of INs.

Chapter 5

EEG Study of Metamemory Informing Users' Information Needs

The present Chapter addresses the first Research Goal to expand the current understanding of the cognitive context of IN (see Section 2.4). The EEG data collected during the experimental task (refer to 3.3.1) will be assessed to identify the spatio-temporal signatures of a specific user's knowledge context, i.e. a representation of the user's states of knowledge. An ERP analysis was developed to study the temporal engagement of cognitive processes involved in realising the user's state of knowledge, emphasising metacognitive and metamemory functional mechanisms. These are responsible for the user's introspective analysis and aid the user in a given situation. In this chapter, we approach the metamemory as a mechanism to supply the user with contextual knowledge information, such as memory cues and guides about their knowledge prospect, i.e. epistemic feelings. Such an introspective insight could be gained by asking ourselves: "What do we think we know?" or "Do we think we might know it/remember it (i.e., the answer) later?".

In particular, we approached the metamemory using Feeling-of-Knowing (FOK), a distinctive cognitive state of temporal unavailability of recalling information accompanied by the user's strong prospect of future recalling [169]. Previous *NeuraSearch* studies investigating IN realisation [11, 23] evidenced on the brain topographies comparable with the investigations of FOK and metamemory (see Section 2.3.4). However, this area remains largely marginal in empirical research of IR and more evidence is needed to employ an IR-based study that would directly target these phenomenons. Our present study provides the means to capture the objective evidence of the cognitive operations involved in the user's realisation of the user knowledge context as a driver of search behaviour [6].

In summary, concerning the contribution to IS&R research, the current segment of our study concerns three IS&R aspects:

1. Rethink a common binary approach of IR studies investigating IN based on two categories of observations (IN and noIN) by introducing a third level (FOK).
2. For studies that dealt with knowledge-gap evoked INs, expand the spectrum of possible IN states depending on the user's state of knowledge continuum.
3. In turn, rethink the IS&R system support acknowledging the variability of cognitive states of knowledge.

5.1 Background

In this section, we summarise the relevant IS&R research concerning the cognitive perspectives about IN that influenced the current research goal. Please refer to Chapter 2 Sections 2.1.2, 2.1.3 and 2.2 that describe these works in more detail. The user contextual multidimensional information defines the users with respect to their information search behaviour. The cognitive dimension involves knowledge perceptions ("What do we know" vs "What do we not know"), implying a necessary knowledge awareness mechanism to maintain the functioning of this segment. We, therefore, aim to establish a link between the user's INs, driven by their neurocognitive context information, and the user's information search behaviours.

5.1.1 INs and Users' states of knowledge

As we presented in Section 2.2, several studies theorised how IN arises concerning the sources of IN realisation [3, 5, 13, 49]. We particularly analysed Taylor's IN taxonomy [13] and Belkin et al.'s ASK Model [3] described in Sections 2.2.2 - 2.2.4 as they dealt with what we can summarise as an introspective representation of IN. Both concern the user's mental and cognitive processes reflected in the user's formations of "State of Readiness" or "Conceptual state of knowledge," respectively, as the users' foundations of interaction with the world. First, Taylor's [13] taxonomy presents IN in a graded fashion with the user moving through consecutive phases of expressiveness of what is their INs. Next, Belkin et al. [2, 3] specified that the user's IN is supplied by a realisation of an anomaly in knowledge with respect to the problem faced. Kuhlthau brought an analogy between these two theories in her Information Seeking Process (ISP) Model [5, 52] by placing ASK at the earliest phases of the model alongside Taylor's Q1 visceral (in-brain) IN level. What is of particular interest to us is Belkin et al.'s further hypothesised that there exist variations of ASK, and each is associated with different anomalies depending on the level of the individual's knowledge. Despite its importance in order to accurately determine the user's contextual information [6], more profound studies into the variants of knowledge gaps are rare and remain on the research's marginal side.

The knowledge monitoring and knowledge awareness element occurring during ASK and Taylor's Q1 level indicates the engagement of higher-level cognitive processes [213] involving the functionalities of metacognitive mechanisms. In particular, metamemory [214] as an introspective awareness about one's memory intuitively evokes its relevancy with respect to the realisation of the anomaly in knowledge. We, therefore, hypothesise that a realisation of IN can be a product of this metacognitive awareness and the epistemic feelings evoked, which prompt the current state of the user's knowledge. However, despite the indication that metacognition plays an essential role in how ASK and, in turn, IN arise, there is little research on this subject. One of the few works that theorised that there is a direct link between ASK and metacognition was brought by McAleese [213]. He presented ASK as "what one does not know", which occurs due to the user's underlying metacognitive mechanism, increasing awareness of one's state of knowledge.

Moreover, empirical evidence supports this theoretical link. Moshfeghi and Pollick [24] conducted a *NeuraSearch* study [21] that found patterns of brain activity associated with metamemory, particularly FOK, which even more underlines the importance of this phenomenon in the context of IN (for details see Section 2.3.4). Recently, a possible new direction into IN has emerged towards acknowledging a broader spectrum of IN variations. Arguello et al. [95] recognised a new representation of IN in the context of the known-item retrieval [37], a cognitive state of future remembering, Tip-of-Tongue (TOT). It is regarded as a subtype of FOK [169]. The authors evaluated users' online forum-based requests, which aimed to find a movie title. The idea was limited to a qualitative analysis of the expressiveness of these TOT requests. Users in their TOT states describe their requests based on how much they remember about the movie, including the facts (i.e., part of factual memory) and events (i.e., part of episodic memory).

In summary, as indicated by the synthesis of theoretical knowledge and the empirical findings, continuing investigations of the underlying activity that triggers the user's awareness in the context of their knowledge can provide beneficial insight into the neurocognitive drivers of anomalies in knowledge and INs. These can give us a new perspective on how users depict their INs, explain the association of INs and variants of ASK, as well as inform us about the variability of user anticipations about the IR outcomes. For instance, a user in FOK state might have different expectations of the retrieved results, as they likely possess some prior knowledge in contrast to a user who does not know anything. As knowledge is a central element in these theories, knowledge-self-oriented awareness (metamemory) can further explain IN variants that might lead to different information behaviours. The combination of objective and subjective data metrics in our data ensures an unbiased insight into this area.

5.1.2 Metamemory and Feeling-of-Knowing

As we mentioned previously, our approach lies within the context of metamemory as an essential part of this investigation. It is a branch of metacognition, which encompasses metacognitive processes of auto-consciousness and self-awareness and whose functioning is demonstrated during the fundamental human operations, such as thinking, learning, knowing and experiencing [215]. Building on the notion of introspective awareness utilising the metacognitive mechanisms, metamemory can be specified as an instrument of monitoring one's memory and capabilities in order to make judgments about the strength of one's memories and the knowledge prospect [214]. The mechanism is believed to work as a feedback loop with an information exchange [214] between 1) Monitoring process, responsible for checks of one's memories and their strengths and the judgments of a person's contextual abilities; and 2) Control process that controls and regulates one's awareness used to guide person's behaviours and judgments.

FOK

Conceptual theory proposes and experimental scenarios often use the concept of FOK in metamemory studies [166, 169, 216, 217, 218, 219]. FOK is perceived as a temporary inaccessibility [19] to recall information in question. FOK represents an intermediate recall state [134], which encapsulates a potential success to recall the information in question after a cue had been given to the user related to that information. Potentially, a user could perceive a temporary inaccessibility [220] of the memory retrieval so-called Tip of the Tongue (TOT), as mentioned earlier, a common phenomenon when the user fails to immediately recall a word from memory, and but feels that a small cue would trigger the instant retrieval. TOT is regarded as a stronger instance of FOK [134].

The concept of FOK was proposed by Hart [169] in 1965 and has been used in numerous experimental scenarios investigating the functioning of metamemory and self-aware mechanisms [166, 206, 216, 218, 221]. FOK's subjective nature allows it to be applied in diverse settings, including its prospective position to inform the user's information search behaviours (see Section 2.2.1). Furthermore, due to the user's relatively accurate inner sense of the availability of internal information, FOK judgments have been used to study correlations with the access to external information on the Internet [71, 110, 136]. FOK is recognised and investigated as a part of Graded Recall methodology [19, 134], which leads to our speculation that variations of the user's state of knowledge could be manifested based on the different specificity of recall outcomes. On the scale of information recall, we could define states such as "full information recall" (i.e., no anomaly), "partial information recall" or "no recall at all" (i.e., anomalous). FOK is a subjective indicator of the prospective (future) successful recall of the information [169]. Human natural ability to recall with feelings, is part of their introspective analysis [222]. However, human feelings are abstract and highly subjective and, therefore, difficult to capture or even often comprehend for the people as the users of IR systems. Relatively large methodological support there is for investigations of metamemory will help us to methodically assess the user's epistemic feelings and perceptions of their knowledge context. Prospectively, exploration of feelings-based metamnemonic outcomes in relation to user's affective feelings in IR process [5] might help to explain the role of feelings in users' information search behaviour (e.g., uncertainty, confidence) and IN characteristics (e.g., expressiveness).

In order to account for a variety of metamemory awareness outcomes, our study used the aforementioned Graded Recall approach [19, 134] to formulate a set of predefined response choices (see Meta levels in the factorial hierarchy in Section 3.2.5). In addition to the two levels of the recall spectrum, i.e. (1) "I know", representing successful recall, (KNOW) and (2) "I do not know", meaning recall failure, (NKNOW), we extended the spectrum of states by utilising a third level, (3) failure to recall information from memory accompanied by FOK. These levels acknowledge a spectrum of the user's state of knowledge on a scale of recall outcomes and describe the users' current knowledge context (i.e., What does the user know?).

5.2 Research Questions

We aim to investigate our hypotheses framed into two Research Questions (RQ).

- **RQ1:** 1) Are there detectable neurophysiological correlates associated with the spectrum of the user's state of knowledge (i.e., Meta Levels) and 2) Do these brain correlates differ across the spectrum of Meta Levels, i.e. when the user experiences different states of knowledge?

- **RQ2:** What implications do these outcomes generate to extend our understanding of the user's cognitive underpinning of IN, and how do they contribute to the IR context?

RQ2 addresses theoretical and practical contributions to the IR process and is reinforced by the results that address RQ1.

5.2.1 Design and Expectations

To address our RQs, we aimed to obtain an insight into the diversity and/or similarity of the physical (brain) manifestations while a person is facing a particular problem, in our case, a question of general knowledge. The Q/A is at its core a prototypical scenario of knowing vs not-knowing, i.e. no-IN vs IN, similarly as used in previous *NeuraSearch* studies [11, 23]. By defining the third option, FOK, we introduced a new perspective on the definition of user perception of INs which we will further evaluate.

Our study design (Q/A), supported by the methodologically valid paradigms (see Section 3.2), triggers user's information processing whose output, then, they themselves associate with pre-defined Meta levels (subjective measure). Their brain signal is monitored (objective measure) during the information processing and retrospectively associated with the corresponding Meta level. Subsequent analysis of spatio-temporal features across the Meta levels, manifested by ERP components (refer to EEG Glossary in Section 2.3.1), will be used to unfold the neurocognitive processes behind the Meta levels.

Our study design has two main contributions. First, despite FOK being supported by an extensive theoretical [169] and user-based knowledge [206], FOK has not been investigated in an IR setting directly in a user-based study. We addressed this issue by creating a computerised interactive Q/A task where participants responded to a series of general knowledge questions (see Section 3.3.2). Second, we investigated neurophysiological drivers of metacognitive processes behind the spectrum of Meta levels. Our decision to employ an electrophysiological neuroimaging technique was further motivated by previous NeuraSearch studies, which benefited from the same approach (see Section 2.3.2). Unbiased measurements of users interactions, in the form of brain signals, help to overcome the potential cognitive overload (including evaluation of feelings, perceptions or other mental processes) often posed to the subjects in a study [223]. The specific choice of EEG as the primary technique was determined due to its non-invasive nature and being a reliable and robust method of capturing the nature of the underlying neurophysiological mechanisms. In our case, it helps to draw an objective display of the formation of the awareness behind FOK and other recall outcomes.

5.3 Experimental Set-Up

The current chapter observes the top level, Meta levels, of the designated factorial hierarchy associated with the outcomes of the user study (see Section 3.2.5). As mentioned in Chapter 4, the study encompasses data from 24 participants who performed the Q/A task (refer to Section 3.3.1), and the generated responses pertain to the three defined Meta levels defined above.

5.3.1 Sample size

As our data exploratory methods (see Section 3.5.2) rely on individual signal averages in order to create level-average ERP waveforms, we need a sufficient data sample at each Meta level. Accordingly, we needed to set how many trials a single participant had to record for ERP components to emerge. We checked the individual records for each participant and sorted them in ascending order by the number of records in each level. Participants with the lowest proportion of Meta level-dependent responses were selected, and their ERP waveforms were visualised. Our results showed that stimulus-triggered activity, i.e. ERP, emerged, and the activity remained relatively stable when averaging at least 12 trials (representing 10% of all trials the participants were subjected to), which we then set as our threshold. Altogether 22 participants fulfilled this condition and whose data will be further analysed. The remaining two participants were outliers and excluded from the further analyses.

5.3.2 Methods of Data Analysis

We followed the methods of the analytical framework described in Section 3.5.2.

5.4 Results

We now report on the outcomes of significant spatio-temporal differences in neural activity subserving different Meta levels.

5.4.1 ERP Analysis

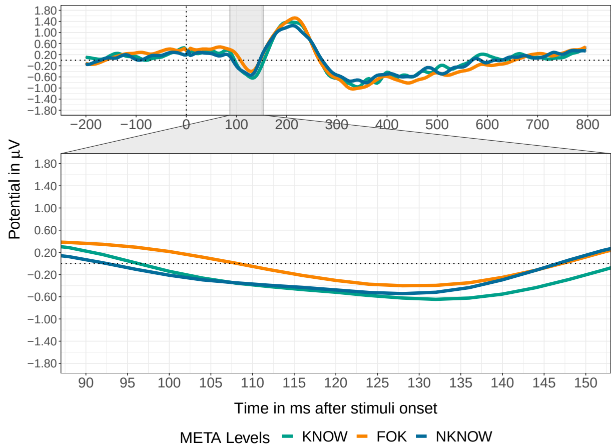
According to Sections 3.5.2 and 3.5.2, describing the methods to detect the significant data features, we identified significant ROIs and time windows with ERP components.

We identified four ERP components with their latencies as follows: N1 (with earliest onset at $\sim$ 84 ms poststimulus, the latest offset at $\sim$ 168 ms), P2 (earliest onset at $\sim$ 144 ms, the latest offset at $\sim$ 284 ms), N400 (with earliest onset $\sim$ 264 ms, the latest offset $\sim$ 584 ms) and P6 with the early onset at $\sim$ 556 ms. Despite the variations in the latencies of ERP components, we created one set of time windows common for significant ROIs (for justification, see Section 3.5.2). This way, we could capture most of the ERP response within a common window. The time windows were set: 1) 90 - 150 ms, 2) 150 - 270 ms, 3) 270 - 570 ms and 4) 570 - 800 ms.

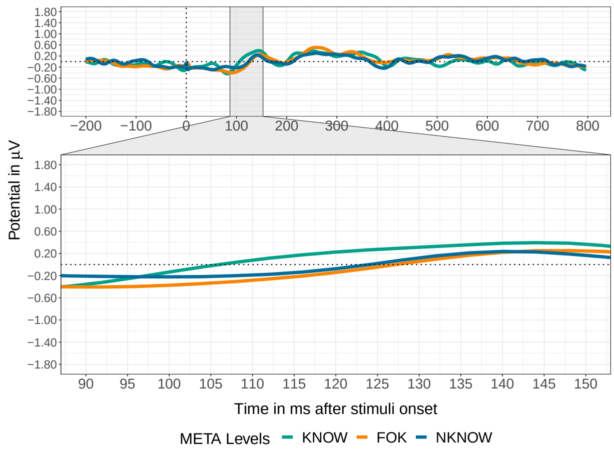
The average activity of such components across relevant ROIs was then submitted to ANOVA to test their discriminative power across Meta levels. Quantitative results of ANOVA and post-hoc tests with Bonferroni corrections are given in Table 5.1.

Time Window 90 - 150 ms

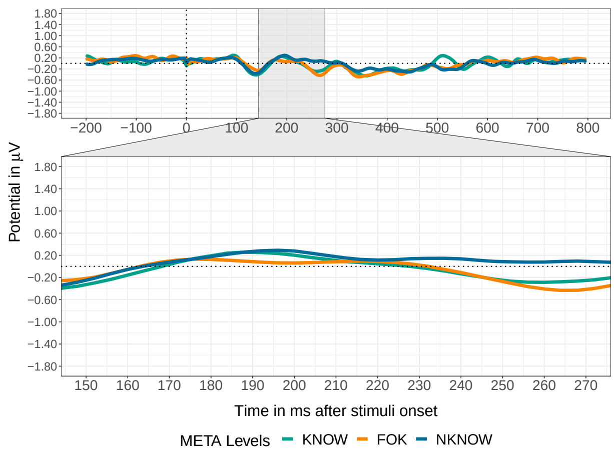
Left frontal (LF) activity differed significantly between KNOW and FOK level. Furthermore, activity in right centro-parietal (RCP) ROI was also found to discriminate between KNOW and FOK level. Both ROIs exhibited a significantly higher mean



(a) N1 (90-150 ms) over LF ROI

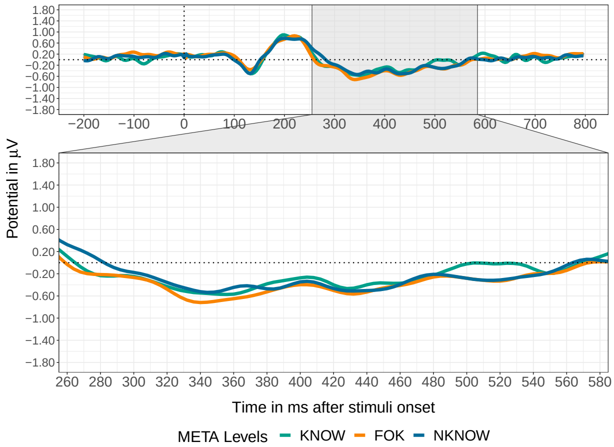


(b) N1 (90-150 ms) over RCP ROI

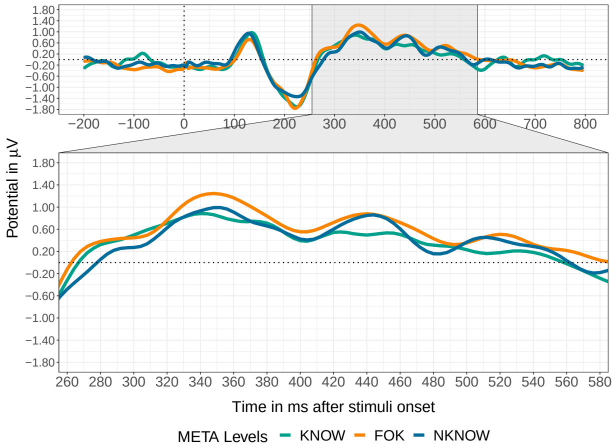


(c) P2 (150 - 270 ms) over RFT ROI

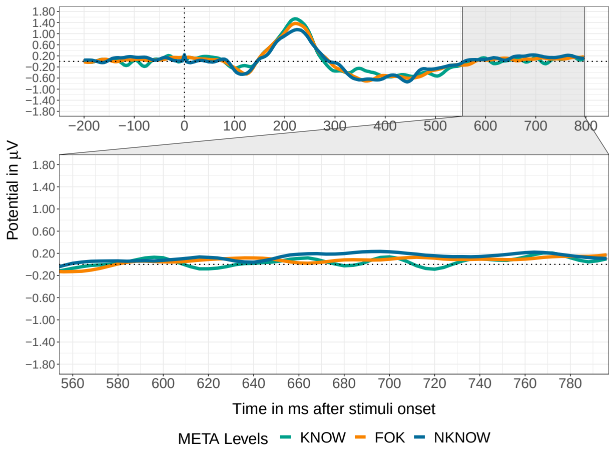
Figure 5.1: ERP waveforms of Meta Levels with a zoom on 90 - 150 ms and 150 - 270 ms poststimulus over significant ROIs (as a result of ANOVA). Averaged over 22 participants.



(a) N400 (270 - 570 ms) over FT ROI



(b) N400 (270 - 570 ms) over PO/O ROI



(c) P6 (570 - 800 ms) over RC ROI

Figure 5.2: ERP waveforms of Meta Levels with a zoom on 270 - 570 ms and 570 - 800 ms poststimulus over significant ROIs (as a result of ANOVA). Averaged over 22 participants.

negativity (p-value<0.05) of N1 amplitude for KNOW level. The contrasting ERP waveforms in LF and RCP ROI are depicted in Figures 5.1a and 5.1b, respectively.

Time Window 150 - 270 ms

Outcomes of ANOVA and subsequent pairwise contrasts revealed significant differences between the neural activity for KNOW and NKNOW level measured within the right front-temporal region (RFT), with NKNOW level exhibiting significantly (p-value<0.05) higher mean activity associated with P2 component. The P2 waveforms of corresponding Meta levels are illustrated in Figure 5.1c.

Time Window 270 - 570 ms

We observed a widespread distribution of activity involved across multiple brain regions manifested as the N400 component. ANOVA revealed the significant impact of anterior-posterior ROIs on mean activity within this time window, precisely sourcing from electrodes in bilateral front-temporal ROI (FT) and occipital ROI (PO/O). Post-hoc tests specified that these effects were significant between KNOW and FOK level, with FOK levels exhibiting a significantly (p-value<0.05) greater activity in both ROIs (greater negativity of P2 in FT and greater positivity of P2 in PO/O). Figures 5.2a and 5.2b depict the ERP waveforms in both ROIs.

Time Window 570 - 800 ms

Results of ANOVA revealed a significant difference in mean activity across Meta levels in the right central brain area (RC). Post-hoc tests identified that the mean amplitude described as P6 differed significantly between KNOW and NKNOW levels, with NKNOW exhibiting a significantly (p-value<0.05) higher mean of P6 amplitude in contrast to the mean signal of KNOW. Figure 5.2c shows the ERP waveforms.

Summary

Early activity linked to the N1/P2 complex indexed significant differences between KNOW and FOK over RCP and LF regions. This pattern then propagated to FRT

Table 5.1: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	ERP	ROI	F value	M_{diff}	p-value
90 - 150 ms	N1	LF	F[2,42]=4.32	$\bar{x}$(KNOW)=-0.40 μV, $\bar{x}$(FOK)=-0.12 μV	*
		RCP	F[2,42]=4.34	$\bar{x}$(KNOW)=0.14 μV, $\bar{x}$(FOK)=-0.10 μV	*
150 - 270 ms	P2	RFT	F[2,42]=3.57	$\bar{x}$(KNOW)=-0.07 μV, $\bar{x}$(NKNOW)=0.11 μV	*
270 - 570 ms	N400	FT	F[2,42]=3.50	$\bar{x}$(KNOW)=-0.27 μV, $\bar{x}$(FOK)=-0.39 μV	*
		PO/O	F[2,42]=3.44	$\bar{x}$(KNOW)=0.45 μV, $\bar{x}$(FOK)=0.63 μV	*
570 - 800 ms	P6	RC	F[2,42]=3.94	$\bar{x}$(KNOW)=0.06 μV, $\bar{x}$(NKNOW)=0.16 μV	*

(ROIs (For spatial reference see Figure 3.2): L - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

ROI to account for differences between KNOW and NKNOW. The highest activity linked to KNOW level could indicate quick access to available knowledge, in contrast to the activity elicited by FOK and NKNOW state. The later activity of the N400 component was apparent over both anterior and posterior regions. Significant effects were triggered by a contrasting activity between KNOW and FOK level. FOK judgments elicited greater amplitude of N400 component at PO/O ROI and FT ROI. At the later processing stage, P6, we found involvement of a central (C) region underpinning the significant differences between KNOW and NKNOW levels, with NKNOW reaching a higher positivity of P6. In summary, in all time windows, we saw the involvement of KNOW level as a driver of the significant effects on the elicited signal with widespread locations, but a consistent frontal/front-temporal distribution that carries out the significant differences. Figure 5.3 maps the locations of ROIs (where significant pairwise differences between Meta levels occurred) onto the brain topological graphs.

5.5 Analysis of Results

We now discuss the findings as they address the RQs from 5.2.

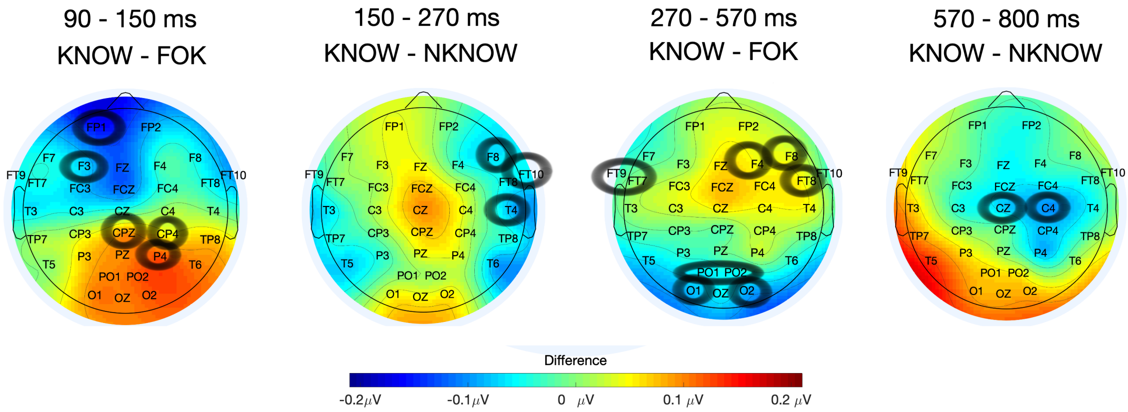


Figure 5.3: Temporal topological plots highlight the ROIs where significant differences between Meta levels were found.

5.5.1 RQ1: Findings underpinned by cognitive processes

Our study identified four ERP components subserving different pre-defined Meta levels. The early activity was associated with the N1-P2 complex. Left frontal lateral distribution activity discriminated between KNOW and FOK before 150 ms poststimulus. The frontal distribution is consistent with previous neuropsychological and brain imaging studies [206, 224, 225] about the vital role of frontal lobes in memory-monitoring processes. Here, the KNOW level recorded greater negativity of N1 over the remaining levels, which indicates quick access to assessment of the knowledge, prompting the user to make a quick decision. Further, the high activity of KNOW propagates into the RFT region to significantly separate KNOW from the NKNOW level.

These early evoked components are thought to reflect the automatic stimulus processing influenced by attention and orientation processes [226, 227]. The P2 component has generally been associated with perceptual processing of stimuli [206, 226] and, in particular, P2 might be an important driver to guide the perceptual fluency (the ease with which perceptual processing takes place) and, therefore, metamemory judgments. Another study attributed the P2 component to an initiation of an attempt to recollect a study episode via episodic memory involving rapid assessment of familiarity, i.e. the ability to recall specific episodes for those stimuli which seemed to be sufficiently familiar [228]. This view could potentially explain our findings of maximal positivity of P2 component reached for KNOW and FOK responses, as the participants might have perceived the stimuli familiar enough to retrieve them from memory. Our findings of early brain responses coincide with the view by Paynter et al. [226], who investigated ERP within a memory retrieval and found that these early rapid neural correlates emerged before a conscious awareness reaching-point.

Negativity at 270 ms onwards might correspond to the presence of N400 component. Alike, N400 was found to occur during word-by-word sentence reading [229]. In addition, our findings of a broad multi-region activation to support N400 further affirm its notion as a highly distributed neural source that triggers a successive level of stimuli processing. Significant activity was found to be distributed in FT and PO/O areas. The discriminative activity was, again, found between KNOW and FOK. However, FOK reached greater values of the activity than KNOW level. At first, the temporal lobe has been highlighted as an important source for the N400 [206] and a switch to controlled functions when perceptual fluency drops. It might explain the significantly greater activity found for the FOK level, as the user might have more difficulty recalling the answer. This pattern could be explained as an enhanced attention to unexpected stimuli that leads to FOK. Moreover, it suggests an additional level of processing in relation to the unexpectedness of stimuli and potential correlation with word familiarity.

Second, the distinction in the posterior N400 component centred over the PO/O area might partially support the notion of a potential gateway mechanism. Through this mechanism, automatically triggered responses activate more controlled functions and possibly memory-driven functions, i.e. binding the internal representation of the input stimuli with the memory output, such as semantic or long-term memory. Also, Moshfeghi et al. [11] found a switch within subregions of the parietal region when the user realised that their internal knowledge is insufficient and, thus, external search is needed. This notion of a gateway mechanism became, thus, a signature mechanism for IN realisation (see Section 2.3.4).

At last, the late positivity prominent for NKNOW level could be attributed to the occurrence of the P6 component. A partial explanation for this activity could be linked to memory processing, observed during memory recognition tests [230]. When syntactic integration does not render familiar signals, more in-depth (later) processes are activated to evoke NKNOW. P6 was found to be sensitive to reading a series of dependent stimuli with different complexity, such as used in our study, causing the reader to recollect a stimulus that appeared earlier [231, 232]. To analogise with our findings, for stimuli of longer length and of higher complexity, recollection of previous (dependent) stimuli might have been triggered in order for the participants to assess their NKNOW state accurately. This could imply that it takes longer for a user to acknowledge their NKNOW state in contrast to previous states, i.e. a higher activity for NKNOW is concentrated in the last time window.

Resolution of FOK Most significant findings contrasted the pair of KNOW and FOK levels with the widespread activation throughout the information processing. It suggests that FOK is supported by neural operations making it a distinctive level in the processing of incoming information and significantly distinctive from KNOW, i.e. when we realise we know the information. No significant contrasts between FOK and NKNOW might potentially indicate no functional distinction between these two levels since they are both interlinked as unsuccessful recall levels, i.e. no information (response to the answer) was recalled. As we presented, NKNOW level substitutes the IN due to the generally accepted idea "what one does not know," which leads to the state of IN [10, 12]. Inferring from this generally accepted theorem, our data seem to support the link between the FOK state and the state of IN, as was outlined in [95]. Our inclusion of a new variant of IN, FOK, was, thus, justified from a neurocognitive perspective that evidenced the relevant pattern of activity signifying IN.

What lies ahead of IR research is understanding how to better support the users in their differing cognitive states of knowing and validating the idea presented in [95]. Even the early example of the ASK-IR model [2] recognised that differentiating the retrieval mechanisms would be required to support variants of ASK [3]. Our data suggest how to approach the support for these variants. One such is the attribute of the stimuli' perceived familiarity, which seemingly modulates the user's response and causes differences in the metamnemonic outcome. Our outcomes suggest that the gradient of familiarity impacts the final perception of the user's state of knowledge, current or prospective. Research expanding on this idea would be beneficial to validate these speculations, using brain patterns of familiarity as a predictor of retrieved documents in the context of IN. Familiarity has been utilised as a criterion of relevance in the context of IR performance evaluation [233], or a factor impacting searcher's information behaviour [234]. In addition, the term familiarity has been a target of several ERP studies, which detected different patterns of activity between familiar and unknown words [235]. In order to extend this idea in the context of IN, the term familiarity can be helpful to disclose which segments of the problem the user is more familiar with. On the contrary, the less familiar segments might indicate a potential for IN to happen. This idea poses a new objective for IR, with respect to its efficacy to satisfy users' states of INs and for the user to achieve a coherent state of knowledge. Accurate recognition of what (i.e., what portion of information) the user needs to know is a key to supplying the user with the right information that completes their knowledge anomaly [3].

5.5.2 RQ2: Implications for IR

Extension of ASK Model by FOK anomaly

ASK Model by Belkin et al. (described in Section2.2.3) is at the forefront of research acknowledging the knowledge context and knowledge anomaly as a predecessor of user's INs. As our study relates to studying processes of awareness behind this knowledge anomaly, the impact of these present findings can be tied to the ASK Model. We specifically worked under ASK's assumption of variants of ASK, i.e. variants of anomalies depending on user knowledge. Our choice of the Graded Recall approach supports the notion of variants of knowledge states depending on the graded recall outcomes, with FOK being one variant of the spectrum of anomalies of knowledge.

Furthermore, by the definition of ASK, feelings themselves could be accountable for early manifestations of the realisation of anomalies in knowledge. Given the current recall failure, the user relies on "a feeling" of prospective knowing (i.e., FOK) to guide their decisions and strategies. Epistemic feelings result from self-aware mechanisms of metacognitive processes passing the information to evoke an accurate state of knowing.

The produced information not only reflects the scale of knowledge, but it can take other accompanying forms of feelings, such as doubts, insecurity, and confidence [5, 18]. This supports the proposition of feelings-evoked ASK types (see Section 2.2.3). See Section 8.3.3 in the final chapter that discusses in detail the link between ASK and metamemory.

Implications for IR and User Support

Under the relationship between ASK and INs, we can derive that different variants of ASK give rise to different INs. This notion implies that IN is a graded phenomenon, with variants of INs associated with different degrees of coherence of state of knowledge [3] and degree of specificity of need.

Therefore a question for IR systems is "How to accommodate these varying INs in the user-system model and how to improve the user support in this respect?". First, INs are triggered by knowledge anomalies. Second, knowledge is not only a representation of what the user knows but also what the system can deliver depending on the system knowledge, i.e., the objective knowledge [15]. This knowledge relationship is activated during the information (knowledge exchange) consisting of querying, retrieval and output assessment. During the iterative nature of the IR process, the user learns what the system can deliver and what the user needs to do to get the expected results. This suggests a need for efficacious query support. As was proved in [95], users in their states of partial knowing (described as TOT) often fail to construct an effective query due to a lack of specificity of INs. As queries are formulated based on what the user knows [30, 38], it is clear that in a case of a failed search, the user likely did not know the "right information", such as the right keywords. Users often remember only episodic events (e.g., an occasion in which the user watched a movie) and lack semantic (factual) memory information. Therefore, INs are described as information requests rather than system queries as the user often misses the keywords that would help them mine the system metadata.

We propose several areas of IR design and evaluation to consider in order to achieve improved support for the user in varying states of anomalies in knowledge:

1. Effective categorisation of documents depending on their associated level of knowl-

edge they describe, e.g. utilisation of metadata about levels of knowledge to determine the document suitability, e.g. beginner or advanced reader.

2. (In interconnection with the first point) Knowledge-based documents presentation of the retrieval output. Effective metadata allows for the information to be presented in a hierarchical fashion to support users in differing stages of knowledge. Improved document presentation would familiarise the user with various investigated topics. Furthermore, it would effectively navigate the user to avoid information overload, as well as allow for a more natural-like occurrence of INs, i.e. INs arise naturally via the user's engagement with the documents and the knowledge these documents cover. The user might, therefore, better understand and formulate their INs in association with their current level of understanding.

3. Multiple interfaces differentiated by the level of knowledge the retrieved document offers. We expect these would further benefit from an automatic (e.g., BCI systems, analysis of search logs) or at least semi-automatic recognition (e.g., questionnaires, surveys) of user's current level of knowledge to determine the right interface to effectively satisfy their specific INs.

4. As has been found, information requests are often formulated in a narrative way and users often use dedicated online forums where other users solve their requests. For instance, built-in support for improved analysis of unstructured text input, e.g. Natural Language Processing (NLP), might be of benefit to the users in TOT or FOK states. In the end, it would not only reduce the interference from a third party (e.g., a manual reply from other users who possess the correct answer) as well make the retrieval mechanism more effective.

5.6 Conclusions

We conclude this chapter by summarising the major outcomes of our study, their contributions and reflecting on the study itself.

This study segment acknowledges a variability of the user's state of knowledge informed by the epistemic feelings triggered by the metacognitive (self-awareness) mechanisms. We investigated the spatio-temporal progression of neurocognitive activity associated with three epistemic feelings, allowing for a more accurate specification of searchers' state of knowing. In particular, level FOK is a novel proposition in IR.

The findings of early neural correlates underpin the view that early levels of stimuli processing are initiated prior to the user's awareness. It indicates that the realisation user's state of knowledge in the context of a graded recall is manifested subconsciously before the user realises the recall outcome. This, in turn, suggests that an IN realisation could happen at a subconscious level at its earliest state. Analysis of the later activity across Meta levels revealed the sequential engagement of more controlled and effortful neurocognitive functions. The summary of results suggests that differences in the brain correlate associated with Meta levels are triggered by the underlying recall outcomes they describe, i.e. successful recall (KNOW) and recall failure (FOK, NKNOW). In terms of the resolution of the FOK state, the lack of any significant differences in discriminating user's failed recall outcomes means that we cannot rule out the potential resemblance of the brain responses of FOK and NKNOW. This outcome supports the notion of FOK as a state of the spectrum of ASK that might progress into a state of IN. We recommend further investigations with larger participants samples to validate these results.

Our findings can further explain behaviours linked to the variability of IN, as in our case, linked to detecting a FOK-specific IN request. Such a position might require to rethink of the current mechanisms and system interface design to support such requests more efficiently. This work opens a follow-up expansion of investigations led by metamemory-induced IN states with the strength of familiarity as a potential indicator of the corresponding state. An extension of this work could benefit from definitions of further, more granular grades of FOK [206] as well as adaptation of the research to new sensory input modalities, such as auditory, especially relevant due to the significant growth of voice technologies and their rapid adaptation by users or search engines.

5.7 Chapter Summary

This present chapter set the conducted user study in the context of our first Research Goal (2.4). The chapter follows:

- Review of related IS&R literature that identified the key points for the present investigation.
- Introduction of the metamemory context in the realisation of INs, with a particular focus on the concept of FOK.
- Formulation of Research Questions.
- Explanation of the aspects related to Study Design and Methodology associated with the current chapter.
- Presentation of the data analyses results.
- Review of the major findings related to our Research Questions and discussion of their potential implications from both user and IR system perspectives.

Chapter 6

EEG Study of Memory Retrieval and Confidence Judgments Further Informing Users' Information Needs

This Chapter presents the investigation addressing the second and the third of our research objectives (see Section Research Goals 2.4). It inspects the i) Memory Retrieval (MR) indicative of the source of IN realisation and ii) how the MR outcomes are sensitive to confidence judgments. Consistent with the previous chapter, we took the approach of observing spatio-temporal modulation of brain activity. However, this time the brain activity was associated with different MR outcomes participants experienced during the Q/A tsk (see Section 3.3.1 and Step 3 in Figure 3.1) and expanded upon how confidence modulates the activity of MR. Furthermore, we investigated if the spatio-temporal patterns of neural activity associated with the perceived gap in knowledge can predict the user's INs and, thus, inform the detection of IN from the neurophysiological data. Finally, we conclude the chapter by presenting the implications of the significant findings informing the field of Information Search and Information Retrieval (IS&R).

6.1 Background

The human evolution stages speak a story of continuity, adaptation and the inevitability to progress and survive. The experiences and knowledge prompted this evolution. The central aspect that allowed this evolution was the development of complex human neurological structures and increased cognitive capacity. These are used in daily life without the need to be consciously reminded of their availability and automatic functioning. The progress meant for humans to turn the encountered episodes into experiences and the experiences to turn into knowledge. Humans can naturally formulate associations, mimic re-occurring events at a later time, recognise novelty in the environment, weigh the impacts of the alternatives and structure the reasoning. All of these are utilised to produce responses, solutions and actions based on higher informativeness of the user. Here, we are finding the analogy with the information search behaviour where knowledge and memory functioning represent a crucial component behind the emergence of IN [15].

In contrast to the previous investigation of metamemory as the mechanism supporting the user's cognitive context, now we delve deeper into the memory as a storage of information, learnt or experienced, known as the declarative memory (explained in Section 6.1.2). Therefore accessing and retrieving the content of memory - memory retrieval (MR) - is another component to process the functioning behind models such as ASK [10] and expand, thus, with a new perspective, the context of the realisation of user's states of knowing, explored in the previous chapter. Thus, the retrieved knowledge represents an input to the user's cognitive system to make appropriate decisions and strategies for the following information behaviour. The ability to access the memory storage and the retrieved information has an irreplaceable role in determining the user's state of knowing (noIN) and not-knowing (IN).

6.1.1 Memory Retrieval in IS&R

Cognitive insight into IS&R reasonably recognised gap in knowledge or incomplete knowledge as a product of user's MR [9, 15]. In addition, an interdisciplinary *NeuraSearch* research (refer to Section 2.3.4) led to a discovery of cognitive processes and brain regions where the brain activity seemingly supports the switch between knowing (no-IN) and not-knowing (IN) [11]. Here, the varied activity was associated with the functioning of MR, the working memory and decision-making. Moreover, the cognitive perspectives in IR expand on the triggers of realisation of IN to include affective feelings [5]. These include feelings of certainty and confidence of the user with a varied intensity exhibited during the search process. Both MR and Confidence in the context of IS&R will be addressed in this chapter.

Memory as the Repository of Knowledge

Internal (conceptual) models as the representations of the user's knowledge were part of Belkin et al.'s "Conceptual State of Knowledge" [3] or Ingwersen's "World Knowledge" [15]. Taylor proposed his IN taxonomy [13] based on the "State of Readiness" by Mackay [145] based on a similar conceptual picture of the world consisting of the user's previous experiences and past interactions. The user's ability to articulate the requests to an information system can be expected to change according to their level of understanding of the problem [13]. Kuhlthau [5] analogised Taylor's visceral IN level (Q1) and Belkin et al.'s ASK. She concluded that initial vague INs are experiential (Q1) and are likely to be connected to the user's existing knowledge (ASK). The clarity and articulation of INs increase once the user's specific gaps in knowledge are identified.

Kuhlthau's own Information Search Process model [5] drew attention to the search process as a process of sense-making for the user who actively searches for new information to fit into what they already know on a particular topic. Therefore, topical knowledge, which Kuhlthau calls "personal frame of reference" [5, 1991, p.361], plays a vital part in the constructive process of the users' understanding and INs. Ingwersen [15] early on referred to the IR process as an interactive problem-solving process where individual knowledge structures play a vital part in solving these problems. Knowledge plays a central element in the information exchange between the user (subjective knowledge) and the system (objective knowledge).

Continuing to expand on this idea, Cole [8], similar to Ingwersen and Kuhlthau, extended the notion of knowledge beyond a product of the information search process and focused on the utilisation of the user's knowledge and cognitive operations. He framed the user's internal mechanism of knowledge usage and generation according to i) Minsky's Frame Theory [17], an internal representation of the world based on knowledge frames, and ii) the person's perceptual cognitive system that utilises dynamic thinking, reasoning and making associations and extracts relevant frames in the form of memory cues and evaluates them to make informed decisions and generate actions (e.g., information search behaviour). Human acts as a self-organising system and alters their state of readiness in response to a received stimulus. We can, thus, define INs as the product of this adaptive process. The user's memory, as an internal source of information and knowledge frames, is the core element in the functioning of this adaptive mechanism. For further description of these works please refer to Sections 2.1.2, 2.1.3, 2.2.1, 2.2.2, 2.2.3, 2.2.4.

Active traces of memory engagement in IN

Ingwersen [15] illustrated that the human perceptual system firstly filters and then passes sensory stimuli data (e.g., a problematic event the user faces) to process by short and long-term memory. Memory recall allows the user to "relive" the past experience during a new (or a re-occurring) event and to generate a solution.

Cole [8] described the flow according to aforementioned Frame theory [17]. IN sets off the cognitive processes by employing memory search. Long-term memory storage is a repository for knowledge. According to the Frame theory, knowledge frames are selected and called to act upon incoming environmental stimuli. These are called into working memory and ready to be processed. Multiple retrieval structures in working memory combine past experiences as an input to form alternatives representing solution possibilities and probabilities for the present stimuli.

Referring to the outcomes of NeuraSearch research, Moshfeghi and Pollick [24] explained IN as a complex phenomenon consisting of the interplay of high-order neurocognitive processes during the introduction of "Neuropsychological model of the realisation of IN". In the light of findings from an earlier fMRI-based user study [11], they conceptualised two components playing a vital part in IN realisation: Memory Retrieval and Information Flow to create a link between internal (memory) and external search (see more in Section 2.2.1). A recent study by Arguello et al. [95] performed a qualitative study of IN expressions when users failed to recall a movie title but were able to recollect other movie-relevant aspects, often subjective (e.g., an occasion they watched the movie). The qualitative analysis of these IN requests found that the users use recollections from declarative memory, both semantic and episodic, to articulate their INs (see definition in Section 6.1.2).

We are, therefore, interested in the investigation of the neurocognitive mechanism of MR to further expand on the area of the knowledge context of the user's IN [6] and the user's states of knowledge, which we established in the previous Chapter 5.

Modelling uncertainty and confidence in IR

There seem to exist two views on uncertainty in IR literature: i) uncertainty as the target measure the searcher is trying to manipulate by engaging in a search and ii) uncertainty as a by-product of IN and the variable depending on the stages of information-seeking.

The first type was described by Atkin [107], and Krikelas [108], who approached the concept of IN as a derivative category of uncertainty. They defined IN as the recognised uncertainty that the user achieves to reduce. Here, uncertainty is described in the context of the searcher's perception of the outside world, such as a feeling of anomaly or an incompleteness [3]. Relevant information that fills this anomaly with coherent knowledge provides the key to reducing this uncertainty.

The second approach sees uncertainty more from the point of the manifestation of both affective and cognitive feelings and, as such, can be an early perceived sign of pre-manifestation of INs [5]. Confidence and certainty are naturally evoked when the user faces a situation relying on their internal information. Both Taylor and Belkin approached the notion of uncertainty as a user-specific aspect of IN realisation in their studies. According to Taylor, the searcher's inquiry is based on an underlying "area of doubt" [13, 1968, p.179], implying the absence of confidence and increased uncertainty.

The term "area" intuitively suggests a broader scope, not only referring to information space, as well to the employment of cognitive and exploratory capabilities. These requirements conform to ASK's realisation of anomaly accompanied by doubts and uncertainty that are hard to express [3], but in paradox, seen as a trigger of one's engagement in IS scenario. For specificities of both see Sections 2.2.2, 2.2.3 and the introduction to the Section 2.2.4.

Later, Kuhlthau studied [52] a shift of physical actions, and cognitive and affective experiences searchers exhibited during an information task. Building upon the findings, she constructed her Information Search Process (ISP) Model [5] which described these varying subjective experiences. She identified information seeking as a process of sense-making highly influenced by personal stances, interests, and prior experiences and knowledge, as well as by affective aspects of attitude, and motivations of the user, with the outcome of the information process, which will be integrated into these as well. The model established two signatures of the search experiences. First, uncertainty causes discomfort and anxiety, affecting the articulation of the problem and the relevance judgments. Second, the intensity of confidence varied depending on the stage of ISP, with the early manifestations of confusion, apprehension, frustration, and doubt transferred into later feelings of satisfaction, certainty and relief. Confidence variability was found to be a factor of ISP, correlated with the levels of information clarity and focused thinking, which corresponds to the evidence of ISP as a sense-making constructive process. Kuhlthau expanded on her findings and established the view of the uncertainty concerning information search [18]. Uncertainty manifested by affective symptoms of anxiety, frustration, and lack of confidence is associated with unclear thoughts about a topic resulting in exploratory actions for information, i.e. search space is broad. The source of uncertainty lies in the lack of understanding and the limited clarity about the problem and INs, i.e. ill-defined INs. Only when a shift toward clear and focused thoughts happens, a parallel shift occurs, causing feelings of user's increased confidence. Alike, Ingwersen's cognitive view on IR [15] accounted for affective issues as a trigger of INs and concluded that ambiguities and obstacles the users might perceive at the beginning of the search process are reduced in the next iterations of the IR process. To remark, the affective feelings are, however, not limited to the user's uncertainty sourcing from the user's lack of knowledge and INs to fill the gaps. The ambiguity might reflect the user's stance on the search process itself [5] and the user's doubts about the outcome of the search process. The question of the relationship between the user and IR in the context of the user's trust is out of the scope of this thesis.

In summary, affective feelings can take different forms indicative of uncertainty, such as a spectrum of confidence. Confidence is a relative and subjective measure and is attributed to an object or process that has been performed. In our case, the object is the outcome of MR and participants' subjective assessment of their confidence about the accuracy of the outcome, i.e. "Is my answer the correct answer?". We hypothesise that different confidence judgments drive a change in behaviour related to MR outcome. For the link between confidence and memory, see further Section 6.1.4.

Epistemic Uncertainty with information content Different and novel opinion about the origin of uncertainty in the context of the textual content was brought by Rubin [4], who discussed the uncertainty from the linguistic standpoint and the users' subjective interpretation of the document text. She questioned if epistemic (i.e., is true) uncertainty encoded in information (often found in documents that contain personal attitudes and subjective opinions of writers) can be during the retrieval process transferred onto the users. In line with the author's stance on information seeking process being a "a heterogeneous discourse" [4, 2010, p. 534], users' levels of certainty and confidence vary depending on user's interpretation of epistemic uncertainty in the encountered documents. Depending on the content, information objects might, thus, be a source or an increment to the uncertainty level of users, which might then lead to evoking new INs purely based on uncertainty posed on the user. Therefore, information content and the inherent uncertainty represent an interesting new addition to model the users' information seeking behaviour, mainly covering the phase of interaction with the text. This thesis does not expand on this relationship any further but acknowledges its relevance for a future study.

6.1.2 Memory Taxonomy

The fact that memory is a complex process proves the existing taxonomy of memory [175], where each memory behaviour might change depending on the desired outcomes [167]. Squire and Zola-Morgan [175] suggested the existence of hierarchically arranged separate memory systems. At the top of the hierarchy, there are two distinct systems; distinctive not only in terms of the anatomical structures, as well as in terms of their functions and operating characteristics, e.g. type of information. First, *declarative memories systems* hold the explicit information composed of facts (semantic memory) and past events user either learnt or experienced (episode memory) during their lives. Second, *non-declarative memories systems* contain implicit information. These relate to how people respond to stimuli or perform under the circumstances, using skills (e.g., how to ride a bicycle), habits (e.g. before going to bed, brush the teeth) or emotional responses to stimuli (e.g., phobia). Declarative memory is important in our setting as the only one that affords a conscious recollection of information it holds [175]. Humans can report their knowledge base and past experiences to some extent. In IR research, this was proved in a paper by Arguello et al. [95], who examined the expressions of INs requests and found that users highly rely on the outcomes of the declarative memory. In addition, declarative memory allows new memories to be encoded according to relationships among multiple items and events and, as such, has an important role in guiding performance and memory tests. Finally, according to Squire [135], it provides a representational model of the external world, which resembles the models of the outside world incorporated as the context of information search in the previously mentioned IR models, such as [3, 15, 28]. Declarative memory is usually regarded as fundamentally distinct from other expressions of memory [167]. Declarative memory is targeted in our study with the employed general knowledge Q/A seen as a prototype of factual memory retrieval. Finally, we address the concurrence of memory and metamemory judgment. We anticipate a link between metamemory (investigated as part of Chapter 5) and memory, particularly during the information exchange between these neurocognitive processes. For instance, whilst we process a question, a memory search is likely to be performed, which can already trigger an automatic retrieval of the answer (fact). A successful instant retrieval then causes the information to be passed onto metamemory, drives the input-output effect and increases the user's awareness. The interaction of metamemory and memory is out of the scope of the current chapter, but is analysed later in Chapter 7.

6.1.3 Memory Retrieval and Information Need

Not knowing the information is generally accepted as a preamble to IN [10]. However, not every knowledge gap can automatically translate as IN. Earlier in the Chapter 3 Section 3.2, we introduced the paradigms used in our study and presented a concept of lower INs [184], which is similar to our understanding of gaps in knowledge where no INs arise. The definition can be taken from two perspectives: 1) the information provider recognised that it is of the user's benefit not to know everything, and 2) users themselves decide what piece of information they want to know. In the first case, the decision maker is the information provider and is heavily present in scenarios involving medical information, e.g. during a doctor-patient dialogue [182, 183]. In the second scenario, we used the notion of relevance to explain the situation where the user is the decision maker. Whereas the document relevance [236], the notable concept of subjective information judgments [29], investigates the value of information to which the user has already been exposed to [237], the relevance of INs is the function of user's information preferences and the information purpose the information in question brings. The user, thus, considers personal and contextual information criteria to engage in a search [233], e.g. topicality, interest and the value of information (see Section 2.1.3). The context of INs was also approached by Krikelas [108], who defined deferred INs as when there is no immediacy between the realisation of an information deficiency and the action to resolve it.

Reflecting on the outcomes of the behavioural data analyses from Chapter 4 Section 4.3.2, we learnt that a majority of participants in our study wanted to know the correct answer to a given question. They reported a genuine interest and curiosity as well as potential usage of the information in the future as the major drivers of their preference to satisfy their knowledge gap. We use the information to categorise our data to construct our supplementary investigation. In addition to learning if EEG data are informative of the user's different MR outcomes, we wish to explore the further level of modulation of neural activity considering the participants' decision to separate IN and the lower INs.

6.1.4 Memory Retrieval and Confidence

Memory is an "imperfect archive of our experiences" [27, 2005, p.4]. Memory is prone to forgetting, which makes it a dynamic system dependent on individual abilities and capacity to remember and recollect. The strength of one's own memory capacity also depends on the knowledge base maintenance and retention, such as updating the knowledge [238]. Unlike the system capabilities (if utilised effectively), human memory retrieval does not always provide accurate results. The results are often fuzzy, and the user is not certain that the information in question is the right or correct one indeed. These are confounded with other factors, such as confusion or familiarity, that modify the strength of memories and knowledge (strong vs weak) [177]. As a consequence, phenomenons of false memory or misattribution of memory [27] might occur, meaning, an incorrect answer choice was consciously (i.e., not by chance) mistaken for a correct one.

Our study employed the RJR paradigm (explained in Section 3.3) to associate the participants' responses with the MR outcome: correct (MR-C), incorrect (MR-I), and not-know (MR-N). According to Diana and Ranganath [177] "recollection leads to high confidence because retrieval of specific details is rarely spurious". It implies that correct responses are expected to be associated with high confidence. Our behavioural data confirm this suggestion (see Section 4.3.2 and Table 4.2). If we decide on one thing, we give up the other due to different confidence levels. The behavioural data further report that the absolute confidence that drove the choice of MR-I is, in most cases, low but still relatively higher in contrast to a (not reported) confidence triggered for the remaining choices. This brings us to the premise of our investigation that confidence is not a standalone attribute relating to a single object but rather a comparative measure of probabilities of multiples objects, e.g. responses, as such provides a useful cue in users' decision-making. Confidence is, thus, a perception driven by interconnected trade-offs in terms of the user's choice as part of the adaptation mechanisms [28].

Confidence and uncertainty have been studied concerning IR using questionnaires, surveys or field studies [5, 130], therefore highly dependent upon the subject's commitment and understanding of their feelings and experiences. Using the NeuraSearch-type of study, we aim to overcome the potential of participants' cognitive overload and to examine the neurocognitive signatures of reported MR outcomes and their associated subjective confidence levels. In addition, we aim to explore to what extent confidence modifies the signal of MR and, thus, get closer to answering the question "Can the signal depicting the information processing, prior to the user's explicit confidence judgments, inform us about the magnitude of user's confidence?".

6.2 Research Questions

Our hypotheses are described as Research Questions (RQ). We aim to bring a comparative ERP analysis of spatio-temporal patterns of activity associated with processes of MR and Confidence (please refer to Section 3.2.5 for the acronyms of factors) and answer the following RQs.

- **RQ1:** 1) What spatio-temporal differences of neural correlates are exhibited for the spectrum of our three defined MR levels, i.e. MR-C, MR-I, MR-N, within our setting, i.e. Q/A task of general knowledge? 2) Can we detect from data related to unsuccessful memory retrieval (MR-N) an indication of the user having an IN (SEARCH)?
- **RQ2:** How do two confidence levels from the opposite poles of the spectrum, i.e. high (H) and low (L), modulate these neural correlates?
- **RQ3:** What implications do the outcomes pose on our understanding of users' INs in a broader context of IR and IIR?

The RQs were constructed similarly to the previous investigation of metamemory and FOK (Chapter 5). The approach reflects the intention to obtain novel insight into the cognitive underpinnings of IN as these have not yet been subjected to an EEG-format of a *NeuraSearch* study (see 2.3.4). The RQ3 addresses theoretical and practical contributions toward IR research and will be supported by the outcomes resulting from answering RQ1 and RQ2.

6.2.1 Design

Refer to Section 3.3.1 that describes the experimental Q/A task with Steps S1 and S3 - S4.2 relevant to the present investigation. Our study aims to uncover unbiased neuro-physiological evidence triggering different MR outcomes and how different perceptions of confidence feeling might modify this brain activity. In short, we will search for the i) Evidence of functional processes leading to declarative MR (explained in Section 6.1.2), ii) Evidence of differentiation between MR-N and MR-N expressed as IN (justified in Section 6.2.1) and at last, iii) Evidence of significant interaction effects on brain signal between confidence judgments and MR (justified in Section 6.1.4).

We followed a consistent analysis (delineated in Section 3.5.2) of spatio-temporal features across the investigated phenomenons manifested as ERP components (refer to EEG Glossary in Section 2.3.1). We created three models of investigations associated with our RQs.

Model MR based on data aggregation according to MR levels (i.e., 2nd level of factorial hierarchy - see Section 3.2.5 in Chapter 3).

Second, Model MR+IN expanded upon the Model MR by subsetting the MR-N level by the factor Search Decision into two categories and, thus, differentiated between IN and noIN.

Third, **Model MR+Conf** included the 2nd tier of aggregation according to the Confidence judgments factor to analyse the effects the confidence judgments yielded on MR correlates.

Model MR

According to hierarchy in 3.2.5, MR consisted of three levels: 1) MR-C, representing successful retrieval, meaning correct factual information was retrieved, 2) MR-I, representing false memory, meaning incorrect factual information retrieval and 3)MR-N level, which conforms to participants acknowledgement of their state of not knowing (i.e., a gap in knowledge).

In general, memory performance has been examined either 1) at the time of information encoding into memory, with the focus on memorability where the researchers have control over the information input, or 2) as a function of events that take place at the time of retrieval [167], similarly as our study aimed. The latter brings out the realisation of distinct memory processes, such as familiarity (usually accompanied by the user's FOK - see the previous investigation in Chapter 5) or a detailed information recollection due to a conscious experience of remembering [167].

Our study employed the Q/A task of general knowledge evoking the factual memory search and retrieval at its core. The premise of two factual answer choices, one signalises a correct answer choice (MR-C) and the other an incorrect choice (MR-I) as a distractor, is often employed as part of the overall RJR paradigm [166]. The participants also had the option to acknowledge the state of not knowing rather than guessing a correct answer. All the pre-defined options are characteristically different, but together they capture the factual MR scenario well. Our data allow us to study the extent of differences and similarities between all three levels.

Model MR+IN

Referring to the sequence of the main task (Figure 3.3.1), we see that the participants who answered MR-N could i) either learn the correct answer (SEARCH) and satisfy their knowledge deficiency or ii) not learn the answer (level NOSEARCH), skip the end of the trial and move to a next question. MR-N level can be, therefore, split into two categories and ideally, these two would represent the overarching classes IN and noIN level (or a category of lower IN presented earlier in Section 6.2.1). The contrast of spatio-temporal patterns of these two sub-levels could, thus, be informative of the prospect of detecting the rise of IN based on EEG data alone.

However, as reported in Section 4.3.2 of Chapter 4, the NOSEARCH level was among the least response-populated levels across and within participants. The low data sample for within-design ERP analysis represents an issue (for the ERP analysis constraints, see Section 3.5.2), and we, thus, cannot follow our cohesive analytical within-design framework. We, therefore, took an alternative perspective on the criteria to obtain IN and noIN levels.

The compound level MR-N+SEARCH level (i.e., not knowing followed by search) is a fine representant of an expressed IN according to the participant's response of "I want to know the answer". Such a response can be seen as an expression of participants' early IN based on the condition that the information supports an information purpose [31, 99]. We use the same criterion to determine the contrasting level noIN. For reference, we look at the previous Model MR as we want to keep the investigation reflecting the underlying MR processing. The remaining levels, MR-C and MR-I, can be interpreted as expressions of noIN (or no expressions of IN). In both instances, the participants share the experience of recollection of memory information (independent of its correctness). Since the participant knows the answer, we consider that these levels do not trigger an immediate rise of IN.

Model MR+IN can be seen as an expansion of the model MR as it contains an important aspect of the participant's cognitive context, i.e. the decision to satisfy their temporary knowledge deficiency. The analysis of this model will provide evidence of data features responsible for MR-N+SEARCH level, i.e. expression of IN. In summary, our initial intention to investigate IN and noIN using the Search Decision factor (SEARCH vs NOSEARCH) has been adjusted to the available data capabilities. We thus employed a slightly different perspective on IN and noIN, but the overall objective remains the same.

Model MR+Conf

By the design of the task (Section 3.3.1 and Figure 3.1), the participants were not asked to asses their confidence in all three MR levels. Instead, they provided these judgments only if their preceding MR resulted in factual information retrieval, i.e. MR-C and MR-I levels.

Lack of confidence and uncertainty has been associated at the early stages of the

IR process with the lack of knowledge triggering INs [52]. In the case of our study, lack of knowledge is manifested by the rise of MR-N responses. MR-N responses per se acknowledge the user's state of not knowing. As we noted in Section 6.1.4) the user's confidence is a comparative attribute that connects several probabilities of the responses and decisions. Moreover, it has been suggested that the users express their INs and the associated uncertainty in terms of what they know, i.e. certainty [109]. Feelings of confidence, however, vary according to the strength of memories and knowledge [177]. We, therefore, question the variability of confidence when the outcome of MR is factual (MR-C or MR-I). To what extent the various confidence levels would modify the neurophysiological signal of MR is the aim represented in the Model MR+Conf. Addressing our RQ2, we look into the notion of confidence as a by-product of the factual MR and explore how sensitive the MR outcome is to different confidence level judgments.

Expectations and Predictions

Theoretical foundations of MR and Confidence have been presented earlier. Likewise, as the investigation of metamemory from the previous chapter, the user-based research in IR is limited in the area of cognitive studies of memory and confidence behind the origin of INs. The benefit of a *NeuraSearch* study (see 2.3.4) is in simultaneous measurements of unbiased neurophysiological (bio)markers of participants, whilst their subjective responses and interactions are recorded via button clicks. The participant's "brain (internal) experience" recorded via EEG enables to draw associations with their external (visible) experiences. Participants do not have to describe aloud the processes behind their memory search (as one of the ways to capture internal processes), which eliminates any cognitive bias and potential overload posed onto subjects of the experiment.

6.3 Experimental Set-Up

As mentioned in Chapter 4, the study encompasses data from 24 participants who performed a Q/A Task (refer to Section 3.3.1) and generated responses pertain to the factorial hierarchy (see Section 3.2.5). The current chapter observes the factorial hierarchy's 2nd (MR levels) and 3rd levels (Confidence judgment and Search Decision levels). The data are encoded into three MR levels: 1) Correct (successful and correct retrieval, MR-C), 2) Incorrect (memory falsely endorsed as correct, MR-I) with two Confidence levels for both MR-C and MR-I, A) High (H) and B) Low (L) and at last, 3) Not Know (no recollection, MR-N) which was further split by the Search factor as i) MR-N+SEARCH and ii) MR-N+ NOSEARCH.

6.3.1 Sample size

Referring to results obtained from the behavioural data analysis in Section 4.3.2 of Chapter 4, specifically Table 4.2, the responses across MR levels were unbalanced. We found that, on average, over half of the responses a participant selected was MR-C, with the remainder split between MR-I and MR-N levels. Because we rely on a large number of samples to perform the within-subject analysis (see the explanation in the Chapter Methodology Section 3.5.3), we applied the same procedure as in Chapter 5 to deal with the unwanted effects of data unbalances. We assessed the individual data and adjusted the sample sizes for each Model based on the mean number of level-dependent recorded trials for each participant. The reliable amount of data sources for **Model MR** was determined to be 15 participants (each with at least 13 trials). For **Model MR+IN**, it was 14 participants (each with at least 12 trials), a subset of the participants identified for the MR model. In order to contrast these two models, as they share the same participants and make the results comparable, we balanced the input samples. We used the same **14 participants** in both models, i.e. one participant from the Model MR was excluded. The mean number of MR-N trials per participant was 33.6 (sd 16.5) for Model MR. The MR+IN Model used the subset of MR-N trials, comprised of MR-N+SEARCH responses, which represented on average 27.6 (sd 12.6) trials per participant, i.e. around 86% (sd 19%) of the MR level. The remaining 14% consisted of MR-N+NOSEARCH level, which was excluded from the analysis (see justification in Section 6.2.1).

Model MR+Conf consisted of two independent factors, MR and Confidence. Here, we checked the individual interaction results as a compound of 2 factors (2x2 levels) MR-C+L, MR-C+H, MR-I+L and MR-I+H. As it is noticeable from Table 4.2, the interaction between MR-I and high confidence was significantly less frequent than between MR-I and low confidence. Following the preceding investigations, we checked the individual results for MR-I+H. Then, we excluded the participants whose number of responses was low compared to the grand average of the MR-I+H group and whose grand ERP waveform was noisy. After the elimination of the participants, we ended up with **9 participants**, which recorded a sufficient amount of responses in each level and will be utilised as the input for the MR+Conf Model.

6.3.2 Methods of Data Analysis

We follow the analytical framework described in Chapter 3 Section 3.5.2.

6.4 ERP Analysis Results

We will report on the ERP analysis's outcomes for each model in a separate subsection. First, each model presents the significant spatio-temporal results followed by their summary. Then, the discussion of the results with respect to the Research Questions is presented in Section 6.5 with the final conclusions given at the end of this chapter in Section 6.6.

6.4.1 Model MR

The data model is based on averages for 14 participants (see earlier Section 6.3.1) calculated over ROIs within the identified time windows. The statistical analysis results, identifying significant differences in ERP amplitudes, are summarised in Table 6.1. Figures 6.1, 6.2 and 6.3 complete the results with a visual presentation of the contrasting

ERP waveforms.

90 - 150 ms The earliest activity within the window 90 - 150 ms was found to evoke N1 component across all MR levels with the anterior-posterior distribution. Our data evidence on three ROIs where the elicited potentials differed across the MR levels. The statistical analysis identified highly significant activity (F[2,26]=11.80, p=0.0002) in the ROI spanning the right frontal and right front-central area of the brain (RF/RFC). The post-hoc test specified that the significance is driven by two pairwise contrasts, both including the level MR-N. The contrast between MR-N and MR-I showed that the negativity of N1 amplitude for MR-N level (-0.39 μV) is significantly greater (p<0.001) than the negativity of MR-I (-0.01 μV). The same direction showed the contrast of the mean amplitudes of N1 between MR-N and MR-C (-0.08 μV) driven by a significantly lower mean value of the elicited signal for MR-N (p<0.01). In Figure 6.1a, we can see larger negativity of N1 amplitude generated for MR-N and the lowered N1 amplitudes for MR-I and MR-C.

The second significant ROI (F[2,26]=4.95, p=0.02) was identified as the temporo-parietal (LTP) ROI where the modulation of MR level-dependent elicited signal was driven by a significantly higher (p<0.05) mean value for MR-N level (0.27 μV) in contrast to mean for MR-I (-0.07 μV). The ERP waveforms of the corresponding MR levels are illustrated in Figure 6.1b with the MR-N amplitude of N1 component exceeding that of MR-C.

At last, we found a statistical significance (F[2,26]=5.22, p=0.01) arising in posterior ROI spanning parieto-occipital/occipital area (PO/O). Here, the amplitude of N1 component elicited for MR-N (0.72 μV) was significantly higher than the amplitude for the remaining two levels, MR-C (0.35 μV, p<0.05) and MR-I (0.33 μV, p<0.05). For reference, see the corresponding ERP waveforms in Figure 6.1c.

All the findings are evidence of the anterior-posterior distributed activity of N1 driven by the highest values elicited for MR-N level.

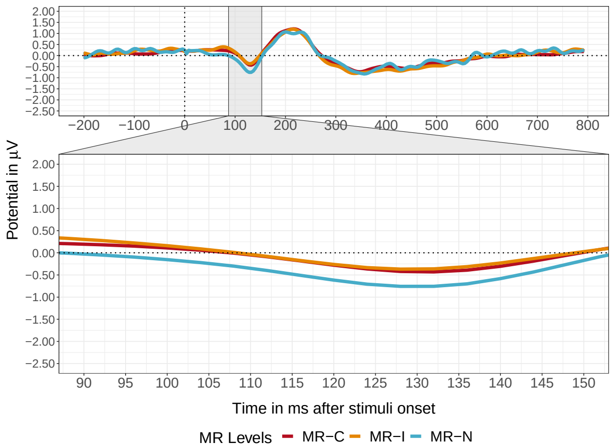
150 - 270 ms The emergence of P2 component clearly describes the underlying activity for each MR level. This outcome suggests the ERP component consistency in activity underlying the information processing in the context of our three MR levels. Statistical tests revealed a significant modality ($F[2,26]=3.97$, $p=0.03$) of the brain activity in bilateral temporo-parietal (TP) ROI. The pairwise post-hoc tests then specified that a significant difference was caused by a significantly greater ($p<0.05$) negativity of P2 amplitude for MR-I (-1.64 μV) than for MR-N (-1.39 μV). Figure 6.2a depicts the P2 amplitude of both levels, with MR-I's clearly exceeding that of MR-N.

270 - 570 ms The window spans the length of 300ms, between 270 - 570 ms, and depicts the occurrence of N400 component in both anterior and posterior regions. The amplitude describing the N400 can be characterised in two consecutive time frames. First, the onset of the window describes the accumulation of the resources to support the cognitive operations until it reaches its peak (i.e., the employed resources are at their peak). Second, followed by a steady decrease of values after the cognitive decision was made describes the component's offset. We, therefore, decided to split the time window into two windows: the 270 - 430 ms, which comprises the onset of the amplitude and the 430 - 570 ms with the activity offset to observe if different ROIs are involved in these two time frames. The findings support this decision.

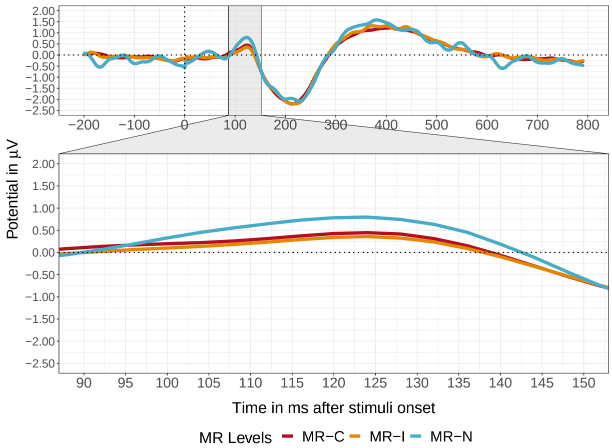
First, in the window 270 - 430 ms, we found the mean activity of MR levels significantly differed ($F[2,26]=5.03$, $p=0.014$) over right front-temporal (RFT) ROI (RFT). Pairwise post-hoc tests specified that this difference was driven by the contrast of different mean for MR-I (-0.73 μV) and MR-C (-0.39 μV) levels, with the former being significantly lower ($p<0.05$). Figure 6.2b depicts the ERP waveforms over RFT ROI with larger negativity of N400 amplitude for MR-I level.

Another significant ROI ($F[2,26]=4.30$, $p=0.02$) was identified as the central/centro-parietal (C/CP) ROI. Here, the different activity across MR levels was found to be driven by a significantly lower mean value of the elicited signal for MR-N (-0.15 μV) in contrast to the mean of MR-I level (0.04 μV, $p<0.05$). Figure 6.2c visualises the ERP waveforms of all three MR levels.

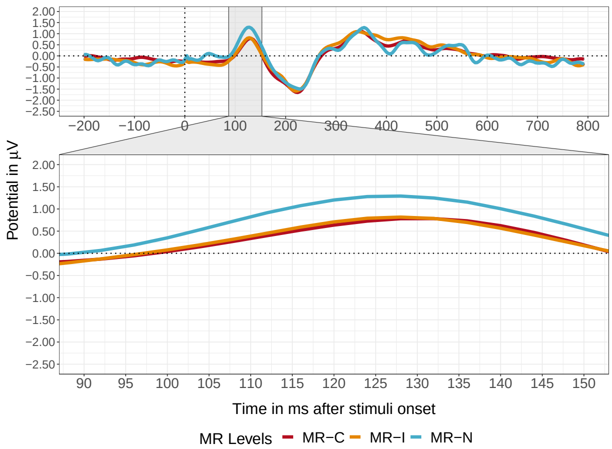
Second, the offset of N400, between the time window 430 - 570 ms, was not associated with statistically significant activity in any ROIs.



(a) N1 (90-150 ms) over RF/RFC ROI

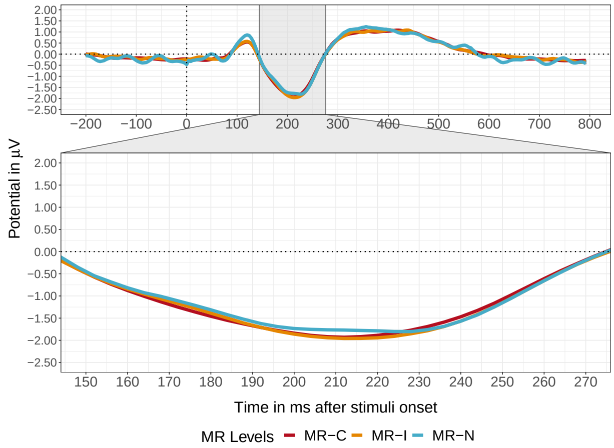


(b) N1 (90-150 ms) over LTP ROI

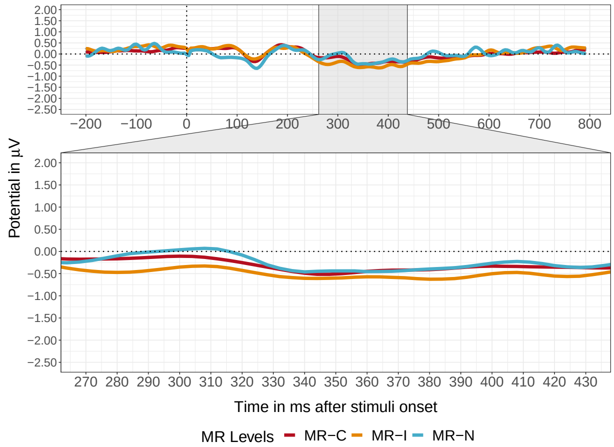


(c) N1 (90-150 ms) over PO/O ROI

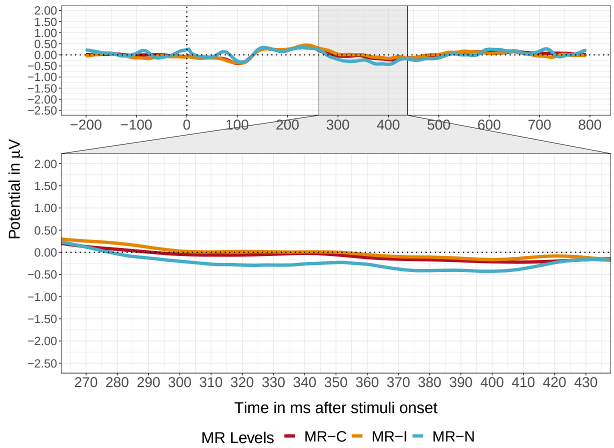
Figure 6.1: Model MR: ERP waveforms with a zoom on 90 - 150 ms poststimulus over significant ROIs (as a result of ANOVA). Averaged over 14 participants.



(a) P2 (150 - 270 ms) over bilateral TP ROI

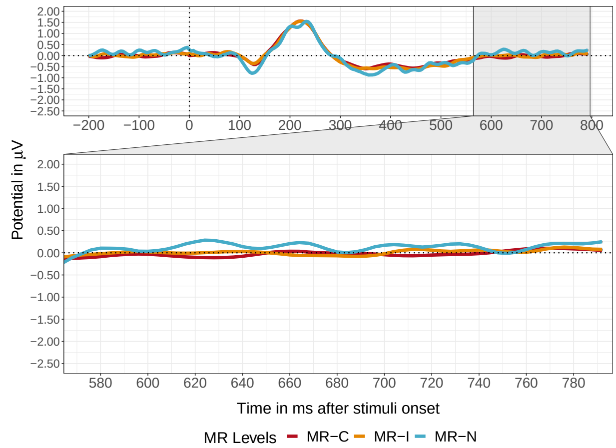


(b) Onset N400 (270 - 430 ms) over RFT ROI

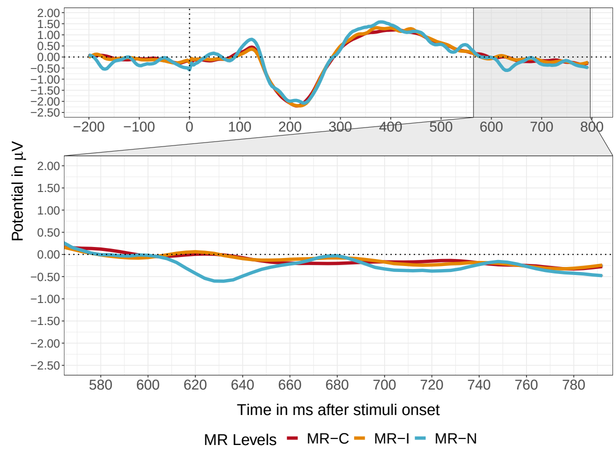


(c) Onset N400 (270 - 430 m) over C/CP ROI

Figure 6.2: Model MR: ERP waveforms with a zoom on 150 - 270 ms and 270 - 430 ms poststimulus over significant ROIs (as a result of ANOVA). Averaged over 14 participants.



(a) P6 (570 - 800 ms) over RFC/RC ROI



(b) P6 (570 - 800 ms) over LTP ROI

Figure 6.3: Model MR: ERP waveforms with a zoom on 570 - 800 ms poststimulus over significant ROIs (as a result of ANOVA). Averaged over 14 participants.

570 - 800 ms At last, we observed a sustained activity over the baseline, indicating the occurrence of P6 component. Figures 6.3a and 6.3b depict the P6 component). Despite a high overlap of the ERP waveforms in the late stages of stimuli processing, the statistical analysis revealed two ROIs and evidenced by the anterior-posterior distribution. The first ROI was identified in the right front-central/right central (RFC/RC) area, where the results of ANOVA showed a significant difference ($F[2,26]=3.97$, $p=0.03$) across MR levels. The subsequent post-hoc tests specified that this difference was caused by a significantly higher ($p<0.05$) mean positivity of P6 amplitude for MR-N (0.19 μV) than the mean amplitude for MR-C (-0.004 μV). The second region, with a posterior distribution, is the left TP ROI found earlier in the time window of 150 - 270 ms. The ANOVA identified a significantly different activity in this ROI ($F[2,26]=4.51$, $p=0.02$) affected by the different MR levels. The pairwise contrasts revealed a significantly greater ($p<0.05$) mean posterior negativity of P6 amplitude for MR-N (-0.28 μV) than the mean amplitude for MR-I (-0.05 μV).

Summary

The results show, at first, a separation of the activity into ERP components: N1, P2, N400 and the late positivity of P6 across all MR levels, which indicates the consistency of the information processing related to MR. Second, the statistical tests supported the time-dependent differences if the participant's neural activity differed between the conditions (i.e., MR levels). ERP modulation was seen to emerge already before 100 ms poststimulus, exhibiting N1 component. The activity differed in three ROIs (RF/RFC, LTP and PO/O), suggesting a widespread anterior-posterior distributed activity. In all of these ROIs, the amplitude of N1 was the largest for MR-N level with a high statistical significance. According to a general interpretation of ERP components (see Section 3.5.2), this finding explains a higher recruitment of neural resources located in these ROIs to support the users when they do not know the answer (MR-N) in contrast to when they feel they know (MR-C, MR-I).

In the second time window, between 150 - 270 ms, the activity over the bilateral TP region was found to affect the amplitude of P2 component that emerged as the greatest posterior positivity for MR-I level. Following the timeline is the onset of N400 component, where we found significant involvement of resources deployed from two ROIs, each supporting different MR levels to different degrees. The onset of N400 was found to be significant in areas with reduced (i.e., smaller) amplitudes (see Figures 6.2b and 6.2c). First, the amplitude of N400 differed over C/CP ROI and was, comparably to the first window, driven by the highest values for MR-N level with a significant contrast over MR-I. Second, the activity measured over RFT supported the processing of MR-I level manifested by the greatest negativity of MR-I over the lowest amplitude for MR-C.

Table 6.1: Model MR: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	*ERP*	*ROI*	*F value*	M_{diff}	*p-value*
90 - 150 ms	N1	RF/RFC	F[2,26]=11.80	$\bar{x}$(MR-I)= -0.02 μV, $\bar{x}$(MR-N)= -0.39μV	***
				$\bar{x}$(MR-C)= -0.08 μV, $\bar{x}$(MR-N)= -0.39 μV	**
		LTP	F[2,26]=4.95	$\bar{x}$(MR-I)= -0.07 μV, $\bar{x}$(MR-N)= 0.27 μV	*
		PO/O	F[2,26]=5.22	$\bar{x}$(MR-C)= 0.35 μV, $\bar{x}$(MR-N)= 0.72 μV	*
				$\bar{x}$(MR-I)= 0.35 μV,$\bar{x}$(MR-N)= 0.72 μV	*
150 - 270 ms	P2	TP	F[2,26]=3.97	$\bar{x}$(MR-I)= -1.64 μV,$\bar{x}$(MR-N)= -1.39 μV	*
270 - 430 ms	Onset N400	RFT	F[2,26]=5.03	$\bar{x}$(MR-C)= -0.39 μV, $\bar{x}$(MR-I)= -0.73 μV	*
		C/CP	F[2,26]=4.30	$\bar{x}$(MR-I)= 0.04 μV, $\bar{x}$(MR-N)= -0.15 μV	*
430 - 570 ms	Offset N400	-	-	-	-
570 - 800 ms	P6	RFC/RC	F[2,26]=3.97	$\bar{x}$(MR-C)= -0.004 μV,$\bar{x}$(MR-N)= 0.19 μV	*
		LTP	F[2,26]=4.51	$\bar{x}$(MR-I)= -0.05 μV, $\bar{x}$(MR-N)= -0.28μV	*

(ROIs (For spatial reference see Figure 3.2): low - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

Furthermore, the onset of N400 was found to be significant in areas with reduced (i.e., smaller) amplitudes (see Figures 6.2b and 6.2c). The offset of N400 lacked to detect any significance. At last, the pattern of activity at the closure of information processing, comprising the last 230 ms, can be attributed to the occurrence of P6 component. The findings indicate the significant variability between MR-I and MR-N distributed over anterior-posterior areas, i.e. RFC/RC and LTP triggered by the greatest P6 amplitude for MR-N. Furthermore, RFC/RC ROI seems to index the contrast between MR-N and MR-C, whilst LTP ROI indexes the contrast between MR-N and MR-I. We will discuss the ERP components in relation to the cognitive processes they support in Section 6.5.1 and use them to explain the differences between the MR levels.

6.4.2 Model MR+IN

As we informed earlier (see Section 6.2.1), Model MR+IN represents a subset of the Model MR, specifically the alteration of the level MR-N. Here, we included only the portion related to MR-N followed by SEARCH (MR-N+SEARCH) decision indicating participants' interest in resolving their knowledge gap and, as such, it can be interpreted as the user's expression of IN.

In this section, we are interested in assessing the consistency of findings with the previous Model MR. For this purpose, we kept the consistency with the previous model and used the same participants (see Section 6.3.1). The present model can either prove invariant to the outcomes of Model MR or provide evidence of the differences between the two models.

The shape of ERP waveforms (i.e., their constancy) is identical to those of Model MR. Likely, the cause is the exclusion of the level NOSEARCH that represented only a small portion of data (ca. 14% (sd 19.4%) of responses) which did not affect the shape of ERP waveforms. Table 6.2 presents a summary of spatio-temporal significant differences. For contrast with Model MR, please refer to Table 6.1. Additional Figure 6.4 shows the location of ROIs on the topological brain maps.

90 - 150 ms Neural activity distributed over the RF/RFC ROI distributed activity was found to be significantly modulated ($F[2,26]=3.5$, $p\text{-value}<0.05$) by the differences between the MR levels. Post-hoc test specified that the difference is driven by a significantly greater ($p\text{-value}<0.05$) negativity of N1 for MR-N+SEARCH level (-0.16 μV) in contrast to the reduced amplitude of MR-I level (-0.02 μV).

150 - 270 ms As informed by the results obtained by ANOVA, activity eliciting P2 component over the LTP ROI was found to be significantly affected ($F[2,26]=4.41$, $p\text{-value}<0.05$) by the differences in MR levels. The pairwise post-hoc test found a significant contrast of P2 amplitudes between the level MR-N+SEARCH (-1.70 μV) and MR-I (-1.93 μV), with a significantly ($p\text{-value}<0.05$) larger posterior negativity of P2 shown for MR-I.

270 - 570 ms Following the Model MR, we also split the window of N400 component into two consecutive time frames. The activity measured in RFT ROI was found to be significantly affected (F[2,26]=5.93, p-value<0.01) by the MR levels. Post-hoc tests specified that the mean signal significantly varied between the pair MR-C (-0.39 μV) and MR-I (-0.73 μV), with the N400 amplitude of MR-I having a significantly greater (p-value<0.01) negativity than the amplitude of MR-C level.

The second re-occurring ROI is the C/CP area, where we found a significant contrast of mean signal over the C/CP area (F[2,26]=4.83, p-value<0.05) for MR levels. Here, the activity according to the post-hoc tests was significantly higher (p-value<0.05) for MR-C (0.65 μV, p-value<0.01) than for MR-I (0.46 μV) level.

In the window 430 - 570 ms, we found a statistically significant contrast between the two ROIs. First, the activity of MR levels was found to drive the significant differences in RFT ROI (F[2,26]=4.69, p-value<0.05). Post-hoc test specified that the direction of this difference is caused by a pair of MR-I (-0.23 μV) and MR-N+SEARCH (-0.08 μV) level, with the mean amplitude of MR-I having a significantly greater negativity (p-value<0.05).

The second ROI with the statistically significant activity (F[2,26]=5.19, p-value<0.01) across MR levels was identified as the parieto-occipital/occipital (PO/O) ROI. Pairwise post-hoc tests then revealed a significantly different pair of MR-I (0.29 μV) and MR-N+SEARCH level (0.08 μV), with the mean amplitude of MR-I level being significantly (p-value<0.01) greater.

570 - 800 ms At the last time window, containing a sustained activity of P6 component, we did not find any statistically significant findings.

Summary

Firstly, as expected, the found ERP components were kept constant with the findings of Model MR. Regarding the identified ROIs, we found partial spatio-temporal associations with the findings sourcing from Model MR. Following the chronological depiction of the ERP components, we now summarise the major differences and consistency with

Table 6.2: Model MR+IN: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	*ERP*	*ROI*	*F value*	M_{diff}	*p*
90 - 150 ms	N1	RF/RFC	F[2,26]=13.50	$\bar{x}$(MR-I)= -0.02 μV, MR-N+SEARCH)= -0.16μV	*
150 - 270 ms	P2	LTP	F[2,26]=3.97	$\bar{x}$(MR-I)= -1.93 μV, $\bar{x}$(MR-N+SEARCH)= -1.70 μV	*
270 - 430 ms	Onset N400	RFT	F[2,26]=5.93	$\bar{x}$(MR-C)= -0.39 μV, $\bar{x}$(MR-I)= -0.73 μV	**
		C/CP	F[2,26]=4.83	$\bar{x}$(MR-C)= -0.10 μV, $\bar{x}$(MR-I)= 0.04 μV	*
430 - 570 ms	Offset N400	RFT	F[2,26]=4.69	$\bar{x}$(MR-I)= -0.23 μV, $\bar{x}$(MR-N+SEARCH)= -0.08 μV	*
		PO/O	F[2,26]=5.19	$\bar{x}$(MR-I)= 0.29 μV, $\bar{x}$(MR-N+SEARCH)= 0.08 μV	**
570 - 800 ms	P6	-	-	-	-

(ROIs (For spatial reference see Figure 3.2): low - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

Model MR.

The analysis of the brain activity in the time window of 90 - 150 ms evidenced the significant variability in RFC ROI driven by the greatest negativity of N1 amplitude for MR-N+SEARCH. Subsequently, we can induce that MR-N+SEARCH level on its own (i.e., excluding NOSEARCH subset of MR-N) is at the earliest stage of information processing supported by an RF/RFC distribution of activity. However, there is a lowered significant difference in contrast to the MR-I level reported in Model MR earlier. Furthermore, the results suggest a consistency with the Model MR in identifying the ROI (specifically, RFC ROI is a subset of the ROIs found in Model MR). Likewise, the MR-N+SEARCH level exhibits the greatest negativity of N1, as was found for the level MR-N in Model MR. Finally, the spatio-temporal activity associated with the higher activity MR-N+SEARCH suggests that IN emerges very early in the process, given by the time interval for N1 component.

In the second window, the originally identified TP ROI in Model MR now shifted from bilateral to left lateralised with the modality of the signal still indexing the highest amplitude of P2 for MR-I. Again, we are seeing a consistency with the previous finding

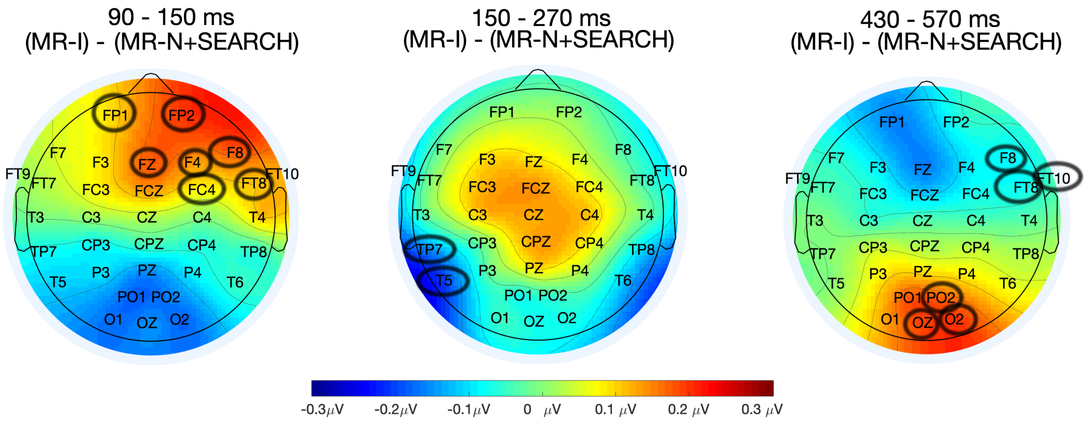


Figure 6.4: Model MR+IN: Topological patterns of significantly different temporal mean activity. Averaged over 14 participants.

and, additionally, the specification of the lateralisation.

At the onset of N400 (270 - 430 ms) for Model MR+IN, we found a resemblance with the findings of significant ROIs from the Model MR. In both models, the depiction of the onset N400 component manifests the activity in RFT ROI with the highest amplitude for MR-I. In addition, the C/CP found a different pairwise contrast between MR-C and MR-I, thus, contradicting the findings of Model MR, where the activity differed between the pair MR-I and MR-N. The present effect was likely caused by the alteration of MR-N level (i.e., subsetting), which now exhibits a lowered amplitude of N400 for MR-N+SEARCH.

The disparity with Model MR is evident at the offset of N400, where Model MR+IN identified two previously unmatched ROIs. The distribution suggests an anterior-posterior pattern, with the amplitude of MR-I being significantly greater than that of MR-N+SEARCH. At last, we lacked to find any significance in the window of P6 and, thus, did not conform to the earlier findings informed by Model MR where the activity differed in RF/RFC and LTP ROIs. The data analysis also did not find any statistically significant quantitative differences between MR-C and MR-N+SEARCH.

Addressing the differences with the Model MR means also detecting any evidence of the data features distinctive for a manifestation of IN, i.e. the proof that the knowledge gap results in IN (see Section 6.2.1. The overview of the discriminative spatio-temporal dynamics suggest a pattern that might be distinctive for MR-N+SEARCH. The pattern follows these markers: 1) MR-N+SEARCH has a lowered amplitude of N1 over RF/RFC ROI; 2) Left lateral shift of the significant activity in TP regions with the amplitude of P2 significantly smaller than that of MR-I; 3) The onset of N400 is not modulated by MR-N+SEARCH; 4) The offset of N400 depicts a sustained activity over RFT and PO/O ROI; 5) MR-N+SEARCH does not alter the later activity (N400, P6).

In summary, we can look at the contrasting results between Model MR and Model MR+IN from the perspective of the main level MR-N, of which MR-N+SEARCH is a subset. A few spatio-temporal differences in the neural activity were identified, contrasting both models. Furthermore, Model MR+IN evidences a pattern dependent on participant interest in knowing, i.e. indication of IN. This outcome can signify our hypothesis from earlier (see Section 6.2.1), asking if the sequence of neural processing associated with stimuli processing can inform us about participants' interest in knowing the answer, i.e. to detect the users' INs. Section 6.5.2 presents the discussion addressing this topic.

6.4.3 Model MR+Conf

We followed the analytical methodology explained in Section 3.5.2. For the investigation addressing our RQ2, we created a mixed linear model containing two independent variables - MR levels and Confidence. As we reported, participants judged their confidence in relation to factual MR levels expressing "knowing", i.e. MR-C and MR-I, regardless of the correctness of their answer. Model MR+Conf inputted 9 participants (see Section 6.3.1). We performed two-way ANOVA over the model, investigating the spatio-temporal effects of independent variables. These can be summarised into two categories: First, main effects of the Confidence levels (H or L), which will answer a question: "Is there a significant spatio-temporal variability in mean signal elicited within participant's high and low confidence judgments?". Second, the analysis of the interaction effects between MR and Confidence seeks to answer the question: "Is there an interaction between MR and Confidence that triggers significant temporal variability of mean signal elicited for specific ROI?".

To note, we did not include the main effects of the MR levels in the model due to the reason that we previously investigated these in Model MR (see 6.4.1). That model used a larger sample of 14 participants, and its outcomes, thus, support a more accurate generalisation of the results.

We now proceed to report on the outcomes of significant spatio-temporal differences in neural activity classified according to MR and Confidence levels.

90 - 150 ms In the earliest stage of information processing, we found a significant main effect of Confidence (F[1,8]=5.0, p-value<0.05) in the left frontal/front-temporal ROI (LF/LFT). The post-hoc tests specified significantly larger negativity of N1 amplitude for low confidence (-0.45 μV) than the amplitude of high confidence (-0.25 μV). In addition to the main effect of Confidence, we found a significant effect of the interaction of MR and Confidence (F[1,1,8]=7.84, p-value=0.01). Pairwise contrasts with Bonferroni corrections revealed the significant difference in MR-I level between low and high confidence. The negativity of the N1 amplitude of MR-I with low confidence (-0.62 μV) was significantly higher (p-value<0.001) than the mean amplitude of MR-I followed by high confidence (-0.16 μV).

150 - 270 ms Statistical tests did not result in any significant outcomes.

270 - 570 ms In the time window spanning N400 component, we found anew a significant main effect of Confidence (F[1,8]=5.15, p-value<0.05) distributed over LF/LFT ROI. Here, the N400 amplitude of high confident responses (-0.35 μV) resulted in a significantly larger mean negativity (p-value<0.05) in contrast to the mean negativity of low confidence (-0.25 μV).

570 - 800 ms In the last stage of information processing, we did not find any spatial activity significantly affected by main or interaction effects.

Summary

The present investigation, supported by the outcomes of the Model MR+Conf, aimed to investigate if different levels of Confidence perception modulate the signal for MR. The early activity differentiated the N1 component over LF/LFT ROI given by the findings of the significant main effects of Confidence, as well as the significant interaction effects between MR-I and Confidence levels. Next, the confidence significantly affected N400 amplitude measured over LF/LFT ROI but seemingly independent of MR effects. MR-C was not affected by Confidence across the entire spatio-temporal space. The main effect of Confidence driving the differences in N1 and N400, respectively, is spatially consistent as the results point to a single LF/LFT ROI location. The results are discussed in Section 6.5.3.

6.5 Analysis of Results

Based on the separate Summaries of Sections 6.4.1, 6.4.2 and 6.4.3. This investigation provides another level of insight into 1) The origins of the users' states of knowing, as informed by the MR mechanism; 2) The spatio-temporal signatures of the realisation INs; and 3) The modality of MR by the perceived confidence judgements. We now discuss the exhibited spatio-temporal differences in neural correlates of information processing in relation to our three RQs (see earlier Section 6.2).

6.5.1 RQ1-1: Relation of ERP to complex cognitive processes

In RQ1, we aimed to bring evidence of the brain activity modulated by the spectrum of perceived MR levels. The Model MR, created for this purpose, investigated the spatio-temporal signatures representing the MR processing and statistically evaluated the neural activity of ERP components between three defined MR levels, MR-C, MR-I and MR-N.

Following the overview of the outcomes in Section 6.4.1, the ERP modulation emerged already before 100 ms poststimulus, exhibiting N1 component with widespread distribution and consistency with the highest activity elicited for MR-N level. The early distinction might index processes of awareness about one's knowledge, demonstrated by N1 component, with a varying degree of activity in several ROIs to be elicited. The lowered amplitude of N1 for both MR-C and MR-I indicates that when people think they know the answer, fewer neural resources are recruited [154] than when they think they do not (MR-N). The early emergence of N1 is believed to be triggered regardless of the task demands [239] and, as such, is used to measure early perceptual processing [240]. The modulations of N1 are contributed to attention [239]. Moreover, the highest neural activity elicited for MR-N level early in the time indicates not only early availability of knowledge cues but also that knowledge cues might predict the absence of knowledge (and potentially lead to an early sign of IN realisation, which we will validate in next Section 6.5.2). Next, larger amplitudes of P2 component with differences between MR-N and MR-N pronounced in the TP region suggest further support for activated processes of attention awareness. P2 component was found to be associated with early low-level sensory processing, triggering early input processing, such as registration and input classification [167]. Higher P2 amplitudes are associated with higher memory strength and are linked to the intentional retrieval of the corresponding information [228]. Significantly higher P2 amplitudes for MR-I in contrast to MR-N might suggest differences in the cognitive effort associated with memory recall [241, 242]. The involved bilateral TP regions, generally considered memory-oriented, imply the engagement of memory search knowledge and deployment of neural resources to link attention and memory. The N1-P2 effect could represent some early recognition of the stimulus with an increased attention [243] to an item with a certain degree of familiarity. It possibly employs the retrieval from contextual memory [244] and recall of past experiences [228], which might interpret the amplified amplitude for MR-I level. Contextual (source) memory stores the background context of the person's past experiences and is, therefore, at the core of episodic memory (see Section 6.1.2). A prior knowledge might facilitate the amplified waveform of MR-I in the TP area and potentially help to integrate words to the context [196].

The subsequent ERP deflection we attributed to the emergence of N400. The immediate sequence of the offset of P2 and the onset of N400 seems to be a sign of a link between early and late processes [196, 228]. P2 emergence confirms the memory availability and, thus, supports the decision by memory search and verification, amplified as N400. Modulation of N400 component is considered to correlate with familiarity, however there is not a consensus on what this component indexes. As Diana et al. [228] suggest, the later ERP effects might index co-occurring memory phenomena or the initiation of memory search and, thus, not necessarily index just one process. The emergence of N400 in connection to MR marks the attempts of deeper memory search [228].

Furthermore, the spatial differences in the mean amplitude of N400 for different pairs of MR levels suggest spatially-dependent support for different MR levels. Specifically, MR-I elicits the highest activity over the RFT region, whilst the CP/P region was found to support MR-N level. A frontal difference between the pair of MR-C and MR-I pronounced in the RFT area signalises memory-driven processes and supports with increased resources (i.e., increased N400 amplitude) false impressions of knowing a correct answer (MR-I). The amplified amplitude of MR-N over the MR-I level with CP/P distribution might indicate the decision of an external search, i.e. a realisation that the internal knowledge abilities are insufficient. This finding is strengthened by the Information Flow component in the Model of IN realisation by Moshfeghi and Pollick [24], which regulates a broader memory search. In case a person realises the unavailability of information internally (i.e., a potential realisation of IN), the attention must be shifted towards external search (see detailed information in Section 2.3.4). Our findings complete this model with the temporal signature of the Information Flow component activity.

The late sustained activity shows the significantly highest positive potentials of P6 over RFC and LTP driven by MR-N level. The pattern of P6 across MR levels indicates that these potentials scale with the success and strength of declarative MR [167]. This pattern is backed by the highest averages for MR-N level, indicating the low success of the memory (information) retrieved, in contrast to reduced amplitudes for MR-C and MR-I. For P6, as the final stage of information processing, more neural resources were, similar to the early processing, found to be recruited for the MR-N level. The late processing might index final verification checks and maintenance of the previously triggered processes of awareness, memory search and the flow of information between significant parts of the brain resulting in conscious response to stimuli, as suggested in [245].

In summary, our results bring evidence of the distinctive ERP signatures of MR processing. On the basis of the spatio-temporal patterns, we distinguished that the significantly greater brain activity is affected by 1) MR-N level, indicating the low success of MR pronounced in components N1, the onset of N400 and the P6 component and 2) MR-I level, indicating successful MR, falsely endorsed as correct that emerged as the highest P2 and the onset of N400. The level MR-C level was found to be present in several pairwise contrasts (N1, N400, P6) and was found to be the one with lower averages. This pattern suggests a relatively lower deployment of resources that support this level, in contrast to a higher cognitive effort found for MR-I and MR-N. Significantly reduced amplitudes for MR-C might indicate immediate memory access to make a quick decision of knowing. The re-occurring contrast between MR-C and MR-I across spatial features might uncover an important distinction between these two. Despite MR-C and MR-I being attributed as factual MR levels (based on participant recognition of the factual answer), they might be supported differently, as data also indicate. This contrast is evident in the N400 that drives the access to memory, where MR-I was significantly higher. Recruitment of more resources might indicate that MR-I utilises a deeper memory search. The source of MR-I can be either a false memory already encoded in the user's memory [27] or a wrong interpretation of the memories and distortion of the memory-retrieved output. In order to prevent the user from false MR outcomes, the focus should, thus, concentrate on N400 component and the proper utilisation of memory search.

Data-Driven Neurocognitive Model with MR component

Our data suggest a transition network of stimuli processing consisting of: 1) *Awareness Process*, produced in early processing demonstrated by early components of N1, P2 and 2) *Memory*, pronounced by evoked components of N400 and P6. This process can be characterised by the early employment of subconscious processes transformed into later conscious processes. Awareness is updated by output from the initialised memory checks, e.g. contextual memory [244]. The pattern of activity signalises an orchestrated activity supporting an adaptive behaviour (the choice of three levels) where the synchronicity between regions, whose resources support different MR levels, is needed to inform other parts of the process in order to make a decision in each level. This proposition is supported by different latencies of relevant ERP components supporting the notion of overlapped cognitive activity (see the earlier discussion of cognitive functions behind the evoked ERP components).

6.5.2 RQ1-2: Detection of IN

The second part of the RQ1 aimed to verify that IN phenomenon is happening prior to the user's explicit decision to search. In other words, can we obtain information from the level depicting the realisation of not knowing (i.e., MR-N level) that would indicate the presence of IN? The MR-N level reflects the unsuccessful MR based on the response "I do not know" the participants provided. The knowledge gap is generally a causality of IN. However, the direct link between information deficiency and the action to satisfy IN does not have to be immediately or at all present (see Section 6.2.1). Using the information related to participants' decisions we obtained during the study, we specified the MR-N level with an added decision of participant, i.e. the want to search (i.e., SEARCH) and, thus, created the level MR-N+SEARCH. We translated this level as an expressed form of participants' INs. The "search" was simplified here, as no actual search was performed as part of the study task, with participants being aware of it.

Keeping the analytical consistency with the Model MR, we obtained the neural signatures of MR-N+SEARCH (Model MR+IN) and contrasted them with the results obtained for Model MR. Topologically, the earliest activity depicting the N1 was concentrated in the F/FC area with right lateralisation, in contrast to Model MR, where the activity was found to have a widespread distribution. The evidence of RF/RFC ROI (being a subset of the activity of Model MR) might be seen as the earliest sign associated with MR-N+SEARCH level (i.e., IN). Next, the shift to left lateralisation of TP ROI was a significant driver of the P2 difference between MR-N+SEARCH and MR-I level, with the lowest averages for MR-N+SEARCH. In summary, the localisation of RF/RFC with an amplified N1 deflection for MR-N+SEARCH and the left lateralisation of P2 activity might, thus, index early dynamic awareness processes responsible for IN realisation.

In the next stage, the processing differed at the offset of N400 component, in contrast to the findings of Model MR where significant differences across MR levels were not confirmed. Here, the reduced amplitudes of MR-N+SEARCH caused significant differences in level MR-I with the discriminative activity distributed in two ROI with the anterior-posterior locality. Next, no differences were found at the latest interval, 570 - 800 ms, not conforming to the findings of Model MR, where we found high P6 amplitude for MR-N level and attributed to final memory checks. The non-conforming findings, with the reduced offset of N400, might indicate that the conscious processes involving memory do not contribute much to detecting MR-N+SEARCH (i.e., IN).

In conclusion, it seems that the signature features of MR-N+SEARCH are concentrated in the early phase of the Awareness process, which implies that IN emerges quite early in the process with employed neural resources to different degrees in the RF/RFC area (N1) and LTP (P2). The second part complements the information process from the engagement of memory. The reduced activity for MR-N+SEARCH in anterior-posterior areas at the offset of N400 might suggest an overlapping activity between N400 and P6, making it difficult to separate the effect.

In conclusion, the results suggest the emergence of IN as an early process indexed by very early ERP components (N1-P2 component). The contrasting early activity was pronounced between the pair MR-N+SEARCH and MR-I. The processes that follow (described in the second half of the information processed) resembled those encountered in the analysis of RQ1-1. However, a larger scale study with more participants is recommended to validate these outcomes.

6.5.3 RQ2: Confidence variability

We hoped to assess the quality of memories, e.g. the strength, using the qualitative judgements of confidence gathered from participants. A measure of the strength of memories could, thus, further subset the brain signal to obtain a more granular insight into data and to investigate the drivers of factual MR. We found that the latency of the early N1 component and late N400 was significantly modulated consistently over LF/LFT ROI by the Confidence condition (main effect of Confidence). It suggests that Confidence is independent of the MR. In addition to the main effects of Confidence, we found the interaction between MR-I and Confidence during the time window depicting the N1 component. That is the only significant interaction our data supports and we can, thus, conclude that the confidence levels vary with MR-I level, which hints at more in-depth processing.

The pattern of activity distributed over F/FT ROI depicting N400 and the largest frontal negative deflection of N400 for high confident responses shows a parallel with the findings of frontal N400 [246] evoked during the MR with subjective confidence judgments. The literature usually relates the frontal negative deflection, peaking between 300 - 500 ms, to the effect of familiarity (i.e., no specifics are retrieved) or recollection (i.e. specific information is retrieved). Our results could support both as our study did not subjectively distinguish between these two.

In summary, confidence awareness seems to emerge early. In the early stages of information processing, low confidence draws more resources in LF/LFT ROI, mainly when the perception of knowing is MR-I. We link this finding to our earlier behavioural data analysis (see 4.3.2), where we found that the increase of MR-I responses strongly correlated with low confidence. This finding suggests that early amplified activity associated with low grades of confidence might index false memory. Later stages saw the opposite pattern, with high confidence eliciting greater activation but in an undifferentiated manner (regardless of MR levels). However, due to a low sample size of nine participants, the results might be overestimated, and we, with certainty, cannot make any further conclusions in this area.

6.6 Conclusions

We conclude this chapter by summarising the significant outcomes of our study and their contributions toward the expansions of IR theory and practice.

The current chapter investigated the neural correlates associated with three distinctive MR levels triggered by a general knowledge question the participants were presented with. Knowledge is naturally linked to the functioning of memory. Derived from this notion, the realisation of insufficient knowledge is coupled with retrieving this knowledge from memory. MR is, thus, an essential function that manipulates the user's internal information and provides memory cues to determine whether the user has a knowledge gap or not. The knowledge gap is generally seen as a trigger of IN realisation. We therefore ask, does the brain activity related to the gap in knowledge contain the information we could link to an IN, i.e. are we able to detect the IN based on EEG data alone?

In addition to an expressed gap in knowledge, can the potential issue with memories be uncovered using the factual MR levels? The quality of memory is changeable over time which causes different strengths of memories and knowledge. We used the information related to participants' confidence judgments over two factual MR levels to observe any indication suggesting a distinctive interaction pattern.

Our cohesive analytical framework revealed distinct significant time intervals and brain regions driven by the outcomes of MR. We formally assessed the overall pattern of electrical activity split into time windows. Our findings differentiated between ERP components elicited by the activity of MR levels and provided us with evidence of orchestrated activity between the cognitive functions. This outcome led us to construct a data-driven MR model (see Section 6.5.1) with two components: Awareness (N1 and P2 as evoked components) and Memory retrieval (supplied by evoked N400 and P6). The construction of this model helped us to determine the overlapping activity and link the cognitive processes activated during MR.

During the investigation, we specifically targeted the brain activity of MR-N, which reflects the participants' expression of a knowledge gap. As a result, MR-N level was discovered to have a distinctive neural signature that varied over multiple time windows and across multiple ROIs from the rest of the MR levels (see Section 6.4.1 and the related Discussion in Section 6.5.1). The findings suggest that we can detect knowledge gaps based on how the brain correlates with the stimuli. We then took a subset of MR-N level using the information related to the participant decision to satisfy their gap (i.e., MR-N+SEARCH) and created a contrasting model. Specifying the spatio-temporal patterns associated with MR-N+SEARCH plausibly affirms the hypothesis that users' perception of IN is integrated inside the neural processing for MR-N. Regarding the investigation of the modality of MR by confidence, we did not find strong evidence suggesting the interaction of MR and confidence. The confidence was only found to modulate the deflection of N1 evoked for level MR-I. To some extent, the findings of the early high levels of neural activity (manifested as N1 component) associated with low confidence might index (and could potentially predict) false memory processing (MR-I).

We realise the limitation of our study posed by a reduced number of participants and, therefore, strongly recommend expanding the study with a larger sample size to validate these results. Due to our unbalanced data set, we had to exclude several participants from the investigations and reduced the generalisation of our findings. More subjects will help to generalise our suggested model of MR (see Section 6.5.2) and would also increase the prediction power employed on top of data dimensions (time and ROI).

6.6.1 Contributions to IR (RQ3)

One of the main points of theoretical and practical IR research is to understand why people engage in search and what the triggers of INs are. We approached this quest from a cognitive viewpoint as the realisation of a knowledge gap, generally seen as a preamble to IN. Moreover, with the use of EEG data, we aimed to explore the objective brain manifestations of these triggers, i.e. to obtain a piece of evidence that the brain alone can inform us about the user having a gap. It is an essential study for any IR system built on a BCI scheme or with a pro-active element (i.e., anticipating INs)

[25, 26]. The distinctive neural signatures attributed to MR-N, significantly different in contrast to remaining levels, support our hypothesis of the ability of EEG to capture the objective (and evaluated as significant) measures to determine the knowledge gap. In addition, we specified that the emergence of MR-N is happening early in the process due to amplified deflections of N1 attributed to MR-N. Expanding on the MR-N level with the inclusion of participants' decision of SEARCH, we specified the differences within the range of IN to detect from brain data. The contrasting results specified the ROIs signature of IN where the neural activity differs. Information Need is, thus, detectable from brain data. We believe our work constitutes an essential step towards enhancing the current knowledge of the concept of IN from the point of underlying cognitive processes determined by the evidence from fine-grained temporal data. Understanding the neural mechanisms involved in constituting the awareness before the user consciously acknowledges their INs is a much-needed input for pro-active systems.

Furthermore, pairwise contrasts between MR levels often indexed the false memory, MR-I level. MR-I level was not our primary objective. However, as already behavioural data indicated (see Chapter 4) and now its occurrence in a pairwise test of EEG, with MR-C and MR-N, its distinctive function should not be neglected. Notably, the amplified frontal signal N400 for MR-I level, significantly different from MR-C, signals a potential issue with the controlled (later) memory search processes. This knowledge can prove to be beneficial for IR research since the overarching aim of IR is the efficacy of retrieving relevant information. In the context of ubiquitous information, the data dimension of veracity is becoming all the more critical [247]. Data veracity affects the data interpretation, which ultimately affects the remembered information. IR could intervene in two ways: 1) to prevent storing incorrect data and employ regular data checks, and 2) to affect the process of MR to prevent misattribution of knowledge or rectify the knowledge. These are yet very hypothetical questions which require more research. Our work supports the holistic view of IR with knowledge generation and regeneration of (misattributed) knowledge, which we proved is highly sensitive to MR. In addition to EEG data, the behavioural data (see Chapter 4) informed us that, on average, 25% of all responses each participant responded were of MR-I level (the second most frequent answer type). Hence, we cannot rule out the significance of this level on its own. Focused research is needed to enquire further information about MR-I to define a new relationship between IR and MR-I. So far, we have proved that the change between a selection of the correct (MR-C) and incorrect answer (MR-I) is conscious and memory-dependent, i.e. it is the aim of the later phases of MR.

Another exploration would be beneficial to gather more evidence that would specify the link between MR-I and MR-N, recognised in several pairwise contrasts (e.g. in the Model MR+IN, the MR-N+SEARCH only significantly varied relative to MR-I level). The important question arises, as the MR-I is seemingly a conscious decision, why do people choose one alternative over the other, e.g. MR-I over MR-N? According to the study's design, the participants were asked to choose the correct answer to the question or acknowledge the state of not knowing. What is the explanation for the choice of MR-I, then? Participants did not know they were wrong or guessed with low confidence (according to Chapter 4, MR-I responses are positively correlated with low confidence). What is the trade-off between the choices, e.g. MR-I and MR-N, and how it can impact the user's behaviours in situations which require assessing their knowledge; these are the questions for further exploration. We hoped the levels of confidence we gathered might bring some insight into the modality of MR, but the evidence is not convincing to make any conclusions.

6.7 Chapter Summary

This chapter addresses our second Research Goal and builds on the initial findings from behavioural data (see Chapter 4). In particular, the chapter provides:

- Review of related IS&R literature with identification of memory retrieval as key cognitive processes behind the realisation of a state of knowledge and its role in the context of users' IN that requires further investigation.

- Presentation of the contextual information relevant to the present study, such as memory taxonomy, false memory or certainty and confidence.

- Formulation of the Research Questions.
- Explanation of the methodological aspects of the study associated with the current chapter.
- Specifying three research models, where each addresses a respective objective of the present investigation.
- Presentation of the significant results based on the investigated modality of spatio-temporal patterns of activity associated with the key cognitive processes.
- Review of the major findings related to our Research Questions and discussion of their potential implications from both user and IR system perspectives.

Chapter 7

EEG Study of the Interaction Between Metamemory and Memory Retrieval

This Chapter presents the investigation of the EEG data based on the interaction of the two primary mechanisms that have been investigated separately as part of the previous Chapters 5 and 6, i.e. metamemory and memory retrieval. It addresses the last (#4) of the Research Goals (see Section 2.4).

We built this investigation on the outcomes obtained by the analyses of behavioural data (see Section 4.3.2). There we identified significant associations and interactions between these two phenomenons. Furthermore, it provided evidence about the patterns of the accuracy of the prior metamnemonic judgments concerning participants' performance in the Recognition phase of the study (see Section 3.2 that explains the paradigm behind the study). Referring to EEG data associated with these two factors, we now investigate if the interactions between the metamnemonic state of knowing in relation to MR outcome are manifested in the EEG data.

7.1 Background

The RJR paradigm (see Chapter 3 Section 3.2) was implemented in our study to methodologically evaluate the user's state of knowledge driven by the subjective responses on the spectrum of metamemory and MR. A contrast of these pre- and post-retrieval mechanisms is part of the metacognitive research [138, 168] with RJR paradigm as one of the applied methods to gather the evidence [166].

The Recall part of the paradigm assesses participants' metamnemonic or epistemic feelings driven by the prospective nature of these feelings (i.e., We think we recall the answer later). Metacognitive judgments are instrumental for controlling the cognitive processing of stimuli [214]. Whereas the Recognition part is built on a function of mnemonic cues to aid the factual MR [208]. The MR outcomes inform how well the user can recognise the correct answer from a set of these cues, including distractors (related but incorrect answer choices). For this reason, the product of this recognition is often termed "cued recall" to indicate the nature of the test [248].

RJR as a sequence can, thus, provide insight into the relationship between prior epistemic feelings (predictions) and the post-MR performance (the actual retrieval). Mnemonic cue effectiveness is a relevant factor that impacts the recognition of the correct answer, but retrospectively affects the epistemic feelings as well [248]. The underlying properties of cues drive this effectiveness, notably, the cue familiarity [249].

Analogically, stimuli familiarity (i.e., question cue) was one of the aspects we discussed during the resolution of spatio-temporal patterns of FOK (see Section 5.5.1) supported by the research suggesting that stimuli familiarity produces higher FOKs [137]. There seems to be a consensus highlighting interconnection and parallel operations between metacognitive processes, memory search and retrieval. The initial metamnemonic judgments are issued rapidly and determined by the quality and quantity of incoming stimuli information (question cue), as well as the information activated from the memory search itself [219, 249].

We now move back to the role of mnemonic cues. In our study, the participants' responses were driven by the set of metamnemonic cues containing the factual retrieval answers corresponding to the question (stimulus). The cues can trigger the correct recognition (MR-C), e.g. a sudden remembering, even though their initial recall failed (FOK or NKNOW). The metamnemonic judgments that put into perspective the user's state of knowledge are, thus, dynamic and alter with the new information the user is exhibited to [249]. Our behavioural data support this observation (see Table 4.1). For instance, participants in their initial FOK i) attributed an incorrect cue as a correct one in 30% of these cases and ii) in 10% of these cases they did not know, i.e. their FOK failed them. Behaviourally, MR outcome evaluates the performance of the prior metamnemonic prediction, e.g. What are the patterns of MR response associated with FOK? In this sense, we approach the current investigation. Having the EEG time course of processes mediating three metacognitive judgements, to what extent do the associated MR outcomes change this course of activity? Each pair of the metamnemonic judgment (Meta levels) and MR (MR levels), thus, contains the information indicating their association and interactivity (see Results in Section 4.3.2). Based on this relationship, can our EEG data confirm that different pairs of Meta and MR trigger different neurocognitive manifestations as a quantitative indication of how accurate the participant Meta prediction was, i.e. user's initial state of knowledge?

7.2 Research Questions

Our objective is to newly categorise and evaluate the collected EEG data for the presence of further neurocognitive signatures. We aim to obtain evidence that the brain signal is informative of the interaction between Meta and MR levels and answer the Research Question **(RQ)**: Is there a significant modulation of the Meta level-dependent brain activity depending on the subsequent MR outcome?

We seek to explore the relationship between Meta and MR manifest and if there are significant differences in neural correlates associated with the compound of these two factors. The evidence would, furthermore, serve as a sign of detectability and possibly predictability of the accuracy of Meta levels based on EEG data alone.

As we will report later on (see Section 7.3.1), we did not investigate the whole spectrum of combinations between Meta and MR levels for several reasons. We only concentrated on significant interactions, as informed by the behavioural investigations in Chapter 4 Section 4.3.2.

7.3 Experimental Set-Up

The current chapter concerns the neurophysiological modulations caused by the interaction between two factors: 1) Meta levels and 2) MR levels, each with three different levels (see Section 3.2.5) associated with the outcomes of the designated user study (see Section 3.3.1). The study collected data from 24 participants. The generated responses pertain to the factorial 2x3 design, i.e. each response is encoded into one of the three levels for each of the two factors.

7.3.1 Sample Size and Data preparation

Referring to the distribution of the responses in Table 4.1, we concluded that our data are not evenly distributed across the levels from the factorial hierarchy. Some interactions between Meta and MR occurred more frequently than others. For instance, the users in their KNOW states were accurate in the majority of cases (over 82%) since their MR state followed the correct recognition, MR-C. On the other hand, the lowest proportion of prior KNOW states (only 1%) was followed by the acknowledgement of not-knowing, MR-N. Such findings help to uncover the strong relationships and significant patterns of associations. However, on the other side, they also introduce another level of data manipulation to fit the data quality requirements given by the analytical framework.

As was mentioned in previous chapters, sufficient level-dependent data samples are necessary to create reliable individual ERP averages (see more in Section 3.5.3). Low data samples cause ERP waveforms to be amplified and noisy in contrast to ERP amplitudes that were generated based on a high number of trials. These might likely cause Type I error, i.e. to report that our findings are significant, but in reality, they have occurred by chance due to different sample sizes.

The outcome of the different distributions of MR levels across Meta levels is that we cannot run full within-participants analyses with a 2x3 factorial design. Having encountered a similar scenario during the preparation of Model MR+IN in the previous chapter (see Section 6.2.1), which resulted in the exclusion of NOSEARCH, we applied a similar strategy in the current scenario. The data preparation for the ERP analyses as the core of our analytical framework started with splitting the analyses into three categories, each observing a separate Meta level. For each Meta level, we explored only the significant interactions, as informed by the significant interactions between Meta and MR levels (see Section 4.3.2). Significant interactions represent the most common associations between pairs of Meta and MR and, importantly, inform the accuracy patterns of each Meta level, e.g. strong pair of KNOW+MR-C.

Following the same procedure and criteria as in the previous investigations (Chapters 5 and 6), the participants with the lowest number of data records were categorised as outliers and excluded.

The results of the spatio-temporal ERP analyses of significant associations between the MR levels and the prior baseline signal of i) Meta level KNOW (KNOW+MR-C) is reported in Section 7.4.1, ii) Meta level FOK (FOK+MR) is reported in Section 7.4.1 and at last, iii) Meta level NKNOW (NKNOW+MR) is reported in Section 7.4.1.

Second, moving beyond the within-design that often causes data samples to be excluded, we supply the data to an experimental framework exploring the clusters of similar data activity, regardless of the unbalances.

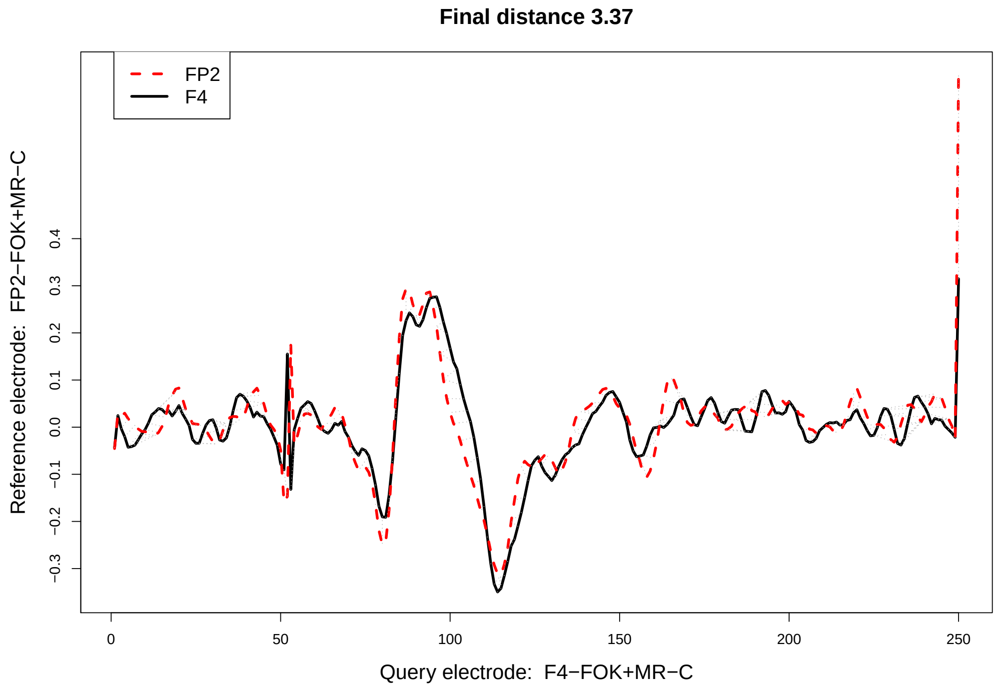
7.3.2 Methods of Data Analysis

The first part of the analysis was consistent with the earlier investigations as part of Chapters 5 - 6 following the ERP analytical framework concerning the spatio-temporal dynamics of each investigated variable (described in Section 3.5.2). The second part, the clustering, was already briefly presented in Section 3.5.5, which we will now explain.

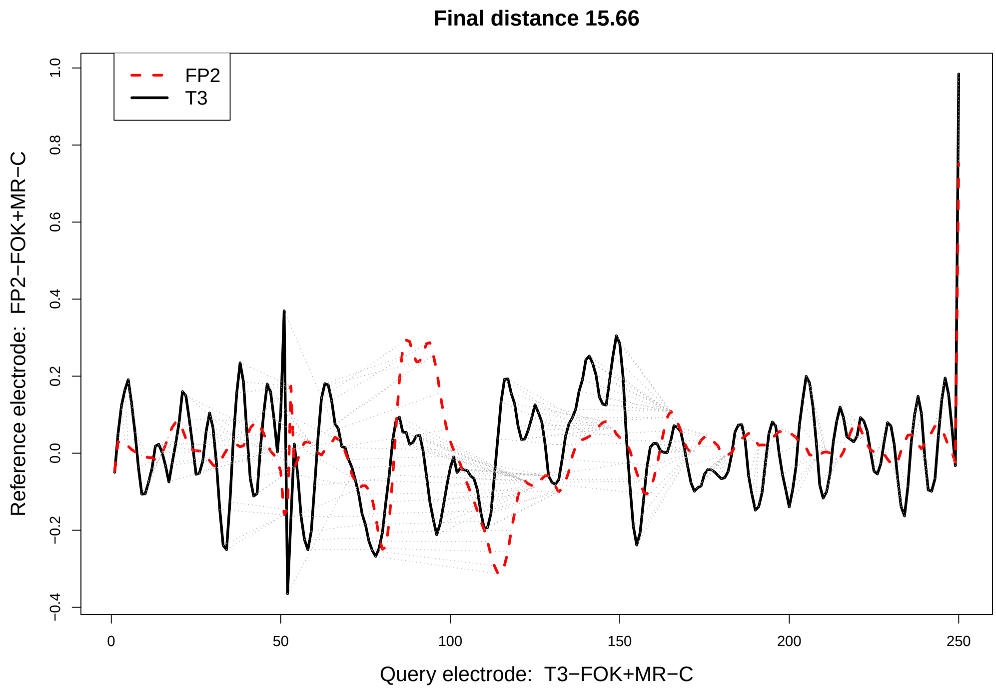
Clustering Analysis

We will provide another perspective on data using a combination of hierarchical clustering and the Derivative Dynamic Time Warping Algorithm (dDTW) [202]. These will generate the similarity measures between the multiple measurements (i.e., electrodes time series) that describe the activity underlying each factor in our data. The purpose of this analysis is to group electrodes with similar patterns as given by DTW cross-distance matrix. It is unknown to us that dDTW was applied to EEG data. The character of the method is suitable for EEG for several reasons: 1) EEG data is a time series type of data, 2) multiple electrode measurements provide a spatial source of these time series, and 3) local differences in latencies as well as the magnitude of the amplitudes (ERP components) present on the time series. The shape of our data is suitable for using DTW to align for minor local differences, e.g. shifted onset of a local activation, different peak heights (matter of scaling), and different longitude of a peak. Calculating pairwise distances between electrodes will be utilised to map the signal of one time series (of one electrode) to any other time series more precisely. Standard Euclidean distance works under precise 1:1 mapping, but using DTW, one point of one time series can be mapped to multiple points of another series. Distance matrix captures a similarity between each two data sources, i.e. electrode measurements, in terms of their distance. The distance matrix is a metric of similarity. The more similar the underlying pattern is, the smaller the distance we get. We show the outcome on two pairwise contrasts generated for the FOK condition.

Regarding the data pre-processing, two steps have to be considered. First, there is the time length alignment which applies the methods of truncation or stretching to contrast time series that differ in the number of time points. This method was not applicable in our scenario as each ER waveform contained the same number of time data points. The second area of pre-processing relates to data standardising (e.g., normalisation o scaling). It is recommended to use in order to obtain an internally consistent and comparable signal with the same scale of the measurement values. The original unstandardised data are, for instance, displayed in Figures 5.1a - 5.2c, where ERP waveforms across different spatial topologies have a different range of values.



(a) Electrodes with high spatial proximity (DTW distance 3.37).



(b) Electrodes farther apart (DTW distance 15.66).

Figure 7.1: Point-by-point comparison and mapping of two electrode vectors generated for the interaction FOK+MR-C.

This was not an issue for ERP analyses done in the previous chapters, as we always compared the measurements for the same electrode (and ROI) vector generated for different factors (e.g., Meta levels). The normalised values help to observe the similarity and dissimilarity beyond the actual values. We applied z-normalization of the electrode vector (with components being the time series measurements), which centres the vector of each electrode by the corresponding centre parameter. As the parameter, we used the descriptive statistics - mean of the electrode vector and the standard deviation. Each vector component had the corresponding mean value subtracted from it and divided by the corresponding standard deviation. The result is a z-score telling us where the actual (measured) value is in relation to the centre (mean) of the time series (negative z-score means the actual value is below the overall mean and positive z-score).

Next, we calculate the local derivatives of each time series. This step reflects the "d" of dDTW, developed as an extension of the original DTW mechanism. Using the fact that each time series is a vector of chronological measurements, we converted it to another vector where each point now refers to the estimates of the local derivatives. The local derivatives contain the information about the change between two adjacent time points and, thus, keeps the input information dynamic.

These data vectors are then used as the input to generate the DTW matrix, i.e. to calculate the similarity measures between the local derivative of each pair of two electrodes. As we noted, the mapping follows the unique approach where one point of the vector can be mapped onto several points, e.g. to account for local differences in the longitude of an amplitude. The more similar the underlying vector of local derivatives is, the smaller the distance we obtain (see Figures 7.1a and 7.1b for references.

Such a matrix is then inputted to the hierarchical algorithm to construct the clusters of electrodes that share a similar activity pattern. Hierarchical clustering is a suitable method since we are aware that the electrodes are spatially associated with the brain areas and the underlying cognitive operations and, thus, create spatial clusters (ROIs) on their own.

This method can be applied retrospectively to previous investigations to contrast two levels of the same factor, e.g. FOK and KNOW level. Additionally, it can be applied as part of data processing to contrast the electrodes of the same level (e.g., FOK) in order to quickly assess the entire timeline of activity, identify the temporal shifts (i.e., oscillations of the activity) or the clusters of significant ROI, so, to complement the standardised methods described in Sections 3.5.2 and 3.5.2. For the purpose of the present chapter, we demonstrate its capability using the measurements combined from two factors.

7.4 Results

We kept consistency with the previous studies by applying the analytical framework (ERP analysis) used in previous chapters. Second, we present the complementary outcomes following the clustering analysis.

7.4.1 ERP Analysis

KNOW + MR

Table 7.1: KNOW vs KNOW+MR-C: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	*ERP*	*ROI*	*F value*	M_{diff}	*p-value*
90 - 150 ms	N1	RCP/RP	F[1,21]=10.25	$\bar{x}$(KNOW)= 0.13 μV, $\bar{x}$(KNOW+MR-C)= -0.08 μV	**
		LF/LFT	F[1,21]=11.73	$\bar{x}$(KNOW)= -0.34 μV, $\bar{x}$(KNOW+MR-C)= -0.13 μV	**
150 - 270 ms	P2	-	-	-	-
270 - 570 ms	N400	-	-	-	-
570 - 800 ms	P6	LFT/LT	F[1,21]=4.74	$\bar{x}$(KNOW)= 0.09 μV, $\bar{x}$(KNOW+MR-C)= 0.01 μV	*
		RTP/RP	F[1,21]=8.70	$\bar{x}$(KNOW)= -0.24 μV, $\bar{x}$(KNOW+MR-C)= -0.15 μV	**

(ROIs (For spatial reference see Figure 3.2): L - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

First, we explored spatio-temporal differences in neurophysiological activity corresponding to 1) the single Meta level KNOW and 2) Meta level KNOW interacting with MR-C, identified as the most frequent MR response that followed the prior KNOW level. The significant pairwise differences are presented in Table 7.1. Data were averaged over 22 participants. The early activity during the window 90 - 150 ms already evidenced the significant differences between KNOW and KNOW+MR-C pronounced in RCP/RP ROI and LF/LFT ROI. In both ROIs, the N1 amplitude exhibited significantly greater means for KNOW level. This finding indicates that the early activity of N1 KNOW is significantly modulated by MR-C response. Specifically, KNOW+MR-C exhibits reduced amplitudes in contrast to the KNOW level. During the occurrence of P2 and N400 components, the neural correlates were not confirmed by the statistical analysis to be significantly affected by MR-C responses. Likewise, the late positivity of P6 brings the modulation of activity as was found for the N1 window. In both identified regions, LFT/LT and RTP/RP, the mean amplitudes of KNOW were significantly larger, particularly the positivity of P6 in LFT/LT and the negativity in RTP/RP. In both significant time windows, we see bilateral activation. Based on the findings, we can conclude that the accuracy of KNOW level could be detected from the brain data, as the MR-C responses are significantly reduced in N1 and P6 amplitudes with a bilateral and widespread distribution.

FOK + MR

We continued exploring Meta level FOK in relation to the MR states MR-C and MR-I, as the two most frequent MR outcomes following FOK level. ERP analysis was conducted with data from 20 participants. Table 7.2, summarising the significant findings from the pairwise contrasts, indicates that the early activity described by the N1-P2 complex is not affected by different MR outcomes. For N400 we see the anterior-posterior distribution of activity significantly differing between the MR-C and MR-I levels. In both regions, the mean amplitude of N400 is greater for MR-I level. In the context of the conceptual models constructed in previous chapters, the late activity supports a more effortful, controlled and memory-oriented process. The present find-

Table 7.2: FOK vs FOK+MR-C vs FOK+MR-I: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	*ERP*	*ROI*	*F value*	M_{diff}	*p-value*
90 - 150 ms	N1	-	-	-	-
150 - 270 ms ms	P2	-	-	-	-
270 - 570 ms	N400	RF/RFT	F[2,38]=7.76	$\bar{x}$(FOK+MR-C)= -0.27 μV, $\bar{x}$(FOK+MR-I)= -0.42 μV	**
		PO/O	F[2,38]=6.02	$\bar{x}$(FOK+MR-C)= 0.58 μV, $\bar{x}$(FOK+MR-I)= 0.72 μV	**
570 - 800 ms	P6	RFT	F[2,38]=6.68	$\bar{x}$(FOK+MR-C)= 0.07 μV, $\bar{x}$(FOK+MR-I)= 0.19 μV	**

(ROIs (For spatial reference see Figure 3.2): L - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

ing might suggest that the associated signal is significantly larger when FOK triggers an incorrect response (MR-I). Moreover, differing activity might indicate modulation driven by the strength of memories as a factor of the strength of FOK [206]. Higher levels indicate weak memories, possibly Illusion of Knowing effect [174], which gives rise to MR-I level. This outcome supports the conclusion we reached in the Chapter 6, that MR-I is conscious and memory-dependent. The last window completes the present interpretation and the activity in the RFT constant. This outcome is particularly relevant as it suggests that the accuracy of FOK can be predicted based on EEG data alone.

NKNOW + MR

The third investigation concerns the remaining Meta level, NKNOW, whose signal was evaluated concerning MR-N level. MR-N preceded by NKNOW represents the user's accuracy of their initial state of (not) knowing (i.e., "We think we do not know the answer" followed by the confirmation "We know we do not know the answer"). ERP analysis was conducted with data from 14 participants. The significant differences

Table 7.3: NKNOW vs NKNOW+MR-N: Significant differences in ERP amplitudes and the pairwise contrasts (p-value adjusted using Bonferroni corrections <0.05 *, <0.01 **, <0.001 ***)

Time Window	*ERP*	*ROI*	*F value*	M_{diff}	*p-value*
90 - 150 ms	N1	-	-	-	-
150 - 270 ms	P2	O	F[1,13]=5.78	$\bar{x}$(NKNOW)= -0.99 μV, $\bar{x}$(NKNOW+MR-N)= -0.78 μV	*
270 - 570 ms	N400	RFC/RC	F[1,13]=7.51	$\bar{x}$(NKNOW)= -0.44 μV, $\bar{x}$(NKNOW+MR-N)= -0.53 μV	*
		LFT	F[1,13]=6.45	$\bar{x}$(NKNOW)= 0.01 μV, $\bar{x}$(NKNOW+MR-N)= 0.10 μV	*
		LTP	F[1,13]=5.62	$\bar{x}$(NKNOW)= 0.77 μV, $\bar{x}$(NKNOW+MR-N)= 0.92 μV	*
570 - 800 ms ms	P6	-	-	-	-

(ROIs (For spatial reference see Figure 3.2): L - Left, R - Right, F - Frontal, C - Central, T - Temporal, P - Parietal, O - Occipital.)

were triggered on the timeline depicting the elicited P2 and N400 components, with the latter supported by highly distributed spatial differences. For P2, the amplitude of MR-N is significantly reduced (i.e., smaller) in contrast to the mean amplitude of the NKNOW level. Referring back to Discussion in Chapter 5, P2 might indicate an attempt to initiate memory recollection using a criterion of familiarity. In the N400 window, the pairwise contrasts resulted in reversed results, with the N400 amplitude of MR-N being significantly larger across several ROIs. This outcome suggests that having access to memory allows for a more accurate assessment of memory to match the initial predictions, i.e., "What we do not think we know (NKNOW) is true (MR-N)".

7.4.2 Clustering Analysis of a selected Meta level

We now demonstrate the results of applying the clustering framework (described in Section 7.3.2) on top of data sourcing from two interactions involving the prior FOK levels: MR-C and MR-I. Following the procedure, we obtained the hierarchy of clusters that is presented in Figure 7.2. As the space of electrode vectors was the same in both interactions, we indexed each electrode name with a suffix to accurately indicate the associations, such as FOK+MR-C or FOK+MR-I. The pairwise DTW distance matrix was used as the input to the clustering algorithm. The final cluster composition observes the proximity with the anatomical properties of these electrodes, i.e. their physical location of the scalp (refer to Figure 3.2 for regional assignment of the electrodes). For instance, we see that Cluster #1 contains electrodes in the proximity of the bilateral frontal/front-central brain area. Similar outcomes are observable for the remaining clusters, e.g. Cluster #4 contains electrodes from the posterior area. This evaluation follows the notion that electrodes in proximity behave similarly, i.e. they evoke similar activity patterns. Another effect of how the electrodes were grouped is the interaction dependency. The lower hierarchies of clusters contain electrodes from the same interaction. Therefore, the distance matrix for these electrodes is the lowest. Afterwards, they are grouped with the same electrodes from the opposite condition as their patterns express a high similarity. For example, cluster #6, with a lower density of members, contains the vectors measured for FOK+MR-I level depicting the bilateral front-temporal/temporal as well as centro-parietal/parietal electrodes. Measurements from these regions generally contain ERP deflections reduced in scale and a higher frequency of smaller local oscillations.

The complementary Figure 7.3 shows the temporal profiles of electrodes assigned to these clusters. Each column represents the data point from the time stimuli onset timeline. Each row is a plot of z-scores of the normalised electrode vector (see 7.3.2). Colour encodes the z-scores accordingly: colours towards red encode points with values higher than the vector mean, and colours towards green values below the mean). The temporal illustration of the progress of z-scores highlights the time windows with high or low values driven by the occurrence of a larger deflection of the activity, likely corresponding to the occurrence of large ERP components such as N1, P2 and N400. These are pronounced for Clusters #1,2,4 with a high density of members.

The activity in the remaining low-dense clusters shows an apparent variability not only in contrast to the higher-dense clusters but also in contrast to internal variability. These specific non-conforming patterns point out specific sources of such activity.

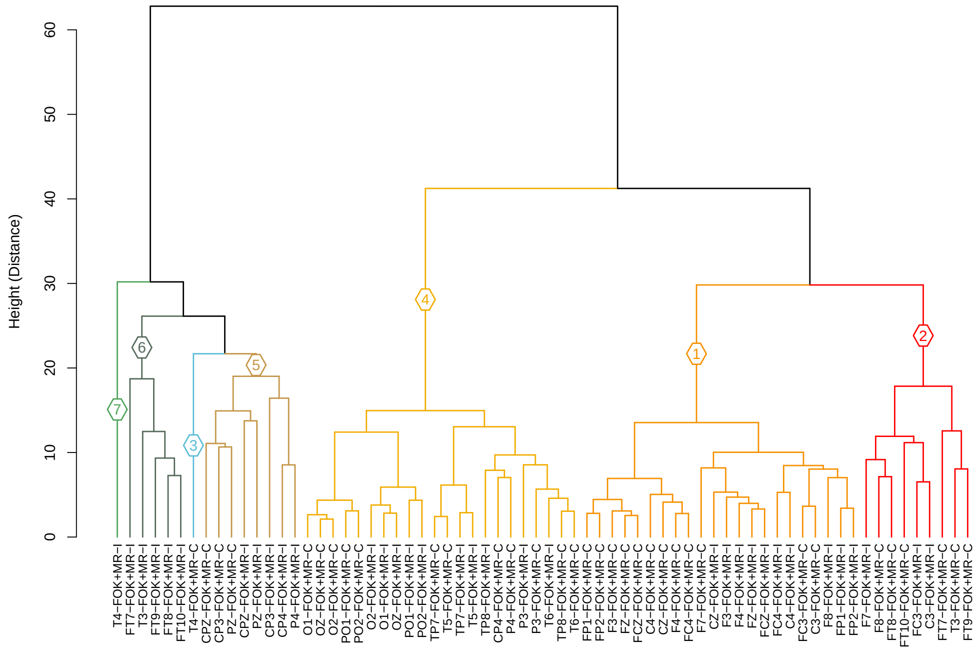


Figure 7.2: The final hierarchy of clusters of electrodes given by the comparison of two factors: FOK+MR-C and FOK+MR-I. The y-axis is the distance measure between the members of the clusters. First, the algorithms clusters pairs of electrodes with the lowest distances (between 0 - 10) and then continue upwards.

Front-temporal/temporal and centro-parietal/parietal electrodes are often described with relatively low ranges elicited signal and frequent small oscillations that cause difficulty in obtaining and interpreting the significant ERP deflections. Data normalisation (z-scores) reduces the uncertainty in interpreting this activity. Referring back to Figure 7.3, we see that the activity manifests differently, e.g. variable length and latency of deflections or constancy of the activity.

To address the interaction modulations between the two pairs of FOK, the activity of both follows the same pattern. There are only smaller dissimilarities, but these are driven in the areas with higher variability. For example, clusters #2 and #6 are separate clusters of FT/T activity for most of FOK+MR-C and FOK+MR-I, respectively (see the complete list of members in Figure 7.2).

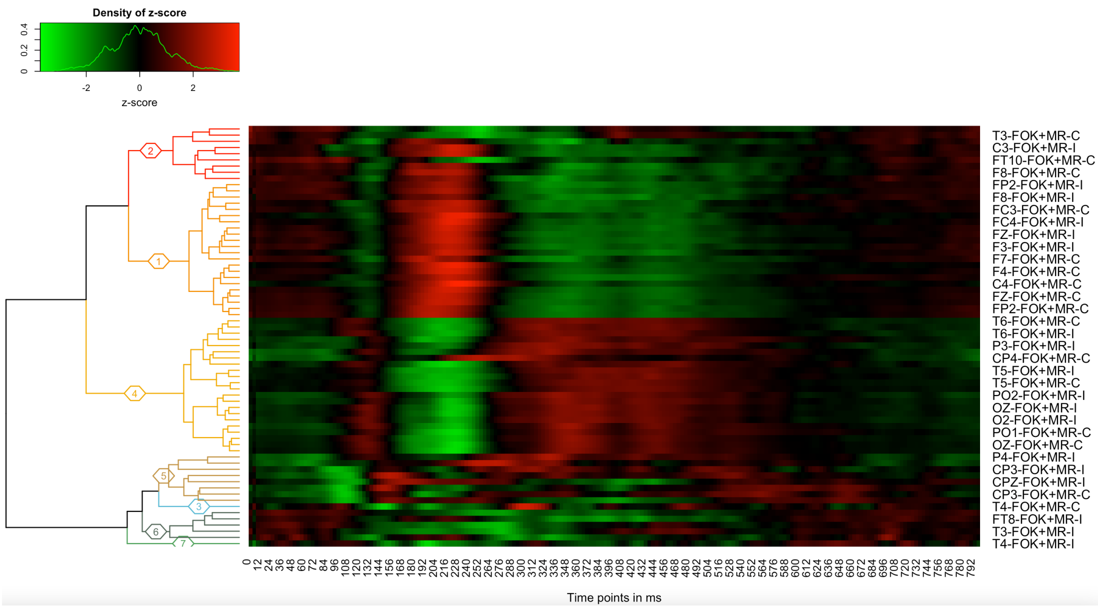


Figure 7.3: The temporal profile of each electrode assigned in a particular cluster.

7.5 Conclusions

We conclude this chapter by summarising the major outcomes of our study and their informativeness for IR. These results complement the earlier findings from Chapter 4. We used a reference model constructed in the previous chapter Section 6.5.1 to explain the temporal variability of the signal.

The ERP analysis of the interactions between Meta levels and MR levels revealed patterns of spatio-temporal differences unique for each corresponding Meta level. MR-C outcomes that followed the KNOW level not only reflect the participants' accuracy with respect to the KNOW level but were found to modulate the early rapid correlates of information processing of KNOW. For the FOK investigation, the evidence showed significant differences in the segment related to participants' conscious, controlled processing. It confirmed thus the significant modulation of FOK depending on the MR outcome. As a result of the NKNOW level investigation, the MR-N level affected the signal of elicited NKNOW level at the intersection of the automatic and controlled processing, indicating memory access. These outcomes support our conclusion that the interactions are manifested using the information of brain correlates of metamnemonic and mnemonic levels.

Both cases of interactions KNOW+MR-C and KNOW+MR-N represent the user's accuracy of their prior metamnemonic predictions (prospective user's state of knowledge). The neurocognitive manifestations show the accuracy being predictable from the brain data alone. Regarding FOK, which is driven by the user's underlying uncertainty and can result in positive or negative prospects, our results suggest that the post-MR outcomes cause significant modulations of FOK. Pairwise contrast of MR-C and MR-I revealed significantly larger means of N400 and P6 amplitudes for MR-I level. This outcome translates as the Illusion of Knowing phenomenon, which we discussed in Chapter 4 Section 4.5, and its association with delayed INs. FOK is a state in which the user feels positively about recalling the information at a later time, depending on a relevant cue. If FOK fails the user and the user cannot recall the information in question, the effect is known as Illusion of Knowing [174]. As the study applied cue-based MR, the emergence of the failed FOK could be attributed to the cue. In the context of our study, this argument is supported only by the type of the study. However, we do not have enough user data to corroborate the relationships between cues and the actual evoked MR outcomes, for instance, whether the correct mnemonic cue caused the correct retrieval (MR-C). As we presented in 4, we judged how the presentation of mnemonic cues altered participants' initial metacognitive perceptions. With respect to mnemonic cues and MR, we, presently, cannot construct a baseline model that we would use to compare the present findings with and statistically verify the effect of the mnemonic cues as the independent factor in the user-based data. For instance, such a baseline model can be founded on a scenario where no cues are utilised. Future extensions of this study could accommodate this modification.

The second part of the analyses presented the outcomes of the clustering framework we devised for this study. It can be utilised in the future as a tool to drive further analyses, such as feature detection or help to objectively split the overall time waveform into smaller units or time windows. The current presentation confirms the applicability of the framework on EEG data.

7.6 Chapter Summary

This chapter addressed the last Research Goal of our empirical investigation (see Section 2.4). It was largely based on the outcomes sourcing from the Chapter 4 Section 4.3.2. The present chapter follows:

- A brief background information about the nature of the mechanisms of the RJR paradigm with the focus on their interrelationship, the factors affecting the success (accuracy) of metamnemonic predictions supported by the findings from the earlier chapters.
- Formulation of the Research Question.
- Explanation of the aspects related to Study Design and Methodology associated with the current chapter and the introduction of a novel clustering data framework.
- Presentation of the data analysis results and the manifestation of the applicability of the clustering framework on the EEG data.
- Review and a discussion of the major findings related to our Research Question.

Part III

Conclusions

Chapter 8

Conclusions

In this final Chapter, we will review the present thesis's outcomes and reflect on how they met its primary objectives (see Section 1.3). We will elaborate on the impact of the findings on the continuing research in the field of IS&R (Information Search and Retrieval). In addition, we will reflect on the study's limitations based on the issues we encountered and offer recommendations on how to improve these for future work.

8.1 The Outline of the Contributions

This thesis investigated a novel perspective to investigate the human neurophysiological signals to address the cognitive drivers of the users' INs for IR. We argued that research of brain data captured in an IR task can: (a) provide a more realistic understanding of the searcher's cognitive context as a premise for the searcher's information search behaviour; (b) fund the novel categories of IR systems in order to better address searcher's INs and, subsequently, (c) lead to more effective as well as efficient search systems.

We first present the overall contribution before going into more detail.

1. We reviewed the current IS&R views on the context of IN and brought an extensive overview of the cognitive perspective behind IN.

2. We proposed a conceptual framework to study the user's state of knowledge as the underpinnings of INs and introduced an analytical data-driven framework to

perform a quantitative analysis of the elicited brain activity. Foremost, the choice of EEG technique was original in the context of our investigation. Its application allowed us to research the related concepts with a high temporal resolution of data capturing, as opposed to the past research focusing on high spatial brain imagery.

3. We utilised the conceptual framework as a tool to support the cognitive foundations of Belkin et al.'s ASK Model and revised the ASK variants using a link with the user's metamemory mechanisms.

4. We analysed both the behavioural and the brain data on the spectrum of the user's state of knowledge, including a novel FOK state, and provided discussions on user search behaviour and expectations. The evidence showed statistically significant differences in ERP components evoked for different states of knowledge.

5. We contrasted the brain signal for a user in (expressed) IN-state with the two other states, including a state suggesting the effect of false memory and explored the modality by differing confidence levels. We further analysed their impact on IR.

6. We proposed a data-driven model of complex cognitive processes evoking the user's state of knowledge as a result of the quantitative and qualitative exploration of found ERP components.

7. We explored the modality of the significantly associated metamemory and memory levels and devised a clustering analysis based on the derivative dynamic time warping method evaluating the similarity of ERP waveforms.

Before we discuss the details of the contributions (see Section 8.3), we provide a summary of the development of our research.

8.2 The summary of the work

The current thesis investigates the neural underpinning of the user's state of knowledge as the driver for their Information Needs (INs). In brief, we can define the user's state of knowledge as the situation-arising input that defines their knowledge capabilities in relation to a situation or problem they are facing. For example, considering the binary solution to a simple Q/A scenario reflects two extreme states: a) "I know" or b) "I do not know". Conceptual models of the user's world in IR, such as Ingwersen's "World Knowledge" [15], Belkin et al.'s formulation of "Conceptual State of the Knowledge" [3] abstracted the users' memory as storage of internal information, learnt or experienced and beliefs. In this sense, memory is vital in the searcher's cognitive context. It acts as a reference object based on which the user determines the level of availability of their knowledge for a given situation. From the research perspective, addressing the operational mechanisms allowing the user to control, access and retrieve the memory knowledge is vital.

From the characteristics of the epistemic feelings [19, 134] and the functioning of memory, we learnt that there is a spectrum of knowing that could reflect the variability of the states of knowledge. This sequence sensibly implies the expansion of variability of INs. We hypothesise that if we prove it is possible to obtain detectable mental signatures of these states and associate them with their respective INs, we become more insightful (and, in the future, more successful) in helping the user to resolve their INs. We admit that it is a long and step-wise journey to reach its final point and to be able to answer this speculation confidently. Nevertheless, our work contributes with meaningful findings that follow up the previous attempts in the context of interdisciplinary IR research concerning users' INs [11, 23, 24].

8.2.1 Conceptual and Operational framework of the study and Decision-Making

The selection of the NeuraSearch framework was motivated by its flexibility and accuracy in capturing brain data while users engaged in a simulated IR scenario evoking

INs. A methodological and methodical assessment of the modality of brain activity to understand the implicit drivers of information search behaviours. Unlike traditional methods of IR user studies relying on behavioural data, questionnaires or surveys, NeuraSearch research offers an unbiased method to combine subjective (participant explicit judgments) with objective metrics (EEG brain data). Participants in IR user studies might often face cognitive overload moving throughout a designed scenario. The results then depend on the individuals' commitments to the study and interpretation of their feelings and perceptions experienced. Monitoring the objective metrics, such as brain activity, describing the objective response of the brain to a given stimulus, is an unbiased method to limit the users' overload [250].

The input of this thesis was an extensive literature review (Chapter 1) conducted prior to the thesis statement. It helped us to familiarise ourselves with the context of IN, the present challenges and the ongoing research in this area (see **Research Objective 1**). In particular, we were motivated by the selected literature depicting the cognitive aspects of IS&IR and IN [3, 9, 10, 15, 20] which helped us to identify the points that lack the empirical investigations and which would contribute to positive benefits in IR and IIR development. The cognitive approaches in user-centric theories of IR are fundamental for understanding the origin of IN, i.e. concerning a perceived gap in knowledge. Being particularly inspired by the NeuraSearch [21, 131, 132] branch of IR studies (featured in Section 2.3), we decided to follow in the footsteps in the research in this area and overcome the difficulty in objective evaluation of internal memory mechanisms. Especially relevant was the model of the realisation of IN [24] that helped us to uncover specific mnemonic functions that lack the investigations concerning IN and, thus, shaped our focus on the appropriate methodology.

The pre-requisite of this thesis and the study features in it was to 1) formalise the definition of the user's states of knowledge; 2) construct the framework to obtain the brain activity associated with the states methodologically, and 3) systematically integrate the framework with the application of neuroimaging techniques to capture the neurocognitive manifestations of these states (see **Research Objective 2**).

The first point we addressed was the conceptualisation of the two mechanisms operating over the knowledge source - memory - whose outcomes determine the user's state of knowledge from two perspectives: 1) metamemory and 2) memory retrieval (MR). For the second point, we explored the multilevel methodological frameworks of the studies involving both of these perspectives [166]. We notably identified RJR and RCJ paradigms (explained in Section 3.2) in which participants are sequentially asked to judge their knowledge level and confidence according to pre-defined levels. For the metamemory part, we used Graded Recall [19] approach differentiating the epistemic feelings into three levels, including the FOK level, which is a novel state not yet directly exhibited in an IR scenario. For the MR part, we used the approach of successful retrieval and failed retrieval [166]. Naturally, input is needed to evoke the brain activity that would determine the state of knowledge.

We were inspired to create a simple scenario of Q/A with general knowledge questions, similar to works [11, 22]. The advantage of Q/A is its one-off and immediate assessment of participants' knowledge suited to our aim. On the other hand, longer periodical assessments are more suitable for observing the effects of memory knowledge changes, which was not our aim. The selection of the NeuraSearch-type of the study was motivated by i) its relatively good applicability of neuroimaging data capturing techniques into IR settings supported by growing research in this field, and ii) efficiency in the assessment of neural correlates elicited for IR concepts [11, 148, 156, 157]. The next decision was a choice of the technique and adaptation of the Q/A scenario accordingly. The choice of EEG technique adhered to several requirements we had in mind: i) light-weight, non-invasive product as we wanted the environment to be as close to natural as possible without much impact on the user; ii) availability of the EEG cap at the university department for research purposes; iii) history and results of the EEG applicability in IR settings given by prior research [22, 148, 157]; iv) after appropriate supervised training, the ability of self-direction of the researchers to conduct the study and operate the EEG device (in contrast to fMRI machine which must be operated by a trained clinician); v) flexible and short-run procedure to obtain the ethical permission was only bound to departmental Ethics Committee (we contrast with fMRI technique, which procedure requires permission by corresponding regional

Research Board of NHS Research Scotland) and vi) applicability and integration of the technique with the future systems with EEG meeting this its growth in development of portable EEG machines and its integration with BCI systems with automatic recognition. Subsequently, we went back to the study design and shaped the Q/A format of the study to meet the requirements of EEG (see Section 3.3.1).

8.2.2 Adaptation of the Study to EEG setting

The core of our study was to expose the subjects to the stimuli that would trigger the internal processes of knowing, we were aiming to investigate. The preliminary analysis of data collected from questionnaires showed that the perception of knowing/not knowing was evoked during the information processing, i.e. sequential question reading (for the details, see Section 4.1.2). It, thus, confirmed a link between information processing to evoke the user's state of knowing automatically. With this premise, we constructed the study (see 3.3.1). In brief, we encapsulated the relevant brain signal by time-locking this signal to the onset of the presentation of each question, specifically of each term in the question (i.e., the stimulus). The explicit participants' responses (i.e., button clicks) for every question then encoded the sequence of corresponding brain data into several pre-defined levels (see Section 3.2.5). This way, we achieved a consistent data acquisition system and equalised the task conditions across the subjects.

8.3 Findings and Contributions

Our data suggest that stimuli triggered significant neural activity associated with particular levels of the pre-defined users' states of knowledge. We are now going to discuss the findings informed by the investigations in Chapters 4 - 7; in particular, how these outcomes extend the cognitive perspective of the user and the variability of their INs.

8.3.1 Effect of Stimuli

Before we discuss the findings of EEG analysis, we review the stimuli used in the study. The role of stimuli, i.e. questions of general knowledge, in the study was to evoke the memory operations behind knowledge retrieval and perception of knowing. In this sense, the stimuli represented the tool to manipulate the brain activity to evoke the activity associated with different users' states of knowing. For this purpose, we intentionally controlled the attribute of the stimuli, the question difficulty, to evoke different states of knowledge and achieve a population of the factorial hierarchy with a sufficient amount of responses (required by the EEG analysis - see Section 3.5.2). The preliminary investigation of the distribution of the responses confirmed our anticipation, e.g. easy questions triggered more or positively recalled responses (for detailed results, see Section 4.4.2). Despite the significant effects of the question difficulty on the distribution across Meta levels, we did not account for this attribute in the subsequent EEG analysis, i.e. if there are significant effects on neural activity posed by stimuli attributes. Justification can be provided first by looking back at our research objectives. Our hypotheses were not related to the effects of the stimuli attributes on neural activity. Moreover, the difficulty attribute of each question was evaluated by the two independent assessors asking them to judge how difficult it is to know the answer to each question in the dataset (see Section ref 3.3.2). To obtain a comprehensive and accurate view of the data attributes, we would have to methodically evaluate the linguistic side of the stimuli, precisely the difficulty of the terms used in the questions and potentially involve more assessors. In this sense, our textual dataset was not optimised and methodically constructed for this purpose. Future work can benefit from a dataset with higher control over its attributes to achieve a separation of brain activity, similarly to the EEG-based user study [156] that applied the term difficulty assessments.

8.3.2 Data-driven model of complex cognitive processes evoking user's state of knowing

Our data findings supported the formulation of a conceptual model of information processing consisting of orchestrated activity between the ERP components N1, P2, N400 and P6 components, which we found in all EEG investigations (see Chapters 5 - 7). Each of these components has a specific role in the information processing, and, altogether, they describe the progress of realising the user's state of knowledge. The variability of the amplitudes associated with these components can be linked to differences behind the single states and, thus, mean a specific signature for that particular level (see the results in Tables 5.1, 6.1 and 6.2). Whereas the early components (N1, P2) index the automatic, less controlled processes, the second portion (N400, P6) is more conscious-oriented, involving memory search and the final verifications before the user makes a direct response or decision. For detailed explanation of the linked cognitive processes, see Sections 5.5.1 and 6.5.1. The model helped us to chronologically uncover which functional processes users employ during the information processing. The early visual processes suggest that information presentation immediately impacts the visual senses. IR systems can utilise these findings to manipulate the visual side of the information and presentation of retrieved documents. We are not going into any specifics of front-end system design as it is not our aim. However, we recommend using the cognitive models of information processing as the source of insight in the context of the presentation and processing of retrieved information.

8.3.3 Metamemory

Following the earlier introduction related to two mechanisms to determine the state of knowledge, we proceed with the discussion resulting from the investigation of metamemory and epistemic feelings determined by the Graded Recall method. The findings based on the behavioural data analysis showed the relationships between the levels of knowledge at different stages of the task (see Section 4.3.2). Besides the primary investigation of the research, the analysis contributed to the identification of the data issues that served as guidance for the subsequent EEG analyses. The highest frequency of FOK responses emphasised its inclusion as the user's state of knowledge. It was an important point to account for this level and explain its relation to IN (see next Section 8.3.3). In the subsequent EEG analysis, we found the first evidence supporting the activity following the data-driven model. The underlying cognitive functions were used to explain the variability between the levels.

In this investigation, we took an introspective approach toward understanding the user. As part of information and database systems, general metadata describes the data stored in these and the links between the inter-related data items. Analogically, the user metadata draws the user in terms of their introspective insight. The acknowledgement of information from the user's introspection in the knowledge context is relevant to IR. This epistemic self-analysis increases users' awareness of their knowledge abilities and insufficiencies. The resulting epistemic feelings are often prospective (oriented towards the future). Utilising this insight means a crucial area for both i) the theoretical (i.e., understanding the neurocognitive drivers of the realisation of INs), as well as ii) the practical side of IR (i.e., adequacy and intensity of system intervention when the user has particular INs).

The link between Metamemory and ASK

In general, the user's state of knowledge is a predecessor for IN. Belkin et al. [2] specified the states with attribute anomalous (ASK) to capture an anomaly in their state of knowledge that should be resolved. ASK depends on the realisation of anomaly, i.e. anomaly has been acknowledged. From the notion of ASK, ASK is modulated by the variants in ASK, depending on the level of knowledge. So far, the variants of ASK have been only hypothesised and have lacked a deeper methodological assessment of ASK variants.

This idea motivated us to elaborate on the analogy between the user's state of knowledge, given that we have established the source as metamemory and the variants of ASK. In particular, how can we explain the ASK variants using metamnemonic user states and, thus, contribute to reframing the nature of INs (see **Research Objective 3**)?

Metamnemonic outcomes (epistemic feelings) are often investigated on the spectrum of Graded Recall [19, 134], which leads to our speculation that ASK variants could be manifested based on the different specificity of recall outcomes. It can be illustrated with two extreme situations on the opposite sides of the spectrum: 1) full recall (the information in question has been recalled; corresponding to our level KNOW) with no IN would likely be triggered and 2) recall failure (no information has been recalled; corresponding to our level NKNOW level) likely evoking IN as the next step. To fill the space between these two extremes of Graded Recall, we chose the concept of FOK, defined as the intermediate state of knowing. FOK can be considered a variant on the ASK spectrum and classified as an ASK state as it is underlain by an anomaly in knowledge, i.e. temporary unavailability of the information in question. From the ASK perspective, we specified the level as "FOK-based ASK". Graded Recall offers a flexible method to populate the spectrum with more states, such as TOT as used in the paper [95] or even define different grades of FOK [206] and investigate further variants in relation to ASK.

In general, FOK, as well as TOT, are subjective indicators [169] sourced from the unique, organic ability to recall feelings as part of the organic processes to re-experience. Prospectively, exploration of feelings-based metamnemonic outcomes concerning user's affective feelings in IR process [5] might help to explain the role of feelings in a user's information search behaviour (e.g., uncertainty, confidence) and IN characteristics (e.g., expressiveness).

Referring back to Section 2.2.3, where we delineated the main components behind the ASK-IR System, our thesis aimed to address the first requirement concerning the methods to define the problem statement. After all, we used the EEG technique to capture the objective realisation of the user's cognitive state of knowing, which is informative about the user's perceived anomaly. We approached the user's brain signal as an objective marker of the user's anomaly. We, thus, provided not only the objective means of the evaluation of ASK anomalies but contributed to the definition of the origin of ASK anomalies. This objective might help in the future to approach the second requirement of ASK-IR, i.e. to construct a viable mechanism behind the representation of anomalies.

In conclusion, considering the embedded metamemory processes and their outcomes support the origin of ASK variants and the graded character of SK. Based on the data obtained for this phenomenon, we discussed the FOK as a variant of ASK.

The link FOK (as the representation of ASK) and IN

We now authenticate the FOK anomaly directly as a trigger of IN and discuss the impact of FOK on the users' information search behaviour (see **Research Objective 4**).

Our EEG data showed that the FOK signal significantly differs from the state of the successful recall (KNOW). Moreover, the neurological variability of FOK was similar to the state of not-knowing (see justification in Section 5.5.1). The latter, even more, supports the need to address the drivers of FOK-based anomalies and extends the spectrum of INs. According to the characteristics of FOK, users in FOK states need a small cue that would trigger instant memory retrieval. Establishing the link between FOK and IN, the solution for FOK should alter the solution for INs. The link implies the alteration of strategies for their satisfaction, which brings out the discussion on the impact on IR systems. These strategies should address these components. Firstly, the retrieved information, that provides the solution for the user's IN. Secondly, the link between the knowledge-based schemas in IR and the mechanisms of retrieval and document representation. Lastly, the query representation of FOK.

The first strategy is the notion of different portions of information satisfying different INs (a result of different variants by the user's state of knowledge or ASKs). Users in FOK states would likely require a form of a cue-lead solution. For this reason, more attention should be placed on the resolution of the cue. In a fact-finding scenario, as a class of the Q/A task, the cue can take a form of an excerpt from the information document containing the answer (fact). For instance, the effective retrieval presents just the answer "1,000" to the question: "What number is represented by the roman symbol **M**?". In a fact-finding/known-item scenario [37], the users with FOK know what they are looking for, as they have some previous knowledge, and the IN might take the form of the confirmatory need [12]. The information cue would increase their certainty and, in a sense, regenerate knowledge. We now contrast the user with FOK with a user with no prior knowledge who looks for the same information but takes an exploratory search approach in order to learn. The object of the retrieval is seemingly the same, although, the user intention is differed by the user's state of knowledge which urges us to consider that the object of IR is not the same. The retrieval efficiency brings us to the second strategy to support multiple stages of knowledge. The difference between the variants of the user's state of knowledge is the variability (i.e., the knowledge level) behind each variant. This notion necessarily raises the question "What element in the retrieval process needs a focus to allow for improved user satisfaction?". We think that the strategy would differ for fact-finding scenarios and exploratory searches. Whereas, in the first scenario, the focus should be on the text retrieval, as the retrieval of "the fact", e.g. a piece of discriminative information, e.g. year when the requested book was published. Analogous thoughts might have been behind the implementation of Google's SERP strategy to emphasise the retrieved fact while presenting it at the focal point for a quick IN resolution (see Figure 8.1).

If the query requires a broader search, the focus of the IR system should be on the knowledge representation in the documents corpus by maintaining adequate metadata that supports the knowledge categorisation [251]. Exploratory searches are more difficult to track and influence. Therefore it is necessary to control the presented retrieval outcome and its form. The search space is broad, INs are dynamic, and the user follows a berry-picking approach [46]. The categorisation of knowledge can, thus, significantly contribute to reducing the information and cognitive overload [250].

To put this idea into operation necessarily lead us to address the main component of the search, which is the user input, i.e. query or other forms of INs input. How to represent FOK (or any other variant of ASK) as a query? Could also IR intervene and help the user, such as query suggestions? For this purpose, we need more research to understand the relation between FOK and other knowledge variants and IS behaviour. We need the understand the patterns, search habits and expectations. Following this view was the recent qualitative investigation of TOT requests [95]. An expansion would benefit from a user-based study with the users' active engagements in the study context.

With respect to expanding on the FOK and other epistemic feelings in the context of IR, we recommend the research concerning:

- Study FOK and the IS behaviour to learn more about the role of FOK in the IR. Even though we performed EEG research, a study of FOK is not limited to

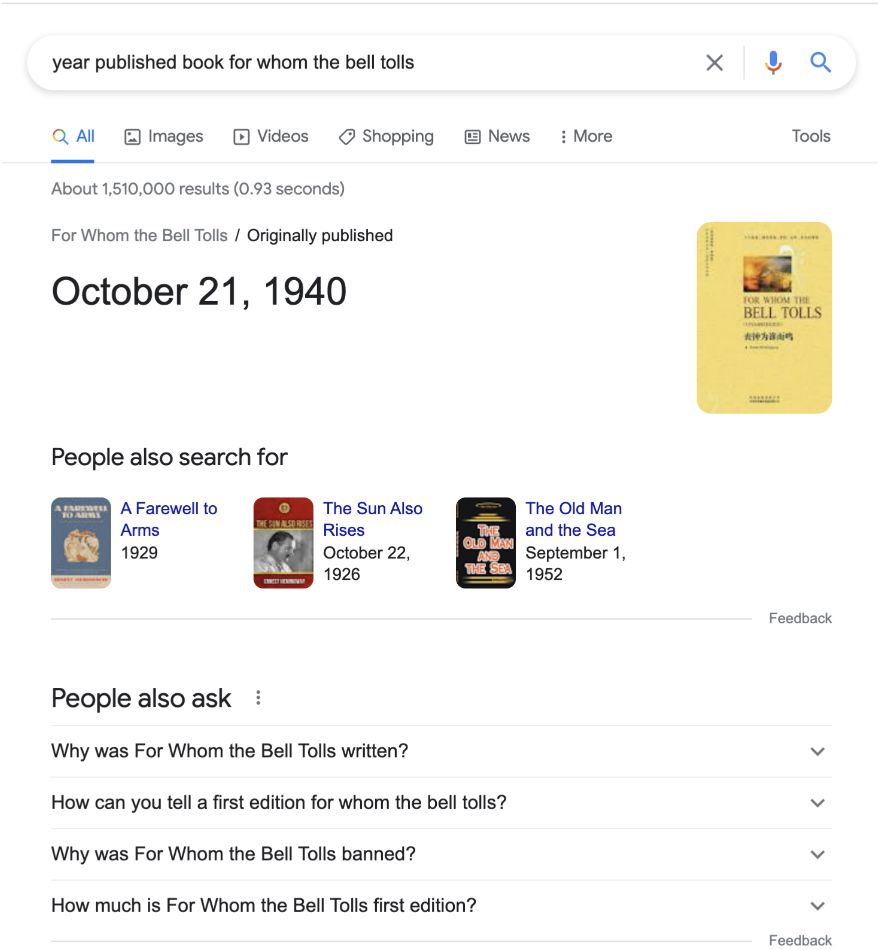


Figure 8.1: Google's SERP for the query "year published book for whom the bell tolls"

the application of EEG. Other traditional behavioural studies involving real-time user assessments of the knowledge perceptions are advised.

- Establishing a new perspective about the user following the meta (introspect) perception to deduce the knowledge and capabilities. Systems already utilise the user's historical data of system interactions to algorithmically recommend a possible match to the user's interests and needs. The question raises "Can we deduce the knowledge in order to utilise this information in search?". Our NeuraSearch approach is broadly situated in this context. We recommend further knowledge assessment or integration of metadata and data about past searches to deduce the past and anticipated activity.

Our data support that FOK has a distinctive neural manifestation and is detectable from the brain, which supports the variability of ASK on the neurocognitive level. It is a state that is naturally evoked and thus should not be neglected. More is, however, needed to understand how these findings can be operated within IR. We will discuss the applicability of EEG in IR in Section 8.4.

8.3.4 Memory Retrieval and Confidence

ERP investigation featured in Chapter 6 categorised the brain signal according to three MR outcomes concerning if the neural processing contains the information that would determine the MR outcome. We affirmed our hypothesis that the spatio-temporal pattern of activity of a person not-knowing (corresponding level MR-N) is significantly modulated in contrast to two levels associated with successful MR. We further exhibited the level MR-N to the decision related to the participant's explicit wish to resolve their gap and use it to authenticate it as IN level (see Section 6.2.1). The variability of these two perspectives pointed to neural signature significant for IN level (for specifics, see Table 6.2). One might argue we previously far-fetched the ASK, FOK and IN. In this scenario, we used the information obtained from the participants to shorten the bridge between the user's state of knowledge and exhibited IN (see **Research Objective 5**). The investigation considers a deeper assessment of memory that underlies the user's state of knowledge and exhibits the actual knowledge information assessment. In a sense, MR outcomes validate the prior Meta outcomes (see details in Section 4.3.2). In the IR context, we can interpret the mnemonic cues as retrieval outcomes, such as documents, snippets or metadata. Any information retrieved from the system affects our perception of this information and, most importantly, how we categorise it. This particular investigation can, thus, have an even more impact on IR research to inform how the brain behaves in relation to the cues that guide the users towards the correct information.

According to results obtained from behavioural data, mnemonic cues impacted the increase in recall of previously not known information (judging by the amount of NKNOW followed by MR-C responses in Table 4.1). Stimuli conformed to its name, as it appears they stimulated the positive recognition. The analysis also found frequent pairwise contrast involving the incorrect level (MR-I). It is an intriguing level. Concerning memory, this level manifests the false memory [27], which, as the name suggests, means the information is encoded in the memory falsely. Our study did not involve control over the information encoding prior to them taking the study. Specifically, the participants were not exposed to the questions and did not learn the correct answers beforehand.

Moreover, coupled with the knowledge that the strength of memories often manifests with variable levels of confidence and certainty [177], we found a pattern of MR-I being likely associated with low confidence. As a result, IR can benefit from further investigation on this level coupled with the notion of data/information veracity. As [4] suggested, data veracity is an influential attribute in data encoding and subsequent retrieval. The increase in measures to control the veracity of the data to maximise data benefits, including the attempts by governments at the national or multinational level (such as EU [252]), indicates the need to increase the trustworthiness of data to intervene and reduce the data misattribution by the users of the information systems.

In addition to these results, we investigated if MR is modulated by the levels of perceived confidence and what such information can tell us about the output of MR (see **Research Objective 6**). The investigation on the level of behavioural data (see Section 4.3.2) informed us that the confidence is driven by the interaction of Meta levels and MR levels. High confidence responses were positively correlated with the recalled responses on Meta level (KNOW), with these followed by correct recognition on MR level (MR-C). In contrast, we found a higher frequency of low confidence with MR-C and MR-I responses, preceded by the NKNOW response on the Meta level. Furthermore, we found that MR-I responses manifest with a significant drop in confidence independently of the Meta level.

8.3.5 Summary and Implications for IR

We demonstrated that there are spatio-temporal dynamics governing the relationships between memory mechanism and the perceived state of knowing judging by the topology and extent of brain activity which varies as a function of the 1) Metamemory and 2) MR. Such variability supports the complex natures of processes underpinning the mechanisms, which, as we point out above, evolved from automatic and more localised functions to controlled cognitive processes.

The present application of the interdisciplinary framework showed an area of great potential for IR system design to objectively and proactively detect the surroundings of the user's cognitive context [6, 7]. Recognising the state of the user's knowledge means for IR to map this state to the retrieval process that would efficiently satisfy the anomaly in their knowledge. IR can also utilise this mapping to limit the search space [92] and address the area of overload of IR users, both information and cognitive (mental) workload [146]. The more accurate information the system possesses about the user, the higher the efficacy in assisting the user and reducing some of the behaviours the users often tend to apply when feeling an overload (e.g., satisficing behaviour [253]). As a response, IR results in improved user satisfaction and acceptance and reduction of searchers' effort [254].

The outcomes obtained from the interaction analysis of Metamemory and MR support the relative accuracy of metamnemonic feelings (see 4.3.2) and their reliability, especially if the user had a positive perception about the correct recall (see **Research Objective 7**). On the level of behavioural data, we also highlighted the potential for the manifestation of delayed IN as a result of the Illusion of Knowing effect (see 4.5.1), i.e. there is not a match between initial perception (Meta) and the recognition (MR). This finding could impact the user during the information search process when they realise their FOK was incorrect (i.e., false FOK), and they might likely need to enquire more information to satisfy their FOK. Further investigation into this concept in the context of information search behaviour might bring more clarity to the (user's) behavioural characteristics as well as search attributes and, thus, open a discussion in the IR community. Chapter 7 then investigated if the EEG alone is informative of the accuracy of the prior metamnemonic predictions concerning the MR outcomes. The results showed a series of neurophysiological modulations informative of the interactivity between Meta and MR detectable from the brain data alone.

In general, the benefit of continuing to explore the cognitively-oriented IR and formulating more empirical studies in this area is likely to impact both the user and the system itself. In the prevalent Interactive IR (IIR), the system interferes with the searcher's cognition and introspective insight in the form of retrieved texts and documents. The system's essential job - providing retrieved outcomes, is assessed by users by employing their cognitive abilities, e.g. by providing relevance judgments. The searcher is, therefore, in a loop of assessing the documents based on how well they fit into what the user already knows [5] causing their initial state of the knowledge anomaly to evolve. The system needs accurate signals from the user to recognise and determine the appropriate actions to increase the effectiveness of retrieval in regards to users' INs. Our study brings more specificity to acknowledging different metamemory and MR outcomes as the basis for information search and can be used to inform about different user behaviours. We advise a follow-up extension of the research of knowledge retrieval determining INs and subsequent information search tactics. The use of memory tests could be a potential route.

In addition, our work introduces the methodological framework, which can be adapted to a vast number of user-based studies concerning interactive systems, search systems or testing a specific design feature. For instance, a typical user retrospective survey can be expanded by monitoring and evaluating the users' responses in real-time to obtain an immediate insight into users' experiences during a tested scenario.

As part of the NeuraSearch research, neuroimaging techniques acquire objective measures of users' cognitive perceptions within IR and IIR. As our findings suggest, EEG data are informative as they capture the triggers and drivers of different cognitive and mental phenomenons with high precision and contrast between the experimental conditions. Many current IR systems implement recommendation features for their users, e.g. recommended articles based on the topicality of the searched information. Recognising distinctive markers based on prior knowledge or past experience is a valuable and desired input to offer more relevant recommendations and explore the level of pro-active user support. Developing an analytical framework that would extract, classify and learn the key features of the user's cognitive context is essential for the integration and deployment of future pro-active IR systems (see Section 8.4 about the applicability of EEG).

IR in the Context of Episodic Memories and Recollections of Memory

The present research supplies the fields of IR and the information seeking and search from the perspective of searching for information facts helping the user to transfer it as knowledge, i.e., could be learnt by the user. The factual memory is a storage of the user's learnt knowledge. Analogically, we can say that web search engines, as the most ubiquitous data retrieval systems, access the factual knowledge scattered through the information sources. As was found in past research, the user accesses both factual and episodic memories in order to determine their state of knowledge and express INs. Supporting this claim, in Chapter 6, exploring the brain response modalities by different MR levels, we found the active traces of the contextual memory as part of episodic memories. The contextual memory describes the memory of the user in the form of situational context (e.g., occasion, event), temporal context (e.g., year, age) or other descriptors (e.g., people the user shares the memory with). Our study targeted, in particular, the retrieval of factual information, being the answer to a question of general knowledge. The potential discussion might arise linking the users' past life events with the information search and IR context. Could IR help us to recollect a memory in order to reconstruct it as a unit and provide general information about "What (happened) - When (did it happen) - Where (did it happen)"? Some attempts by the search engines showed such signs. For instance, Google Photos[1] likes us to remember the things we did in the past in the form of photos, which acts as a personalised service to browse through "the memories" we collected. The form of images as a method of recollection offers additional benefits, such as self-reflection or emotional triggers. The implementation follows the ad-hoc unintentional retrieval with the user not triggering the retrieval (i.e., the recollection). Could IR, then, integrate intentional retrieval of memories? Precisely, extraction of memories and the integration of the information retrieval on top of that. The episodic memories as the data trigger could, thus, represent a potential route for

[1] https://www.google.com/photos/about/

exploring a new form of specialised IR. The motivation increases, considering that the information obtained from the recollection might serve to handle the daily activities of specific categories of users who would primarily benefit from these types of information, for instance, the users experiencing short-term memory loss. Current sophisticated data mining techniques, e.g. facial recognition, allow for information extraction across several data formats, expanding the potential episodic memory recordings independent of the data format. A framework is needed to conceptualise the objectives and related data collection questions, such as data privacy or user trust, as they would likely require separate investigations.

8.4 Applicability of EEG

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Our process was similar to other NeureaSearch studies based on the interaction of the stimuli and brain data, i.e. brain response evoked by the stimuli. Therefore, the choice of stimuli has to be considered with respect to the aim of the study. Furthermore, as we mentioned, IR scenarios must be adequately adapted to use with EEG. In this sense, the Q/A core of our study proved to be an appropriate scenario reflecting our aim and the constraints of EEG. We reflect on the study in the next section and recommend a few modifications following this research.

The next question arises, how to integrate EEG, as the source of user input, into IR (see **Research Objective 8**). In the current setting, the discriminative neural activity underlying the user's state of knowledge is sufficient to conclude their distinctive manifestation and the possibility of their detection. The utilisation of EEG helped in this regard to understand the brain mechanisms. However, more research is needed to apprehend the user information search behaviours accompanying these states.

A challenging area is the deployment of EEG within IR and search, where the system reacts to the brain signals. Many current systems allow for advanced reactive user support, such as recommendations of similar data items based on user data inputs and activity, e.g. the list of clicked data items. All the more, the systems' proactive support is discussed [25]. The proactive system is an anticipatory system with a dynamic logic to adapt to the dynamic mind of the user. The proactivity replaces the user decision by adapting to the received input describing the user and their state of needs and automatically delivers what the user most likely needs. In a situation where the user feels uncertain whether the whole search engagement delivers the outcome they expect and would be satisfied with, proactive support can substantially help reduce the user's uncertainty. We can define several levels of proactivity on the system intervention scale. The highest level is a situation where the user communicates with the system via the brain waves, whilst the system is in full control of the retrieval output and presentation even before the user consciously realises the need. In order to scale down and model the integration of EEG with IR, we have to decompose its main components. First, it is essential to know what portion of data to target that would be descriptive of the users' states and needs. Like the brain response, an input triggers a reactive and proactive system response. Attention to stimuli is therefore critical, including their content and the modality - audio, visual or haptics. Following the set-ups of the previous EEG studies, we were aware of the concept of the stimuli employed in order to evoke the brain response. Coupled with the time-locking method of the stimuli presentation, we knew what portion of the data brain signal to select, extract and analyse that describes the corresponding brain state.

Second, proactivity can only work as long as it contributes to solving the users' needs, i.e. as long as the system knows what it reacts to. From this point, it needs a broader interaction, as we cannot know what the person actually needs unless we monitor more data or multiple signals, i.e. simultaneous activity and real-time interactions. Diversified signals are helpful to create a logic considering multiple sources of user's experience and for the system to become more adaptable to the user's current state of knowledge. Brain Computer Interfaces (BCI) integrate the users' biological signals as the input to the system, which uses it to learn, react and adapt its response accordingly [152]. Examples of BCI systems employ a single feature detection, e.g. mouse cursor click, in order to replace the user's hand movement. In the area of IR, Eugster et al. [147] created a prototype of the system inferring text relevance from the brain data. In order to scale down, it is necessary to start with a feature selection to model and validate its presence, such as the ERP components analysis we performed. Larger sample sizes help to obtain a more robust set of data features used as the input to the model.

Third, the EEG device itself is challenging. EEG devices are still perceived as a form of clinical and laboratory-exclusive settings. This exclusivity is, however, not relevant anymore. EEG has been present in the development of BCI systems, IR-based NeuraSearch and emerging fields of neuroinformatics and neuromarketing. The wearable market has been recently expanded with EEG headsets as a form of an audio accessory to monitor brain waves. Portable EEG devices [255, 256, 257] address the challenging side of EEG, i.e. intervening with the natural way of working. Considering the link between the technical and engineering side might also ease the deployment. Also, the quality of the signal is another vital feature to consider. As we mentioned, the raw signal is contaminated by artefacts, requiring meticulous inspection and data cleaning. Automating the cleaning pipeline or even research into self-cleaning EEG [155] would mean for the researchers to speed up their work, filter out the non-relevant data and focus on the meaningfulness.

As we described, the true operationalisation of EEG and IR is a gradual process. The first results of NeuraSearch research expanded the knowledge in the IR field following the investigations of relevance [22, 148], search process [159] and query terms [156]. With our contribution, we helped to uncover the neural correlates corresponding to different states of users' knowledge.

8.5 Future improvements of the study

One might argue that Q/A is not an IR scenario per se as it does not follow the typical structure of the IR process. Our choice of the Q/A method was motivated to study the input states, determined by the neurophysiological properties of EEG data, as the predecessor for the user's information search behaviour. We did not aim to assess the user-system interaction per se. In NeuraSearch research, Q/A is a common scenario due to its adaptability to a range of investigations concerning relevance [22] or IN [11]. The stimuli and their context (i.e., general knowledge facts) triggered the memory processes underpinning the user input states. In this sense, the Q/A proved to be beneficial. Considering the data issues we encountered during the scenario, we will now reflect on the study's alteration.

8.5.1 Participant Sample

We relied on data from 24 participants, which was still more than the power analysis had predicted. Behaviourally, it was not an issue. The analyses of behavioural data (e.g., responses distributions across the data factors) identified the patterns of responses informed by the strengths of interactions between the factors (see Section 4.3.2). The issues arose during the EEG analyses, especially those that relied on data subsets with a two-layer aggregation (e.g., Model MR+Conf in Chapter 6). The low individual samples of responses caused multiple participants to be excluded from the analyses (to avoid the counter-effects explained in Section 3.5.3), and the final samples might have reduced the reliability and generalisation of our findings. Due to the Covid-19 pandemic, which effectively interfered with our study in March 2020 and caused the termination of any lab-based human-subject studies across the entire University, we could not recruit more participants and resume the data collection.

8.5.2 Alteration of the study

Concerning modifications of the study, in particular, we reflect on four categories and recommend the modifications that would contribute to increasing the prospect of the following study: i) reduce the data issues, ii) enhance the validity of the outcomes, iii) increase the space of relevant information and iv) escalate the applicability of NeuraSearch research and ease-of-use of the EEG within IR.

1. Stimuli The presentation of the stimuli as the trigger to evoke the brain responses to make associations with the corresponding state of knowledge was a critical factor to consider prior to developing the Q/A system. To synchronously capture the brain activity with the word presentation, we applied the sequential presentation of the question with the method of time-locking the stimuli to the onset of the word presentation with equal time spent, also known as the fixed RSVP. One might be critical of this manipulation as the user's information processing might appear "forced". Despite this critique, this form of manipulation is methodologically valid and commonly used [11, 22, 148] including the studies of NeuraSearch. Then, the sequential presentation of the stimuli [22, 156] was used to obtain a large amount of data epochs to average to subsequently obtain a relatively stable EEG component per investigated conditions. The choice of fixed RSVP was then driven by the desired data outcome format. Firstly, to have the same amount of time points in each data epoch (see 3.5.3) and secondly, to reduce the further data manipulation on the time dimension, e.g. time compression [258]. Other approaches based on self-paced RSVP [187] consider factors such as word difficulty and length during the information processing, as they require longer processing time and might be, thus, worth considering in a future study.

As an extension, we can consider utilising the obtained brain responses triggered by single words and look for discriminative terms, i.e. words that impact the user's state of knowing (similar to the task in questionnaires posed to participants in Section 4.1.2). For that purpose, we would also need a term assessment by the participants, which could be done as the immediate step after the question run in full, i.e. (to fit an additional step between S1 and S2 in the task diagram in Figure 3.1). In addition, evaluating the EEG properties of these discriminative terms would be beneficial for further research (similar to what was done for term specificity in [156]).

Moreover, as prevalent in NeuraSearch studies, the participants in our study interacted with textual stimuli with the reading required. In the same way, the experimentation with different stimuli modalities might prove helpful from the research perspective as well as from the participants' perspective, considering their comfort in participating. From the research point of view, these can bring new insight into information processing and IN through different sensory-driven processing, which might prove to be a valuable enhancement of the current knowledge. For instance, orientation to sensory voice inputs can prove beneficial, as it is a very current modality, due to the increase of voice-based mobile technologies and their adaptation by users, such as intelligent personal voice assistants [43, 44]]. Specifically, auditory input might ease the demands on participants of these experiments regarding their physical interaction within the strict laboratory conditions. For example, participants could have their eyes closed, increasing their comfort and considerably reducing the eye artefacts, posing a significant artefact in the data cleaning procedure.

2. Expanding the range of user interactions Due to the overall study time and comfort of the participants, we minimised the user-system interaction into three judgments with pre-defined responses (see S2, S3, S4.1 and S4.2 in Figure 3.1) to focus on the relevant phenomenons in the study and explore their brain manifestations. The follow-up expansion of the study can 1) manipulate the spectrum of answer choices, including the strength of FOK judgements (S2) or mnemonic cues (S3), or 2) request the users to provide the exact answer (typed or voice-recorded) when they know the answer (corresponding KNOW level) and, thus, have a higher certainty when evaluating the accuracy of the Meta outcomes. The latter would result in an additional step placed between S2 and S3.

Second, our Q/A study can be characterised as a purposeless scenario from the participant's point of view. Participants provide a series of answers to trigger the subsequent trial, and the study is over when it runs out of questions from the data set. In this regard, we see the option of contextualising where the user's engagement fulfils some purpose, e.g. the user gets rewarded. The Q/A itself can be a part of a scenario to extend the information purpose, e.g. a point-based game, where the correct self-judgment/reflection of their state of knowing would contribute to a final reward. Such a scenario might investigate a novel perspective on the user's state of knowledge driven by the context and observe if the context stimulates the brain and the user's attention. We believe this might also increase user engagement throughout the whole study.

3. Expanding the space of relevant EEG signals This category relates to the diversification of the relevant data to increase the informativeness of the brain responses. For instance, expand the spectrum of judgments and the variability of the answer choices, as was introduced in paragraph 1. This idea would be associated with more granular insight into the categories of brain responses.

Second, we can obtain relevant signals by normalising the presentation of stimuli. In our study, the time-locking method of data acquisition is practically a type of signal normalisation, with relevant signals concentrated in a particular time and space. This way, we normalised the sequence of stimuli (S1). If we keep the current design of the study following the 3.1, a subsequent study can similarly investigate the signal associated with mnemonic cues (S3) to study another portion of the EEG timeline describing the users' information processing. Mnemonic cues were not in our study evaluated in relation to the brain response per se but rather to encode the prior signal (S1) that was then analysed. In the present setting, the mnemonic cues were presented simultaneously and not EEG normalised (i.e., time-locked presented one at a time). Therefore we could not associate a particular (single) mnemonic cue with its spatio-temporal signature. Future sequential processing of these cues could uncover another piece of information related to the investigation of memory recall. In particular, to observe how the brain reacts to a correct or an incorrect answer. In the area of IR, this information can help to uncover how data veracity modulates brain activity to address the points mentioned in the previous Section 8.3.4.

4. Within-participant design Within-participant design is a robust method of exploration of significant patterns whilst the user was tested under different conditions. During the investigation of behavioural data, we encountered data unbalances (some of the levels were hardly populated, such as NOSEARCH; see Table 4.3), which caused differences in the sample sizes available to analyse, depending on the specific EEG investigation. The effect of the unbalanced data decreased the comparison of the results between the studies. In an ideal case, these would have used the same data samples.

The ERP averaging method requires many trials, especially when combined with repeated measures. In order to increase the generalisation of the results and reduce the potential data unbalance issues, the study needs to recruit the number of participants exceeding the outcome determined by the power analysis.

8.6 Final Reflections

The present thesis supplied the cognitive context of the realisation of users' INs with the NeuraSearch-based investigation of the neurocognitive mechanisms as the drivers of users' decisions in the information search domain. In this spirit, the current thesis applied the qualitative inspection and the quantitative analysis of the real-time captured brain data concerning different users' states of knowing. We brought a multidisciplinary view on the metamnemonic and mnemonic underpinning of INs as an input informing the user's cognitive context. We believe this approach can potentially inform IR research, both theoretical and practical challenges. However, the implications of our findings are yet conceptual and require more research before the decisions about their operationalisation can be made.

In conclusion, our research embraced a still relatively novel branch of IR research, *NeuraSearch*, to examine the differing neural manifestations in the user's cognitive context underpinning INs. The contributions of this thesis are threefold: (1) Scientific contribution, where we unfolded the spectrum of the user's state of knowledge by providing evidence of levels not addressed to date. First, we demonstrated that the selected ASK levels that span a spectrum of anomalies have different neurocognitive underpinnings disassociated across the space (brain regions) and time (temporal dynamics) in healthy young individuals. (2) Academic contribution, where this thesis brought together knowledge from Computer & Information Sciences and Cognitive Neuroscience to develop a comprehensive framework that advances the understanding of the behaviours linked to INs and the associated neural mechanisms. (3) Social contribution, where we introduced the tools that can objectively assess the behavioural and neural drivers of INs that can be implemented into solutions in the field of IR, for instance, the already mentioned pro-active systems, conversational assistants or systems with BCI elements. The advantage of the collected data is their reusability in other, and not necessarily IR-dependent, computer science/data science projects, e.g. EEG signal processing, feature detection or large-scale dimensional data processing.

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Appendix A

Participant Information Sheet, Consent and Debriefing Form

A.1 Information Sheet for the Study

Participant Information Sheet

[FOR USE WITH STANDARD PRIVACY NOTICE FOR RESEARCH PARTICIPANTS]

Name of the department: Computer and Information Sciences

Title of the study: An EEG examination of neural activity during the process of experiencing information need awareness

Ethics Approval No.: 1017

Introduction

My name is Dominika Michalkova and I am a PhD candidate at the Department of Computer and Information Sciences at the University of Strathclyde, Glasgow, Scotland. We are currently conducting research into Information Retrieval process and brain imaging, where we are investigating brain activity during an information need realisation, employing electroencephalography (EEG). You are being invited to take part in a research study conducted as a part of a PhD project. Before you decide to participate, it is important for you to understand why the research is being conducted and what will be involved during the procedure. Please, take time to read the following information carefully and ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the purpose of this research?

The aim of the present study is to investigate the process of information need realisation using EEG during specifically designed question-answering tasks. The experiment is designed to create the situation of experiencing an information need. Through examining the difference between person having an information need vs. not having an information need, we would like to understand the neurological processes underlying neurological activity and associated cognitive processes. In order to investigate this, we will record your brain activity using EEG.

What is EEG?

EEG is a completely non-hazardous and non-invasive brain imaging technique that allows us to measure electrical currents produced by the neurons in the brain, while the brain is at rest or performs different tasks. EEG offers us an insight into dynamics of neuronal activity and associated cognitive process, with very accurate temporal resolution.

Is there any contradiction for EEG?

There is no known contradiction for EEG.

Do you have to take part?

No. Your participation in this research study is completely voluntary and you may withdraw at any time (including during the procedure) without giving any reason and without any consequences.

What will you do in the project?

At the beginning of the study, you will be given two questionnaires. During the first questionnaire, you will be asked to fill in basic demographical information and provide details about any existing medical conditions you might be diagnosed with which may impact EEG signal. In this way, your eligibility for taking part in the study will be evaluated. If you are assessed as being eligible, you will then be asked to fill in the second questionnaire, the Pre-Task Questionnaire, which will help us to understand your interests and area of knowledge.

After this, the main part of the experiment will follow. You will be seated comfortably in a chair. We will attach electrodes for measuring electrical activity on your scalp (which is painless) using an EEG cap. To achieve this, we will use a conductive gel to obtain a signal transmission, as the amplitudes of the signals produced by the brain are very small. The EEG are then connected to a computer which records brain activity, while you are performing experimental tasks. In the experiment, we will continuously record EEG. This will give us valuable information on the processes in the brain.

The study will consist of 120 trials which will be split into two identical sessions (60 trials each) via two breaks in between (one after each 1/3 of trials completed). First, you will have an opportunity to go through the practice trials first to familiarise yourself with the procedure until you are confident with the task. After the study completes, you will be asked to fill in an additional questionnaire: the Post-Task Questionnaire, targeted at understanding your experience during the experiment.

Every trial consists of the following parts: question presentation, prospective judgment, answer indication, confidence assessment or search (based on the indicated answer). At the beginning, you will be first presented with a question. The question is going to be presented as a set of words, presented sequentially. After that, you will be asked to judge your initial perception related to this question by three categories. Immediately after your response is submitted, no matter the content of your response, three answer choices related to the above question are going to appear on the screen.

There is always one correct answer, one incorrect answer and an option to indicate if you do not know the answer. You will be instructed to press the corresponding button as soon as you make your decision, whether you know or do not know the answer. There is no time limit for you to provide the response. The next flow will depend on your answer.

Flow 1: If you choose one of the two options, whether it is actually a correct or incorrect answer, you will move to the confidence assessment to indicate how confident are you with the just provided answer. After this, a correct answer for the current question appears on the screen. Fixation cross will follow, which is a marker of the start of the next question trial.

Flow 2: If you choose the option indicating you do not know the answer, you will be moved to the search screen where you mark your interest in looking up the answer. If you provide positive response, a correct answer appears on the screen. Next, the experiment will move to a next question.

You will receive instructions again prior to the experiment and you will have an opportunity to ask questions. The entire duration of the experiment is estimated to be around 116 minutes. You will be asked to sit still during the measurements since movements will interfere with getting accurate data. You will be notified in advance when it is requiring you to remain still. In addition, we will ask you to keep your gaze still. At the end of the experiment, the conductive solution will leave you hair slightly wet. However, you will be provided with towels and hairdryer if required.

Why have you been invited to take part?

You have been chosen to take part in the experiment because you are a fluent English speaker, over 18 years old, neurologically healthy and computer-literate.

What are potential risks for you in taking part in the experiment?

There are no risks associated with EEG. The test is painless and safe. However, to avoid you feeling uncomfortable, as it is required to sit still throughout the recordings, we will ensure enough breaks which you can use to move around.

What information is being collected in the project?

Participants' demographics information, views and experiences with the experiment will be collected through the questionnaires. Researchers will also collect behavioural and physiological data using e-Prime2 and EEG.

What happens to the information collected from the project?

All information and data collected during the experiment will be anonymised to the best possibilities. Your personal details will be stored securely in digital format and will be encrypted. The search logs and survey data we collect will be retained by the below-mentioned researchers (Dr Yashar Moshfeghi, Dr Mario Parra Rodriguez, Dominika Michalkova) and may be used in future project publications, following similar ethically approved research protocol. Your participation will remain confidential, and your name or any other directly identifiable information will NOT appear in any published documents relating to the research conducted.

The University of Strathclyde is committed to transparency and to complying with its responsibilities under data protection legislation. All collected data will be processed in accordance with the General Data Protection Regulation and the Data Protection Act 2018 and treated with the strict adherence to the Code of Practice of the University of Strathclyde. All personal and demographic data obtained will be used and presented in the aggregated format. Due to the sensitive nature of this research, data obtained in this experiment will not be openly available.

You may request for your personal data to be destroyed at any point in the future. Please note, however, that it will not be possible to remove your experimental data from analyses that have already been completed (e.g., once your data is combined with data from other participants). If you wish to request withdrawal of your data please contact yashar.moshfeghi@strath.ac.uk.

Please also read our Privacy Notice for Research Participants (see supplement). This can also be found here: https://tinyurl.com/y6wa4nzu

Who will have access to the information?

Only below-mentioned researchers (Dr Yashar Moshfeghi, Dr Mario Parra Rodriguez, Dominika Michalkova) will have access to the data. It is possible that the data may be used by the below-mentioned researchers for other similar ethically approved research protocols, where the same standards of confidentiality will apply. Due to the sensitive nature of the data, the data will not be shared (unless approved by the Principal Investigator, Dr Yashar Moshfeghi).

Where will the information be stored and how long will it be kept for?

The collected data will be stored and kept for as long as it is required by involved researchers. After that, the data will be securely deleted. The collected data will be stored privately at a secured location, which will be password protected. All data will be anonymised to the best possibilities.

The data will not be shared due to the sensitive nature (unless approved by the Principal Investigator, Dr Yashar Moshfeghi).

What happens next?

If you are happy to be involved in this project, please read and complete the following consent form. Then we can proceed to begin the experiment. Otherwise, we thank you for your time and dedication.

Thank you for reading this information. Please, feel free to contact the researcher if you are unsure about this experiment.

Researcher Contact Details:

Dominika Michalkova
PhD Candidate
Department of Computer
& Information Sciences
University of Strathclyde
Livingstone Tower
16 Richmond Street
Glasgow, G1 1XQ
dominika.michalkova@strath.ac.uk

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Strathclyde Chancellor's Fellow
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16 Richmond Street
Glasgow, G1 1XQ
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Dr Mario Parra Rodriguez
Lecturer
Department of Psychology
University of Strathclyde
Graham Hills Building
40 George Street
Glasgow, G1 1XQ
mario.parra-rodriguez@strath.ac.uk

Chief Investigator Details:

This research was granted ethical approval by the Department of Computer and Information Sciences Ethics Committee under application number 1017. If you have any questions or concerns, before, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought form, contact details are provided below:

Department of Computer and Information Sciences Ethics Committee
University of Strathclyde
Livingstone Tower
16 Richmond Street
Glasgow
G1 1XQ
United Kingdom
E-mail: ethics@cis.strath.ac.uk
Telephone: 0141 548 3707

A.2 Consent Form

University of Strathclyde Science

Research Informed Consent Form

Title of the project:
An EEG examination of neural activity during the process of experiencing of information need awareness

Ethics approval no.: 1017

Researcher's name: Dominika Michalkova
Researcher's e-mail: dominika.michalkova@strath.ac.uk
Name of department: Computer and Information Sciences

Please, read the following statements and insert your initials for each statement you agree with:

- I confirm that I have read and understood the information sheet for the experiment. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

  Participant's Initials: ……………………………………..

- I understand that my participation is entirely voluntary and that I am free to withdraw from the experiment at any time, up to the point of completion, without having to give a reason and without any consequences.

  Participant's Initials: ……………………………………..

- I understand that I can withdraw from the study any personal data (i.e. data which may identify me personally) at any time.

  Participant's Initials: ……………………………………..

- I understand that anonymised data (i.e. data which does not identify me personally) cannot be withdrawn once they have been included in the study.

  Participant's Initials: ……………………………………..

- I understand that any information recorded in the study will be treated confidentially and no information that identifies me will be made publicly available.

  Participant's Initials: ……………………………………..

If you would like a copy of this consent form to keep, please ask the researcher. If you have any complaints or concerns about this research, you can direct these to Departmental Ethics Committee, in writing by e-mail at: ethics@cis.strath.ac.uk

- I confirm that I have read and understood the Privacy Notice for Participants in Research Projects and understand how my personal information will be used and what will happen to it.

  Participant's Initials: ……………………………………..

- I understand that anonymised data will be stored in a secured location for as long as it will be required by involved researchers.

  Participant's Initials: ……………………………………..

- I consent to be a participant in this study.

  Participant's Initials: ……………………………………..

______________________________ ______________________________

Signature of the investigator Signature of the participant

Date:

If you would like a copy of this consent form to keep, please ask the researcher. If you have any complaints or concerns about this research, you can direct these to Departmental Ethics Committee, in writing by e-mail at: ethics@cis.strath.ac.uk

A.3 Debriefing Form

Debriefing Form

Title of the project:
An EEG examination of neural activity during the process of experiencing of information need awareness

Ethics approval no.: 1017

Researcher's name: Dominika Michalkova
Researcher's e-mail: dominika.michalkova@strath.ac.uk
Name of department: Computer and Information Sciences

Thank you for taking part in this research. The aim of this research is to investigate the information need realization process using electroencephalography (EEG) during specially designed question-answering tasks.

If you would like more information about this study, once it is completed, please contact the researcher: Dominika Michalkova by e-mail: dominika.michalkova@strath.ac.uk or my supervisor Dr Yashar Moshfeghi by e-mail: yashar.moshfeghi@strath.ac.uk.

If you are interested in this area of research, you may wish you read the following references:

Yashar Moshfeghi, Peter Triantafillou, Frank E. Pollick.: *Understanding Information Need: An fMRI Study.* In: Proceedings of the 39th Annual ACM SIGIR Conference Pisa, Italy, pp. 335- 344, July 2016.

Yashar Moshfeghi, Frank E. Pollick: *Search Process as Transitions Between Neural States*. In: The Web Conference 2018, Lyon, France, pp. 1683-1692, April 2018.

Yashar Moshfeghi, Frank E. Pollick: *Neuropsychological model of the realization of information need.* In: Journal of the Association for Information Science and Technology, 00(0):1 14, 2019

If this research has caused you any distress or discomfort and you would like to speak to someone, please, contact the following sources of support and advice: The Disability & Wellbeing Service, University of Strathclyde, e-mail: disability-wellbeing@strath.ac.uk, tel: 0141 548 3402.
More information can be found at:
https://www.strath.ac.uk/professionalservices/studentcounselling/

If you would like a copy of this consent form to keep, please ask the researcher. If you have any complaints or concerns about this research, you can direct these to Departmental Ethics Committee, in writing by e-mail at: ethics@cis.strath.ac.uk

Appendix B

Questionnaire Forms

B.1 Pre-Task Questionnaire A

Questionnaire A

Participant Code: ....

1. Age ....
2. Gender

   ☐ Male

   ☐ Female

   ☐ Prefer not to say

   ☐ Other
3. Nationality ....
4. Highest level of education completed ....
5. Field of work/study ....
6. If currently a student, please specify the level and year ....
7. English Language Proficiency

   ☐ Native

   ☐ Level C1/C2 (advanced/fluent English)
8. Interests (select all that apply):

   ☐ Visual Art (including films and TV)

   ☐ Music

   ☐ Literature

   ☐ Foreign languages

   ☐ Science and technology

☐ Politics

☐ Sport

☐ History

☐ Quiz shows

☐ Performance, e.g. musical performing (musical instrument playing, singing), visual art (painting, photography, DIY crafts)

☐ Other (please specify): ....

9. Any medical neurological diagnosis or conditions:

....

....

10. Current condition need to be mentioned:

☐ Headache

☐ Nausea

☐ Other: ....

B.2 Pre-Task Questionnaire B

Questionnaire B

Participant Code: ....

1. How often do you use search engines (e.g. Google) to look up information:
   - ☐ Multiple times per day
   - ☐ Once per day
   - ☐ Frequently
   - ☐ Occasionally
   - ☐ Not at all

2. What is your preferable source of finding information quickly, e.g. fact finding:
   - ☐ Online search engines
   - ☐ Libraries and their catalogue and databases
   - ☐ Other (please specify):..

3. Preferable source of information and materials for a thorough research:
   - ☐ Online search engines
   - ☐ Libraries and their catalogue and databases
   - ☐ Other (please specify):..

4. Please select all that apply:
   - ☐ I often run multiple simultaneous searches
   - ☐ I usually complete one search before I move to another one
   - ☐ One search usually leads me directly to another one I start
   - ☐ I often find myself overload with information even though I know exactly what I am looking for

5. Now you will be given a serie of general knowledge questions; we want you to reflect upon each of these:

5.1.

Which country features a maple leaf on its flag?

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

5.2.

Name the play by Shakespeare that features a brooding Danish prince?

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

5.3.

What band featured Sting, Stewart Copeland and Andy Summers?

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

5.4.

What vegetable in the mustard family is named for a European capital city?

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

5.5.

What is the translation of this Morse code: · · · – – – · · ·

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

5.6.

What Korean martial art translates as "the way of the hand and foot"?

A) Imagine reading the sentence sequentially word-after-word. Please underline the word or a sequence of words when you start feeling that (please select) :

☐ I might know the answer

☐ I might not know the answer

B) After reading the whole question, (please select):

☐ I know the answer

☐ I do not know the answer

B.3 Post-Task Questionnaire

Questionnaire C

Participant Code: ....

1. In your opinion, how did you find the task you had to perform in general (select all that apply) :

   - ☐ Easy
   - ☐ Not so easy
   - ☐ Slightly Difficult
   - ☐ Difficult
   - ☐ Challenging
   - ☐ Familiar
   - ☐ Interesting
   - ☐ Understandable
   - ☐ Stressful
   - ☐ Other: (please specify) ....

2. How did you find the set of general knowledge questions you were given?

   ....

   ....

3. The experiment contained the option to look for a correct answer, in case you had identified that you do not know the right answer.

   A) In case, you at least once, responded POSITIVELY to search for the answer, please, reflect upon your motivations/ interests in finding and so learning the answer

   ....

   ....

B) In case, you at least once, responded NEGATIVELY to search for the answer, please, reflect upon your motivations or interests in NOT finding and so NOT learning the answer:

....

....

4. The study you have performed consisted of 3 sessions (separated by a break after 13 of questions completed). How would you assess your performance and effort ? (select all that apply).

- ☐ Honest. I answered all questions based on my knowledge.
- ☐ I know I occasionally pressed a wrong button, i.e. a typo.
- ☐ My effort was constant throughout all parts of the study.
- ☐ I put the highest effort in 1/3 part
- ☐ I put the highest effort in 2/3 part
- ☐ I put the highest effort in 3/3 part

5. Any comments you wish to share about the experiment and your experience, e.g. challenging parts

....

....

....

....

Your participation at the experiment is greatly appreciated. Thank you.

Appendix C

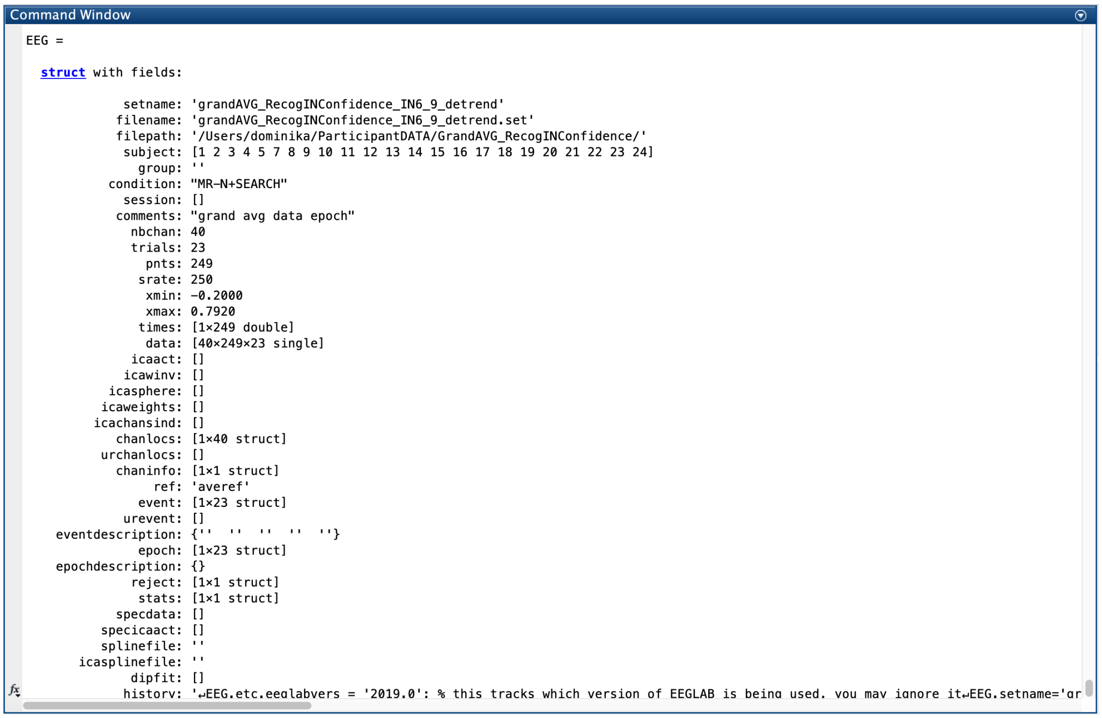
Q/A Dataset

#	Question	Correct	Incorrect	Difficulty	Source	TRIAL
1	What Asian nation has the world's largest religious monument?	Cambodia	India	D	B-KNorms	main
2	What type of animal was the Egyptian god Horus?	Falcon	Jackal	D	B-KNorms	main
3	What was the first nation to picture Albert Einstein on banknotes?	Israel	Switzerland	D	B-KNorms	main
4	What did physicist Lord Rutherford discover inside the nucleus of the atom?	Proton	Positions	D	B-KNorms	main
5	What country do Walloons call home?	Belgium	Netherlands	D	B-KNorms	main
6	What Canadian province was named after a daughter of Queen Victoria?	Alberta	Adelaide	E	B-KNorms	main
7	What fish the Old man battled with in one of the Hemmingway's novels?	Marlin	Catfish	D	B-KNorms	main
8	What U.S. state has the longest shoreline?	Alaska	California	D	B-KNorms	main
9	Which islands were the site of Columbus' first landing in the New World?	Bahamas	Antilles	D	B-KNorms	main
10	What part of the cinnamon plant is prepared for use as a spice?	Bark	Leaf	E	B-KNorms	main
11	What is the pure spirit distilled from wine?	Brandy	Vinegar	D	B-KNorms	main
12	What sea lies between Riga and Stockholm?	Baltic Sea	Black Sea	E	B-KNorms	main
13	What bean provides the coloured inks used in most U.S. daily newspapers?	Soy	Black	D	B-KNorms	main
14	What country maintains administrative rule over Greenland?	Denmark	Russia	D	B-KNorms	main
15	What nationality was the painter Rembrandt?	Dutch	French	E	B-KNorms	main
16	What is the northernmost Scandinavian country?	Norway	Finland	E	B-KNorms	main
17	Who was assigned to steal the girdle of the Amazon queen Hippolyte?	Hercules	Achilles	D	B-KNorms	main
18	What country dropped Christmas public holiday in 1969 to harvest more sugar?	Cuba	Dominique	D	B-KNorms	main
19	What is the fastest healing part of the body?	Tongue	Lips	D	B-KNorms	main
20	What is the last name of the author of Sherlock Holmes stories?	Doyle	Stevenson	E	B-KNorms	main
21	Color is determined by what physical property of light?	Wavelength	Deflection	D	B-KNorms	main
22	What company invented the microprocessor in 1971?	Intel	IBM	E	B-KNorms	main
23	Which are the only birds able to fly backwards?	Hummingbird	Swallow	D	B-KNorms	main
24	What terms describes series of uncontrollable air intakes by sudden contraction of diaphragm?	Hiccups	Hypertension	D	B-KNorms	main
25	People of which major nationality invaded Russia in the war of 1812?	France	Spain	D	B-KNorms	main
26	Which UK prime minister was a singer in the band Ugly Rumors?	Blair	Cameron	D	B-KNorms	main
27	A bone is joined to a muscle by which structure?	Tendon	Ligament	D	B-KNorms	main
28	What country suffered the slaughter of half million Tutsis and Hutus in 1994?	Rwanda	Uganda	D	B-KNorms	main
29	What is the standard unit of sound intensity?	Decibel	Hertz	E	B-KNorms	main
30	What is the name of the furry animals that attack cobra snakes?	Mongoose	Rabbits	E	B-KNorms	main
31	What is the name of the Roman Goddess of Love?	Venus	Aphrodite	D	B-KNorms	main
32	What nuts are used in marzipan?	Almond	Hazelnut	E	B-KNorms	main
33	What is the mythological creature with woman's head and lion's body?	Sphinx	Pandora	E	B-KNorms	main
34	The play 'Julius Caesar' is considered to be part of what genre?	Tragedy	Comedy	E	B-KNorms	main
35	Which organ in the body stores excess sugar as glycogen?	Liver	Pancreas	D	B-KNorms	main
36	What element is a diamond made out of?	Carbon	Germanium	D	B-KNorms	main
37	A bowl of 'pho' is a traditional soup in what Southeast Asian country?	Vietnam	Thailand	D	B-KNorms	main
38	What is the name of remains of plants and animals found in stones?	Fossils	Sediments	E	B-KNorms	main
39	Who was the the only U.S. President who resigned to avoid impeachment?	Nixon	Clinton	D	B-KNorms	main
40	What is the name of Socrates' most famous student?	Plato	Aristotle	E	B-KNorms	main
41	What is the only liquid metal at room temperature?	Mercury	Zinc	D	B-KNorms	main
42	In which game are the standard pieces of Staunton design?	Chess	Backgammon	D	B-KNorms	main
43	What bird cannot fly and is the largest bird on Earth?	Ostrich	Emu	D	B-KNorms	main
44	What color appears an object reflecting light of all wavelengths in equal amounts?	White	Blue	E	B-KNorms	main
45	What transparent material is produced by heating lime, sand, and soda?	Glass	Cellophane	E	B-KNorms	main
46	What is the shape of a stop sign?	Octagon	Square	E	B-KNorms	main
47	Bamboo is a favourite food of which member of the bear family?	Panda	Koala	E	B-KNorms	main
48	What material is associated with a couple's third anniversary?	Leather	Cotton	D	B-KNorms	main
49	In what city were the cancelled 1940 summer Olympics supposed to take place?	Tokyo	Berlin	D	B-KNorms	main
50	Jesse James was called the 'Robin Hood' of what U.S. state?	Missouri	Louisiana	D	B-KNorms	main
51	The berries of what plant give gin its flavour?	Juniper	Mulberry	D	B-KNorms	main
52	Which scientist first studied genetic inheritance in plants?	Mendel	de Vries	D	B-KNorms	main
53	What medical term describes a procedure of taking issues for microscopic examination?	Biopsy	Endoscopy	D	B-KNorms	main
54	Which priest began 16th Century Reformation in Germany?	Luther	Calvin	E	B-KNorms	main
55	Which animals did the Russian physiologist Pavlov use in studies of reflexive behavior?	Dogs	Monkeys	D	B-KNorms	main
56	An equestrian is skilled in working with what kind of animal?	Horses	Eagles	E	B-KNorms	main
57	What country has the ancient ruins of Machu Picchu?	Peru	Mexico	E	B-KNorms	main
58	Who is the author of the painting 'Guernica'?	Picasso	Bracques	E	B-KNorms	main
59	What is the Taj Majal made of?	Marble	Gold	D	B-KNorms	main
60	What fruit is the main ingredient of guacamole?	Avocado	Cucumber	E	B-KNorms	main
61	Who was the first doctor to successfully transplant a liver?	Thomas Starzl	Christian Barnaard	D	TREC	main
62	When was London's Docklands Light Railway constructed?	Late 1980s	Late 1960s	D	TREC	main

#	Question	Correct	Incorrect	Difficulty	Source	TRIAL
63	What is the acronym for the rating system for air conditioner efficiency?	EER	ACE	D	TREC	main
64	What is ozone depletion?	The reduction of the amount of ozone in the stratosphere	The reduction of the amount of ozone in the exosphere	D	TREC	main
65	Who played the part of the Godfather in the movie, "The Godfather"?	Marlon Brando	Al Pacino	E	TREC	main
66	Who invented the telephone?	Alexander Graham Bell	Thomas Edison	E	TREC	main
67	What is caffeine?	World's most widely consumed psychoactive drug	Natural compound that decreases activity in the brain	E	TREC	main
68	What is a shaman?	Master of higher spiritual awareness and realms	Fictional comic book superhero	E	TREC	main
69	What does cc in engines mean?	Cubic centimetres	Car club	E	TREC	main
70	What is the pH scale?	Scale of how acidic a water-based solution is	Scale of human performance at the workplace	E	TREC	main
71	What type of currency is used in Australia?	AUD	AUS	E	TREC	main
72	What is amoxicillin?	Antibiotic	Antidepressant	D	TREC	main
73	What is the oldest university in the US?	Harvard	Yale	E	TREC	main
74	What is acupuncture?	Alternative treatment with roots in Chinese medicine	Oldest form of surgery coming from ancient Egypt	E	TREC	main
75	Who first circumnavigated the globe?	Ferdinand Magellan	Amerigo Vespucci	D	TREC	main
76	Who won the Nobel Peace Prize in 1991?	Aung San Suu Kyi	Nelson Mandela	E	TREC	main
77	Who was the second man to walk on the moon?	Edwin Eugene Aldrin Jr.	Alan Bean	D	TREC	main
78	What is sodium chloride?	Table salt	Bleach	E	TREC	main
79	What French ruler was defeated at the battle of Waterloo?	Napoleon I.	Louis XIV.	E	TREC	main
80	What is Wimbledon?	Tennis tournament	Series of boat races	E	TREC	main
81	During which season do most thunderstorms occur?	Summer	Spring	E	TREC	main
82	What is supernova?	Exploding star	A giant cloud of dust and gas in space	E	TREC	main
83	What does the Peugeot company manufacture?	Motor vehicles	Household appliances	E	TREC	main
84	What is the name of the highest mountain in Africa?	Kilimanjaro	K2	E	TREC	main
85	Who leads the star ship Enterprise in Star Trek?	James T. Kirk	Han Solo	E	TREC	main
86	What is the average weight of a male yellow Labrador?	29-36kg	35-42kg	D	TREC	main
87	What is a biosphere?	Global ecological system	Alternative agricultural system	E	TREC	main
88	Who founded American Red Cross?	Clara Barton	Florence Nightingale	D	TREC	main
89	What is the oldest city in the United States?	St. Augustine	San Francisco	D	TREC	main
90	What mineral helps prevent osteoporosis?	Calcium	Zinc	E	TREC	main
91	Who discovered radium?	Marie and Pierre Curie	Sir William Ramsay	E	TREC	main
92	What is amitriptyline?	Antidepressant drug	Antidiabetic drug	D	TREC	main
93	What is the length of the coastline of the state of Alaska?	6,640 miles	3,520 miles	D	TREC	main
94	What is Hawaii's state flower?	Yellow hibiscus	Pink orchid	E	TREC	main
95	What is phenylalanine?	An enzyme used in the artificial sweetener	Artificial food color additive	D	TREC	main
96	What primary colours do you mix to make orange?	Yellow and red	Red and green	E	TREC	main
97	Where is the Euphrates River?	Turkey	Egypt	E	TREC	main
98	What is the longest suspension bridge in the U.S.?	Verrazano-Narrows, New York	Golden Gate, San Francisco	D	TREC	main
99	What trade name polymer is used for bulletproof vests?	Kevlar	PVC	E	TREC	main
100	What are amphibians?	Animals that live in both water and on land	Coarse-grained metamorphic rocks	D	TREC	main
101	How did Janice Joplin die?	Heroin overdose	Food poisoning	E	TREC	main
102	What are Quaaludes?	Sedative and hypnotic medication	Ethnic group inhabiting India and Pakistan	D	TREC	main
103	What hemispheres is the Philippines in?	Northern and eastern	Southern and eastern	D	TREC	main
104	What do bats eat?	Insects	Arachnids	E	TREC	main
105	Material called linen is made from what plant?	Flax plant	Corn plant	E	TREC	main
106	What is the longest bone in the human body?	Femur	Humerus	D	TREC	main
107	What were Christopher Columbus' three ships?	the Niña, the Pinta, the Santa Maria	the Lucia, the Navidad, the Santa Maria	E	TREC	main
108	What imaginary line is halfway between the North and South Poles?	Equator	Prime Meridian	E	TREC	main
109	What are invertebrates?	Animals lacking a backbone	Anti-obesity medication	E	TREC	main
110	What are coral reefs?	Underwater ecosystem with reef-building animals of corals	Underwater ecosystem with reef-building plants of corals	D	TREC	main
111	Why does the moon turn orange?	The moon is low in the sky	The moon is high in the sky	D	TREC	main
112	Which country gave New York the Statue of Liberty?	France	Spain	E	TREC	main
113	When is the official first day of summer?	June 21st	June 23rd	E	TREC	main
114	What is the active ingredient in baking soda?	Sodium bicarbonate	Sodium chloride	E	TREC	main
115	Where are the British crown jewels kept?	The Tower of London	Buckingham Palace	E	TREC	main
116	What is vertigo?	Sensation of whirling and loss of balance	Fear of heights	E	TREC	main
117	What is Teflon?	Trademark for non-stick cookware coatings	Synthetic fiber	E	TREC	main
118	What is the atomic weight of silver?	107.8682	101.1566	D	TREC	main
119	What country did Ponce de Leon come from?	Spain	Cuba	D	TREC	main
120	When was China's first nuclear test?	1964	1958	D	TREC	main
121	What continent is Egypt on?	Africa	Asia	E	TREC	practice
122	What is an ulcer?	Open sore on the body	Skin tag	E	TREC	practice
123	When is St. Patrick's Day?	March 17th	March 23rd	D	TREC	practice
124	For which country was Drachma the monetary unit?	Greece	Syria	E	B-KNorms	practice
125	What number is represented by the Roman numeral 'X'?	10	100	E	B-KNorms	practice

Appendix D

EEG Metadata File Structure



```
Command Window
EEG =

  struct with fields:

             setname: 'grandAVG_RecogINConfidence_IN6_9_detrend'
            filename: 'grandAVG_RecogINConfidence_IN6_9_detrend.set'
            filepath: '/Users/dominika/ParticipantDATA/GrandAVG_RecogINConfidence/'
             subject: [1 2 3 4 5 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24]
               group: ''
           condition: "MR-N+SEARCH"
             session: []
            comments: "grand avg data epoch"
              nbchan: 40
              trials: 23
                pnts: 249
               srate: 250
                xmin: -0.2000
                xmax: 0.7920
               times: [1×249 double]
                data: [40×249×23 single]
              icaact: []
             icawinv: []
           icasphere: []
          icaweights: []
         icachansind: []
            chanlocs: [1×40 struct]
          urchanlocs: []
            chaninfo: [1×1 struct]
                 ref: 'averef'
               event: [1×23 struct]
             urevent: []
    eventdescription: {''  ''  ''  ''  ''}
               epoch: [1×23 struct]
    epochdescription: {}
              reject: [1×1 struct]
               stats: [1×1 struct]
            specdata: []
          specicaact: []
          splinefile: ''
       icasplinefile: ''
              dipfit: []
             history: '↵EEG.etc.eeglabvers = '2019.0'; % this tracks which version of EEGLAB is being used, you may ignore it↵EEG.setname='gr
```