

**Drawing the wrong conclusions:
Cognitive conflict and biases of
dual-process theory in conceptual
product design**

by

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Abstract

Design cognition research has long recognised the importance of intuitive and analytic reasoning in design, yet the field continues to face persistent challenges regarding theoretical advancement and impact in this area. Specifically, there is a lack of alignment of design cognition with established ontological and methodological standards, limited design-specific instruments grounded in established cognitive theory, and limited integration of quantitative and qualitative methods. This thesis addresses these challenges by adapting dual-process theory (DPT) from cognitive psychology to the study of conceptual design.

Dual-process theory categorises cognition into two types of processing: Type 1 which is intuitive, autonomous processing, and Type 2 which is analytic processing that burdens limited executive cognitive resources (i.e. working memory). In particular, little is known about how individual differences in dual-processing constructs shape design behaviour, or how such differences can be measured in a way that is both theoretically grounded and ecologically relevant to design practice.

Building on the default–interventionist account of DPT, this research proposes a novel theory of cognitive conflict in design grounded in the Function–Behaviour–Structure (FBS) framework. This FBS conflict theory conceptualises design conflict as arising from mismatches between intuitive and analytic interpretations of function, behaviour, and structure. This thesis undertakes a cycle of theory building and theory testing across two descriptive studies.

Descriptive Study I operationalised this theory through a novel psychometric instrument - the Design Conflict Test (DCT) - which was developed as a design-specific version of heuristics-and-biases reasoning tasks from cognitive psychology. Designed to elicit and measure design-specific dual-processing tendencies, the DCT combines visual design stimuli with multiple-choice responses to induce intuitive lure answers and opportunities for analytic override. In this study (n=23), designers were asked to complete the DCT and other psychometric tests (the Cognitive Reflection Test, and a working memory capacity test). Eye-tracking and feelings-of-rightness

measures were used alongside performance data to examine whether the test engages cognitive mechanisms consistent with dual-process theory. Results indicated that the DCT elicits cognitive conflict and engages both intuitive and analytic processing, while remaining independent of working-memory capacity. However, divergence from predicted correlations with the Cognitive Reflection Test highlighted both the design-specific nature of the construct and the need for further item refinement.

Descriptive Study II investigated how individual differences measured by the DCT manifest in observable design behaviour. Using linkographic analysis of a conceptual design task, designers from the first study (n=6) positioned across scores on the DCT and Cognitive Reflection Test were examined. The findings revealed distinct process patterns consistent with dual-process theory, including behaviours aligned with the fundamental heuristic bias and the fundamental analytic bias. These results demonstrated that design-specific dual-processing tendencies can be meaningfully linked to real design activity.

Overall, the thesis demonstrates that dual-process constructs can be meaningfully adapted to design cognition when grounded in design-relevant theory and methods. While the DCT remains a prototype requiring refinement, the work establishes a credible empirical and theoretical foundation for measuring design-specific dual-processing tendencies and connecting them to real design activity. The strengths, limitations, and opportunities for future research are discussed, with particular emphasis on refining psychometric instruments, extending investigation across expertise levels, and advancing mixed-method approaches to design cognition research.

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List of Published Papers

This thesis is partially based on one conference paper and one journal article described below. These are referred to as Paper A and Paper B in this thesis.

Paper A

Lawrie, E., Hay, L., and Wodehouse, A. (2023). A Classification of Methods and Constructs in Design Cognition Research. *Design Computing and Cognition DCC'22*, edited by John S Gero, 97–114. Cham: Springer Nature Switzerland.

Paper B

Lawrie, E., Flus, M., Olechowski, A., Hay, L., & Wodehouse, A. (2025). From theory to practice: a roadmap for applying dual-process theory in design cognition research. *Journal of Engineering Design*, 36(12), 2204–2224.

The work reported in Paper A was conducted by the author of this thesis as an individual PhD student. The work reported in Paper B was led by the author of this thesis with contribution from another PhD researcher and editorial guidance from additional co-authors. The contributions of Paper B written by the other researcher do not feature in this thesis. In each case, co-authors provided the same level of general and editorial guidance for the work included in this thesis as they provided for the PhD thesis as a whole.

Signed: 

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Abbreviations

Term	Meaning
CRT	Cognitive Reflection Test
DCT	Design Conflict Test
DRM	Design Research Methodology
DPT	Dual-Process Theory
FOR	Feeling of Rightness
FBS	Function-Behaviour-Structure
PASAT	Paced Auditory Serial Addition Test
WMC	Working Memory Capacity
DS I	Descriptive Study I
DS II	Descriptive Study II

1 INTRODUCTION

1.1 Background literature

1.1.1 Conceptual design cognition in product design

The scientific investigation of mental processes is known as cognitive psychology (Anderson, 2015). When this investigation focuses on the mental processes of designers while designing, this is the discipline of design cognition research. Much design cognition research has focused on the conceptual design phase - an early stage of the design process that aims to identify the basic outline and foundational principles behind a design concept (Dinar et al., 2015). While a lot has been learnt about conceptual design cognition, the field faces persisting challenges.

According to Blessing and Chakrabarti (2009), design research has two objectives within the aim of making design more effective and efficient. The first is “the formulation and validation of models and theories about the phenomenon of design with all its facets”, the second objective is “the development and validation of support founded on these models and theories, in order to improve design practice, including education, and its outcomes”. However, the lack of a solid theoretical foundation in design research has been often discussed (Blessing & Chakrabarti, 2009; Dinar et al., 2015; Hay et al., 2017a, 2020). Furthermore, the discipline’s complexity requires a diverse range of research methods to fully contend with the topic (Blessing & Chakrabarti, 2009). The field’s reliance on methods such as protocol analysis -

examining a designer's cognition through the verbalisation of their thoughts (van Someren et al., 1994), has driven a tendency towards qualitative, subjective, and small-scale research. The think aloud aspect of protocol analysis presents further limitations in that it affects the cognition of the designer (Shealy et al., 2023). Such limitations have aided in preventing the scientific rigour required to build a more solid theoretical foundation for design cognition research (Dinar et al., 2015; Hay et al., 2017a).

Despite limitations, there has been recent rapid growth in design cognition research which requires comprehensive overview to support the field's progression. Reviews in design research across recent decades have continuously noted the persisting i) lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research (Blessing & Chakrabarti, 2009; Cash, 2018; Dinar et al., 2015; Hay et al., 2017a, 2017b). These form the three core challenges this work addresses by following appeals to introduce and align with the research methods, ontology, and theory from the more established field of cognitive psychology (Cash et al., 2019; Hay et al., 2020). However, diversifying research methods by using those established in other fields is often done with an incomplete understanding of the foundational paradigms involved (Blessing & Chakrabarti, 2009). This can lead to using unsuitable and unfamiliar methods in an improper way, and the production of flawed data (Blessing & Chakrabarti, 2009).

1.1.2 Defining cognitive constructs and accounts

To support the investigation of design cognition in this thesis, it is pertinent to distinguish both the phenomena being researched and the ways of explaining the relationships between them. Two key formalisms are used throughout this work: (1) constructs; and (2) accounts.

Constructs are taken here to be conceptualisations of cognitive processes, defined in psychology and neuroscience as “entities that transform or operate on mental representations”. From this, ‘mental representations’ are “mental entities that stand in relation to some physical entity... or abstract concept”. (Poldrack et al., 2011)

Accounts are defined here as models, theories, and frameworks that formalise and explain relationships between design cognition constructs. A framework denotes a group of defined constructs and potential relationships between the constructs and concerned phenomena; however, it lacks the organisation required for a theory (Anderson, 1983; McGregor, 2018). Theories can be derived from frameworks when the relationships between the constructs can be described, and testable hypotheses can be deduced (Anderson, 1983; Karakaş & Başar, 2006; McGregor, 2018). A theory remains broader still than a model, which is created when a theory is applied to a certain phenomenon (Anderson, 1983; Fried, 2020). Models are often accompanied by schematic representation (McGregor, 2018). A cognitive model of conceptual design would therefore depict the designer's cognitive processes used while designing, and the relationships between these cognitive processes, with the goal of understanding how these processes influence the designer's behaviour (Adelson, 1989; Finger & Dixon, 1989).

1.1.3 Research focus - dual-process theory

The discussed consistent reference to rigour as a key concern in design research is operationalised within this work across both theoretical and methodological domains. Within these concerns, reference is often made to tackling this challenge through aligning with standards in other fields (Cross, 2008; Hay et al., 2017b), ensuring internal validity alongside external validity, ensuring construct validity, using triangulation and multiple data sources, maintaining consistency, and targeting a close connection between thinking and verbal reports (Haupt, 2015; Hay et al., 2020). Theory-driven research has been presented as a path to achieving such standards both for theoretical rigour and subsequent methodological rigour built on these foundations (Cash, 2018). Indeed, research that is theory-driven supports the development of methods and acts as a foundation for considering the rigour of the method (Cash, 2018). In having a strong understanding of underlying mechanisms of design behaviour, insights can be brought together and act as a better foundation for developing design tools and interventions based on findings.

In following this theory-driven approach, this work is supported by a strong theoretical foundation which aims to tackle the discussed challenges in design

research. To address these by aligning with cognitive psychology, one well-established theory with reliable methods is dual-process theory (DPT). This was taken as the foundation of the theoretical and experimental work documented in this thesis.

DPT was developed in cognitive psychology and categorises cognition into two types of processing: intuitive, autonomous processing, and analytic reflective processing that burdens limited executive cognitive resources (De Neys, 2018b; Evans & Stanovich, 2013). In many tasks, Type 1 processes generate an initial response, which may be accepted or overridden depending on whether conflict or uncertainty is detected and whether Type 2 engagement is initiated. As DPT research has evolved, emphasis has been put not only on the distinction between the two types, but also how individuals differ in their tendencies, abilities, and metacognitive regulation of intuitive and analytic thought (De Neys, 2018a; Evans, 2019).

Despite the fundamental nature of DPT - research applying the theory in design is limited. Design is an interesting domain in which to explore these dynamics, requiring an iterative approach with different focuses at each stage of the design process. Such activities likely involve different ratios and frequency of switching between intuitive and analytic processing. Prior work in design cognition has suggested that designers rely more heavily on intuitive processes during generative phases and on analytic processes during evaluative phases (e.g. Cash & Maier, 2021; Gonçalves & Cash, 2021). These accounts take important perspectives in applying DPT to design. However, there is limited focus on understanding how individual differences affect design cognition relate to DPT constructs.

This thesis, therefore, adopts dual-process theory as its theoretical foundation extending it to design cognition. It develops a theory of cognitive conflict based on established design frameworks as a mechanism for Type 2 engagement in design, constructs a prototype psychometric instrument - the Design Conflict Test (DCT) - to measure individual dual-processing tendencies, and examines how these tendencies manifest in design behaviour using linkography.

1.2 Aim and objectives

This thesis is motivated by a lack of theoretical and methodological rigour hindering the impact and progress of design research. To address this, the aim of this research is to provide a greater understanding of intuitive and analytic cognitive processes of product designers during the conceptual design phase. To achieve this aim, the following objectives are defined:

- O1.** Identify challenges facing conceptual design cognition research to define the research focus and determine a theory as a means of tackling these challenges.
 - O1.1. Determine the current state of knowledge on conceptual design cognition.
 - O1.2. Identify shortcomings in the literature on conceptual design cognition research.
 - O1.3. Select an appropriate cognitive theory from established literature as a basis for addressing the identified shortcomings in design cognition research.
- O2.** Determine a model from the chosen theory and align it with design cognition insights as foundation for investigating conceptual design cognition.
 - O2.1. Gather observations on the determined theory from design cognition and cognitive psychology literature to inform the selection of a model.
 - O2.2. Select a model of the chosen theory that can be used to investigate design cognition.
 - O2.3. Make inferences about the cognitive processes involved in conceptual design cognition from this model.
- O3.** Assess the validity and utility of the model through both quantitative and qualitative methods.
 - O3.1. Based on the inferences, develop a quantitative test of design cognition through adapting established methodological techniques.
 - O3.2. Apply the developed test to investigate conceptual design cognition.
 - O3.3. Evaluate the results through qualitative analysis to ensure alignment with theoretical expectations and deepen understanding of cognitive processing.
- O4.** Evaluate the work to recognise the advantages, disadvantages, and potential areas for future research.

1.3 Thesis structure

The objectives laid out in Section 1.2 ultimately revolve around a theory that was developed, tested, and documented in this thesis. Therefore, the thesis is structured into three main parts documenting the development of the theory, evaluation of the theory, and a critique of the work. The content of each part and its chapters is outlined in the following and relationships between the objectives and the thesis are noted.

1.3.1 Part 1: Theory Development (Chapters 3, 4, and 5)

Chapters 3, 4, and 5 focus on the identification of the research focus (O1) and the development of a theory for studying design cognition (O2). Chapter 3 presents the findings from a literature review of existing research on conceptual design cognition (O1.1). This chapter explores the methods and constructs currently used in design cognition research and highlights shortcomings from the literature (O1.2). Specifically, these shortcomings relate to i) the lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research. The overarching research aim is framed to address these challenges, focusing on providing a greater understanding of the intuitive and analytic cognitive processes of designers during conceptual design cognition.

Through Chapter 3, dual-process theory is identified as a suitable theory for addressing the identified shortcomings in the literature (O1.3). Chapter 4 follows with a literature review of how dual-process theory (DPT) aligns with design cognition research (O2.1) documenting the methodological approaches and theoretical constructs used in both DPT and design cognition literature. In Chapter 5, a DPT model is selected as a basis for experimental work based on the literature reviews (O2.2). From the selected model, inferences about conceptual design cognition are made (O2.3) and a theory of design cognition is proposed.

1.3.2 Part 2: Theory Evaluation (Chapters 6 and 7)

Chapters 6 and 7 present the research approach taken to evaluate the theory developed in Chapter 5 (O3). Two aspects to this evaluation are identified based on Part 1: cognitive conflict (the focus of Chapter 6), and cognitive bias (the focus of Chapter 7). In Chapter 6, the developed theory is operationalised in a novel psychometric test targeting cognitive conflict (O3.1) and tested experimentally (O3.2). In Chapter 7, a smaller sample of key participants from the test are examined further using linkography of a design task based on identifying cognitive bias (O3.3).

1.3.3 Part 3: Reflections (Chapter 8 and 9)

Chapter 8 provides a discussion of the work in its entirety. Advantages and disadvantages are highlighted as well as recommendations for future work in the field (O4). Chapter 9 concludes the thesis with a summary of the work, its findings, and an outline of more immediate future work.

1.4 Research questions

The research documented in Part 1, Part 2 and Part 3 was guided by four overarching research questions (RQs) that emerged throughout the work. The first RQ guided the initial literature review (Chapter 3):

RQ1: What are the methods and constructs used in design cognition research?

From this initial inquiry three key challenges were identified (see Section 1.3.1) and dual-process theory was selected as the theoretical foundation to address these challenges. This led to the second literature review (Chapter 4), and a proposed theory of design conflict (Chapter 5) which was guided by:

RQ2: How do DPT methods and constructs align with design cognition methods and constructs?

The second literature review completed under RQ2 led to the last two research questions that guided the empirical work in this thesis. This work conducted in Chapters 6 and 7 was led by:

RQ 3: How can individual differences in dual-processing tendencies be measured in design cognition?

RQ4: What differences in conceptual design do individual differences in dual-processing tendencies cause?

These four research questions are discussed in greater depth in their respective chapters, hypotheses are made where relevant, and sub-research questions are posed. The four overarching research questions discussed here provide context for reading this thesis. These questions, the challenges they address and the chapters in which they are asked are displayed in Figure 1-1.

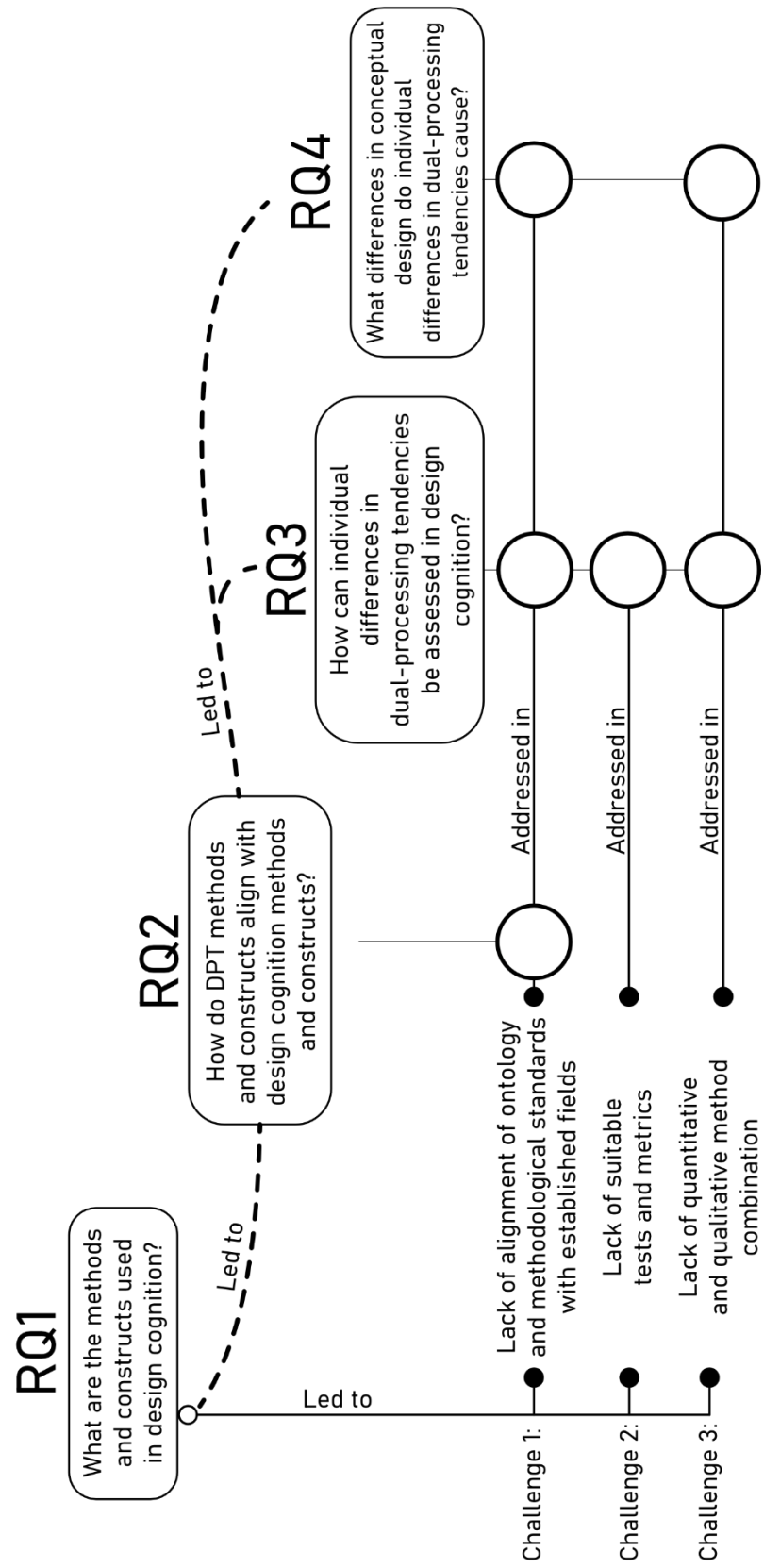


Figure 1-1 - Main research questions, challenges, and corresponding chapters.

2 RESEARCH APPROACH

A research approach consists of the plans and procedures involved in research ranging from broad assumptions to data collection methods, analysis, and interpretation (Creswell & Creswell, 2018). A research approach was determined to effectively address the aim and objectives. This can be divided into research philosophy, research methodology, and research design (Creswell & Creswell, 2018).

2.1 Research philosophy

The philosophical worldview from which research is conducted is hugely influential and necessitates clear identification (Creswell & Creswell, 2018). A philosophical worldview can be considered the “set of basic beliefs that guides action” (Creswell & Creswell, 2018; Guba, 1990, p. 17). There are many philosophical worldviews that can be adopted, the main assumptions involved are: ontology, epistemology, axiology, and methodology (Guba & Lincoln, 1994; Saunders et al., 2023). These are assumptions about the nature of reality (ontology), how knowledge about that reality is understood (epistemology), how your own values shape this knowledge and to what extent (axiology), and how this knowledge can be discovered (methodology) (Guba & Lincoln, 1994; Saunders et al., 2023).

There are many philosophical positions that have become paradigms of research. Rather than ascribing an existing paradigm to this work, the underlying main research

assumptions taken are outlined in Table 1 and discussed in the following.

Table 2-1 - Philosophical Assumptions

Type of assumption	Implications
Ontology	Critical realism: an objective reality exists although it can only be understood imperfectly.
Epistemology	Epistemological relativism: knowledge is shaped by theoretical assumptions and remains open to revision through empirical testing
Axiology	Value-laden: absolute objectivity is unattainable, and researchers must be aware of their own biases
Methodology	Methodological pluralism

2.1.1 Ontology

Critical realism focuses on explaining observations and experiences through the underlying structures of reality. Reality is seen as external and independent - something that cannot be accessed directly through observation. Rather, we understand reality through our sensations which are seen as manifestations of reality. Following concepts discussed in critical realism, this thesis follows several assumptions: (Saunders et al., 2023)

- There is only one reality that exists but there can be multiple discourses that serve as interpretations of this reality (Fleetwood, 2015).
- Reality is stratified and can be categorised into three domains: Empirical (what we can observe), Actual (what happens independently of observation), and Real (the underlying causal mechanisms that determine events) (Fleetwood, 2015).

Not all of reality is directly observable. Indeed, in this thesis the aim is to provide a greater understanding of intuitive and analytic cognitive processes of product designers during the conceptual design phase. That is, these processes occur in the actual domain and are targeted through studies conducted in the empirical domain

which can only be explained with reference to underlying mechanisms in the real domain.

2.1.2 Epistemology

The epistemological stance of this research also aligns with critical realism in that epistemological relativism is assumed:

- Knowledge is shaped through the theoretical assumptions and people of its times. Further, this determines that causality is not purely determined by statistical and quantitative methods. Therefore, a range of methods are acceptable within this worldview. (Saunders et al., 2023)
- Knowledge is provisional, it is always open to revision, refinement, or falsification as new data emerges (Elder-Vass, 2022).
- Multiple interpretations of reality exist, but some models have greater explanatory power than others (Fleetwood, 2015).

This perspective is particularly relevant for design cognition research, where there is a drive towards studies that can rely on hypothesis testing, statistical validation, as well as richer qualitative insights to determine the underlying cognitive processes.

2.1.3 Axiology

Following from epistemological relativism, critical realism assumes the researcher's axiological position to recognise that our understanding of reality is shaped by their socio-cultural background and experiences. These biases are to be minimised as far as possible in the search for objectivity. While the research strives for objectivity, it acknowledges that:

- Absolute neutrality is unattainable - the researcher's background, theoretical orientation, and methodological choices inevitably influence the study.
- Reflexivity is necessary - this includes acknowledging potential biases in experimental design, data analysis, and interpretation.

- Methodological rigor helps mitigate bias, but transparency in reporting findings is equally critical.

The research documented in this thesis was conducted in a way that intended to minimise the influence of researcher subjectivity. However, qualitative aspects of the work are more prone to this bias. Multiple raters were used in qualitative analysis and interrater reliability measures were taken to mitigate such bias. This work does not prescribe a measure of good or bad design within its aim of providing a greater understanding of intuitive and analytic cognitive processes of product designers during the conceptual design phase. Through first building this deeper understanding, future work can be built on this with the goal of improving the design process - a stage which contains inherent value judgements.

2.2 Methodology

Research methodology refers to the theory of how research will be conducted (Saunders et al., 2023). This differs from research methods which are the specific techniques or procedures used to gather and analyse data (Saunders et al., 2023). This research follows a mixed methods approach employing both quantitative and qualitative data collection techniques and analysis methods - a common approach taken within critical realism (Saunders et al., 2023). An explanatory sequential mixed method design was used whereby a two-phase data collection occurred involving: quantitative data in the first phase, which was analysed and used to build on a second qualitative phase. This design allowed the quantitative results to inform the participant selection for the qualitative phase - enabling a deeper theoretical understanding (Creswell & Creswell, 2018; Saunders et al., 2023). This research employed two underlying frameworks to ensure the work was rigorous and well-structured: the Design Research Methodology and the Theory Building/Testing Cycle. Their application to this work is outlined in the following.

2.2.1 Design Research Methodology

This research was structured using an adaptation of the Design Research

Methodology (DRM proposed by Blessing and Chakrabarti (2009)). The methodology aims to support the development and validation of scientifically rigorous theories and models of design (Blessing & Chakrabarti, 2009). The DRM framework (see Figure 2-1) consists of several stages including research clarification, and descriptive and prescriptive studies. The DRM emphasises the development and validation of prescriptive supports that directly support design practice. However, this work focused predominantly on developing understanding and new tools for design research rather than practice. As such, adaptations to the DRM were made to reflect the primarily descriptive nature of the work. Several tools from the DRM were useful for structuring the work and were applied accordingly.

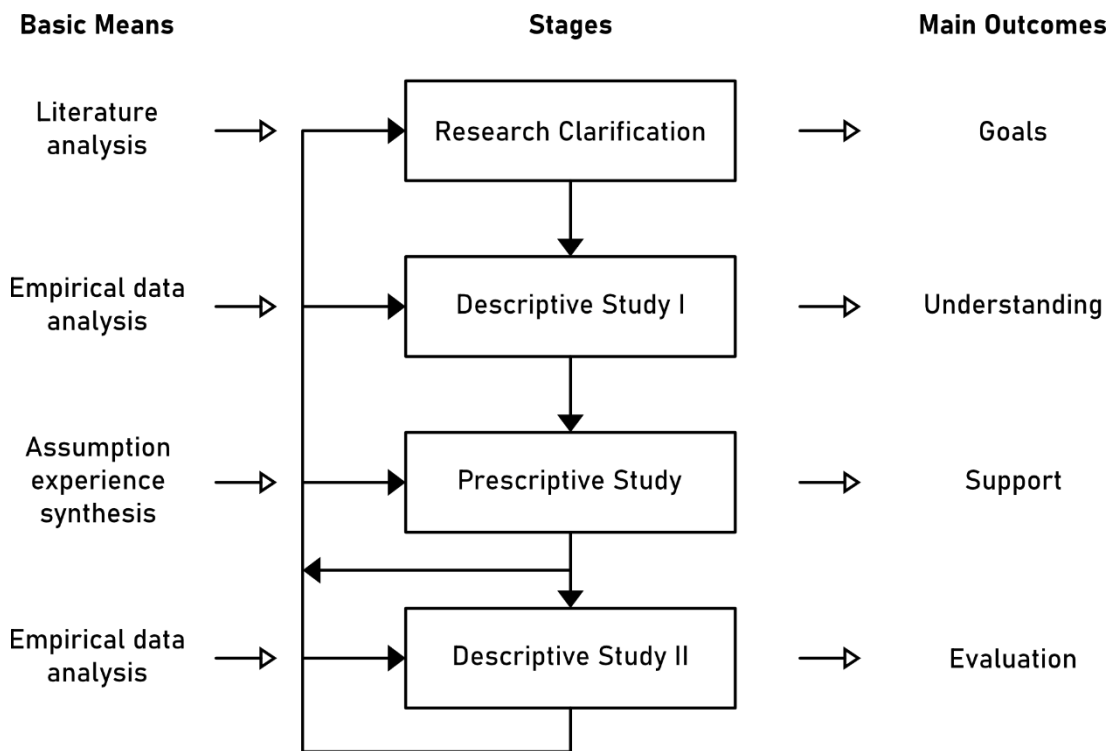


Figure 2-1 - The Design Research Methodology (adapted from Blessing and Chakrabarti, 2009)

The adaptation of the DRM methodology that is most suitable for this research consisted of three stages: research clarification (RC), a first descriptive study (DS-I), and a second descriptive study (DS-II). This most closely aligns with the Type 2 design research project of the DRM, whereby the purposes is to conduct a Comprehensive

study of the existing situation. This is relevant whereby a better understanding of the current situation is needed to identify factors that can improve the situation. These stages are outlined in the following:

2.2.1.1 *Research clarification*

Research Clarification (RC) involves finding evidence to support assumptions that can be used to formulate a realistic and worthwhile research goal (Blessing & Chakrabarti, 2009). In this thesis this is achieved through two literature reviews: the first focused on constructs and methods of conceptual design cognition research, and the second reviewed dual-process theory models and existing use in design research. The first review highlighted the existing challenges facing design cognition research of lacking a common ontological foundation, consistent method use, and established research practice norms (Blessing & Chakrabarti, 2009; Cash, 2018; Hay et al., 2017a). Calls for theory-driven research and greater rigour (Cash, 2018; Chakrabarti & Blessing, 2014) highlighted a course for tackling these challenges by introducing and aligning with the research methods, ontology, and theory from the more established field of cognitive psychology. Through this review, dual-process theory was identified as a well-established theory with reliable methods, which had the potential to address these limitations. The second review was conducted to further understanding of the identified theory and identify research opportunities. From this, cognitive conflict and cognitive bias were identified as factors that could be used to found new methods and theory for DPT research in design.

2.2.1.2 *Descriptive study I*

Descriptive Study I (DS-I) involves obtaining a better understanding of the existing situation by further detailing the factors affecting the situation being addressed and identifying key factors that will lead to an improvement in the current situation. This work involved a 'Comprehensive' DS-I whereby an empirical study was conducted based on the review of dual-process theory research. The knowledge gained from the review led to the development of a theory of cognitive conflict in design, upon which a new psychometric test was created and tested empirically in a quasi-experimental design. Correlational analyses were performed across several psychometric tests,

including the one developed for this research. While the DRM often links DS-I to early tool development for prescriptive use, this study retained a descriptive focus. The psychometric test was developed not as a prescriptive tool but to generate deeper understanding of dual-process theory constructs in design.

2.2.1.3 *Descriptive study II*

Descriptive Study II (DS-II) involved furthering the understanding of the existing situation by testing if the work conducted in DS-I could provide insights into the design process by analysing design work from a sample of key participants taken from DS-I. While DS-I developed a new measure for analysing dual-process theory in design (by applying the controlled format of psychometric testing), DS-II focused on determining if research questions derived from theory and findings could be answered through existing design research methods used to study more naturalistic design - namely, linkography. Linkography is used to map idea generation patterns and trace thought patterns throughout the design process. This method was analysed through a DPT lens to determine whether designers exhibit distinct patterns of thought development that aligned with DS-I measurements and DPT constructs.

2.2.2 **Theory-driven research**

The disconnect between ‘theory building’ and ‘theory testing’ within the drive for theory-driven research has been a recent topic of discussion regarding design research quality (Cash, 2018, 2020). In line with the theory development model that aims to strengthen this disconnect (Cash, 2020), this research strives to achieve the highest level of both theory building and theory testing. The work both “introduces a new construct or significantly reconceptualises existing constructs” (Cash, 2020) (theory building), and “grounds prediction with existing theory” (Cash, 2020) through applying the existing dual-process theory (theory testing)(Colquitt & Zapata-Phelan, 2007).

Design research often relies on descriptive studies whose impact is limited due to a lack of theory integration (Cash, 2018). The more rigorous approach of explicitly linking hypothesis testing and proposition development is a rare approach in design research (Cash, 2018). Within design cognition research, the lack of well-established

and widely endorsed theory is likely a contributor to this. The theory building/testing cycle of Cash (2018) emphasises that qualitative and quantitative methods provide the richest contributions when combined. This is aligned with the normal progression from building theory using qualitative methods to more quantitative research used to test these theories (Cash, 2018; S. K. Shah & Corley, 2006). Tradeoffs taken in simplicity, accuracy, and generalisability can be balanced when both qualitative and quantitative measures are used (S. K. Shah & Corley, 2006). Through building on dual-process theory as an established theory from cognitive psychology, a mixed-methods confirmatory approach can be taken to determine if these theories are applicable in design and to what extent.

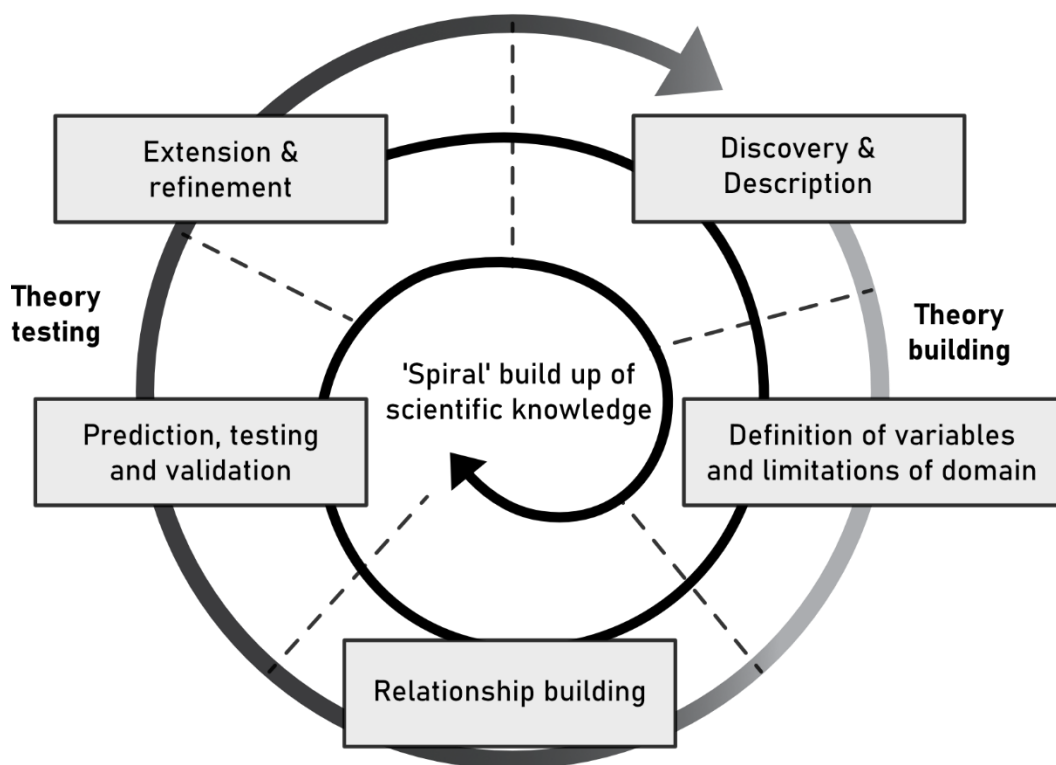


Figure 2-2 - The theory building/testing cycle (redrawn from Cash (2018))

The theory building/testing cycle involves five fundamental steps - creating an iterative cycle of building and testing (see Figure 2-2). These steps involve discovery and description, definition of variables and limitations of domain, relationship building, prediction testing and validation, and extension and refinement (Cash, 2018). This understanding of how scientific knowledge is created and developed aligns well with the DRM stages followed in this work, discussed in the following. Figure 2-3

shows this alignment and highlights the efforts taken towards rigour and relevance in this research, chapters are listed within this alignment to show contextualise the stages within the thesis structure. This is followed by an overview of considerations regarding quality relevant to the theory construction across the thesis.

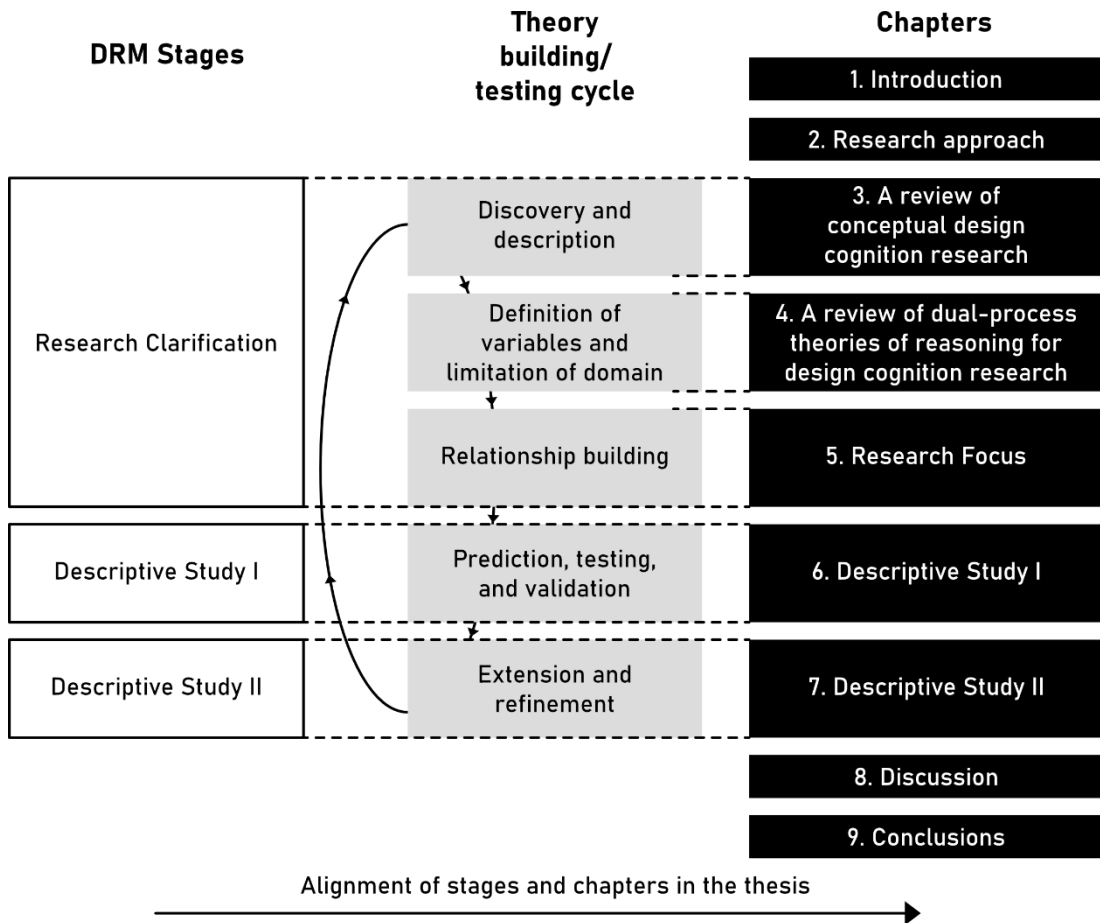


Figure 2-3 - Overview of thesis methodology alignment

2.2.2.1 *Discovery and description*

Discovery and description, within the theory building mode, pertains to identifying key areas of interest and issues. The goal is to establish the characteristics of a situation and the importance of research in this area. The first literature review conducted in this thesis (Chapter 3) fulfils this stage of the theory building/testing cycle by examining existing constructs and methods used in design cognition research and the challenges the field faces.

2.2.2.2 Definition of variables and limitation of domain

This stage is in the theory building mode and covers the identification of variables, interconnections, and boundaries. While this stage can employ experimental methods, the second literature of this thesis (Chapter 4) broadened the understanding of dual-process theory as it relates to the design cognition constructs and methods determined in Chapter 3. Given the breadth of existing research in cognitive psychology, the key variables, themes, patterns, and categories of dual-process theory regarding design cognition could be identified.

2.2.2.3 Relationship building

Relationship building is the last stage that occurs in theory building mode and involves describing connections between the identified variables and underlying mechanisms involved. Relationships between the variables are established and supported by questioning why these relationships should exist. In Chapter 5 of this thesis, this is done by proposing a new theory of dual-process cognitive conflict that through a priori reasoning builds directly from insights gathered from design cognition literature (Chapter 3) and cognitive psychology literature (Chapter 4).

2.2.2.4 Prediction, testing, and validation

This is the first stage of the theory testing mode and involves testing the theoretical model that was developed during the previous stages. Predictions are made for future outcomes to determine the validity of the theory and results are compared to theoretical predictions. This was conducted using the exploratory approach outlined in Section 2.2.1.2 and presented in Chapter 6. A psychometric test was developed during this stage based on the insights from the prior work. Through experimentally applying the psychometric test, and the proposed theory on which it was built, predictions linking dual-process theory and design cognition were tested.

2.2.2.5 Extension and refinement

The final stage of the theory building/testing model involves the expansion and mapping of the theory developed thus far. Questions are posed to determine the explanatory or predictive power of the theory and it is refined according to empirical

observations. To further explore the theory developed and tested in the previous stage, another study was conducted and presented in Chapter 7 using key participants from the original sample. The participants performed a think aloud design task that was analysed through linkography to determine if preliminary hypotheses on the predictive power of the developed theory could be validated in a more naturalistic design context. (Cash, 2018)

The research documented in this thesis is a first step in providing the much-needed theory and method development needed for applying dual-process theory in design cognition contexts. Indeed, the theory building/testing cycle is portrayed as a ‘spiraling’ process whereby additional iterations of the cycle are where knowledge build-up occurs. From this, the work should be contextualised as existing in an initial spiral, whereby additional refinement and extension of the work fell beyond the scope of this research but is a future step in increasing the impact and power of the work.

2.2.2.6 Quality and rigour in theory construction

Given the theory-driven nature of this work as a path to tackling challenges regarding theoretical and methodological rigour in design research (see section 1.1.3), the definition of rigour regarding theory construction in this thesis is crucial to consider. That is, rigour in theory construction is considered this thesis through explicit definitions, clearly bounded domains, internally coherent relationships, and empirically testable propositions, consistent with established principles of “good” theory building (Wacker, 2008). That is, whereby “good” theory is defined by a “fully explained set of conceptual relationships used for empirical investigations (Wacker, 2008).

These principles of “good” theory informed the work presented in this thesis. Conceptual clarity of definitions was founded in the explicit adaptation of dual-process theory into a design cognition context. Situating this adaptation clearly within a bounded established model within DPT ensured constructs were clearly defined within the epistemic and representational characteristics of conceptual design. This tackled the barriers to theory development of conceptual ambiguity (Wacker, 2008).

Further, this work explicitly defines the domain of proposed theory. Rather than

claiming applicability beyond the exploratory context of the work, the domain focus lies in conceptual design reasoning for tasks involving visual reasoning, concept generation, and concept evaluation. This boundary reflects that “good” theory requires explicit specification of where and when a theory applies (Wacker, 2008).

Additionally, this thesis sought to develop internally consistent explanatory relationships between cognitive psychology and design cognition. Proposed theory is deductively derived from DPT constructs and integrated with design reasoning constructs. Associations were identified alongside explaining the how and why within the determined domain (Wacker, 2008). Internal consistency was strengthened through refinement between conceptual development and empirical observation across DS I and DS II.

The thesis also addressed the requirement that theory should generate empirically testable predictions. Proposed theory was operationalised through measurable hypotheses relating to both DPT and design cognition constructs. The use of multiple methods to test these hypotheses provided methodological triangulation and strengthened confidence that the investigated constructs were observable across different forms of evidence (Wacker, 2008).

Through this, this work’s alignment with principles of “good” theory outlined by Wacker (2008), can be seen. This research generates a novel theory of cognitive conflict in design, new avenues for investigating individual differences in design cognition, and proposes methodological approaches capable of supporting future theory building. Beyond this, limitations inherent in exploratory research are recognised. The research is therefore positioned as a exploratory, requiring further refinement and validation.

The research emphasises empirical risk and refutability as important indicators of quality theory construction. Where hypotheses were not supported as originally predicted, rather than weakening the contribution, these divergences were treated as theoretically informative, prompting refinement of both the instrument and the underlying theoretical assumptions. This reflexive and iterative process is consistent with rigorous exploratory theory-building research, where the goal is not immediate

confirmation, but the progressive refinement of explanatory frameworks grounded in empirical evidence.

2.3 Research Design

The research approach in terms of the research philosophy and methodology have been outlined in sections 2.1 and 2.2. As introduced in Section 2.2., this work employs an explanatory sequential mixed method research design within the research approach. A summary of these aspects of the research approach can be seen in Table 2-2.

Table 2-2 - Overview of research approach

Research Approach	Selected approach for this thesis
	Ontology: Critical realism
Research	Epistemology: Epistemological relativism
Philosophy	Axiology: Value-laden
	Methodology: Methodological pluralism
Research Methodology	Design Research Methodology
	Theory Building/Testing Cycle
Research Design	Explanatory sequential mixed methods design

Figure 2-4 visualises the overall design of this research which can be broken down into the following sections corresponding with chapters of this thesis:

- State of the art review

The state-of-the-art in design cognition research was mapped by reviewing the methods and constructs discussed in the design cognition literature (Chapter 3). This work was published and presented at the Design Cognition and Computing conference 2022 (Lawrie et al., 2023) and is the first of two published papers from this work.

- Research knowledge gap

The knowledge gap identified in applying dual-process theory from cognitive psychology within design cognition research was investigated through mapping design cognition constructs to dual-process theory constructs (Chapter 4). Significant sections of this stage was published in the Journal of Engineering Design as a paper in the Research Notes collection (Lawrie et al., 2024) and is the second of two published papers from this work.

- Aim and objectives

Based on the identified issues found in Chapters 3 & 4, the research aim and objectives were defined (see Section 1.2).

- Theory development

On the basis of the constructs and methods mapped in Chapters 3 & 4, a theory of how cognitive conflict occurs in a design cognition context was proposed (Chapter 5).

- Theory evaluation

The validity and utility of the developed theory were evaluated through a deductive mixed methods approach involving developing a novel psychometric test from the theory, and a linkography study of a design task whereby a sequential mixed methods sampling technique was used to select participants from the first study for the second study sample (Chapters 6 & 7). Chapters 6 and 7 will be developed into two subsequent papers to ensure that the experimental work from this thesis is published and disseminated alongside it's earlier theoretical framing.

- Reflection

The findings of the evaluation were analysed to gather conclusions on the validity and utility of the proposed theory and psychometric test (Chapter 8). The advantages and disadvantages of the work were discussed and proposals for future work were made (Chapter 9).

- Consolidation

Throughout this research, the findings were documented and disseminated through both publication and informal media (e.g. reports to supervisors, departmental presentations, and notebooks). This thesis represents the consolidation of this documentation.

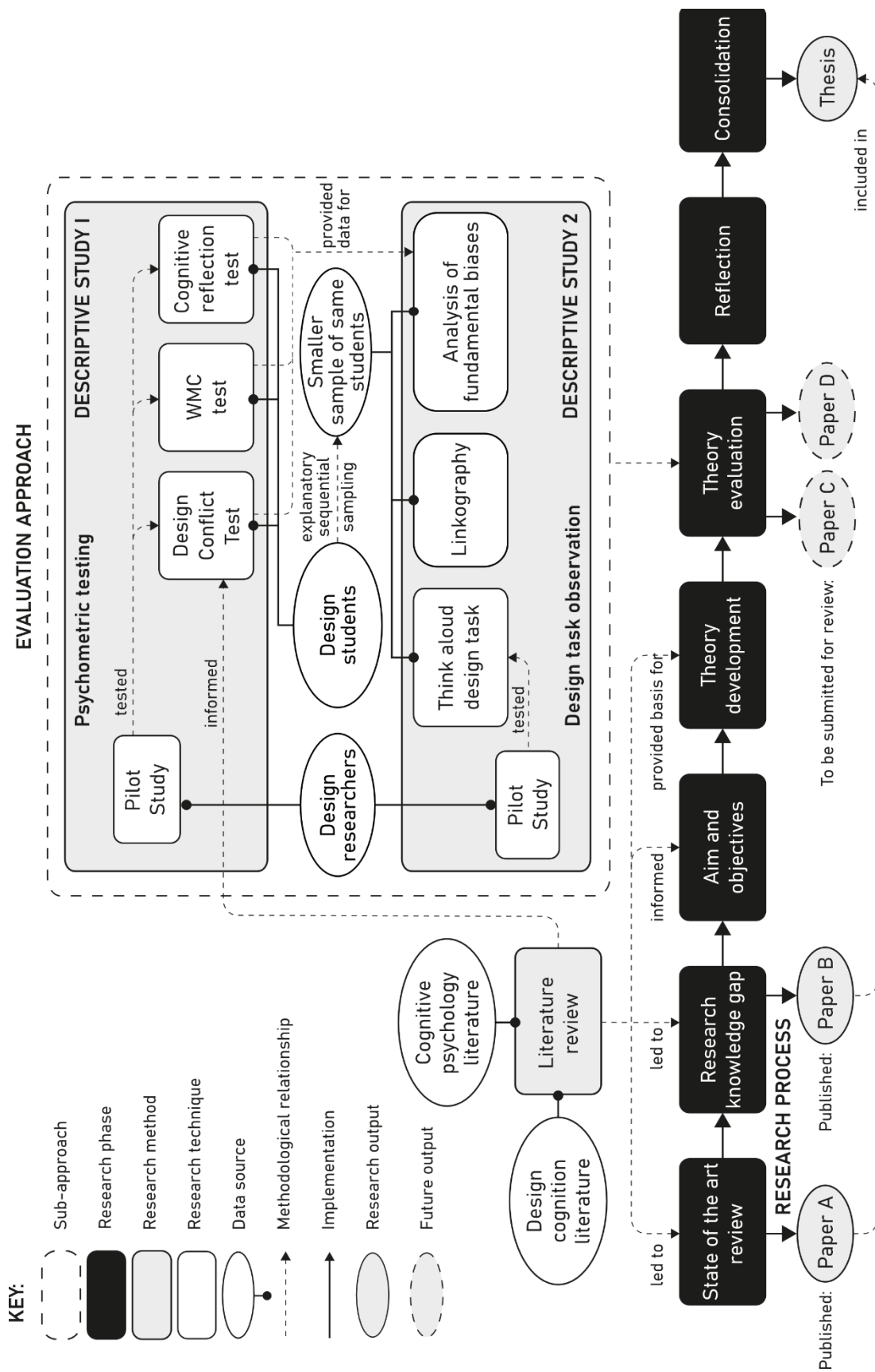


Figure 2-4 - Overall Research Design

PART 1:

THEORY DEVELOPMENT

3 A REVIEW OF CONCEPTUAL DESIGN COGNITION RESEARCH

Part 1 of this thesis documents the identification of the research focus and the development of theory on which subsequent empirical work is based. These chapters answer:

RQ1: What are the methods and constructs used in design cognition research?

RQ2: How do DPT methods and constructs align with design cognition methods and constructs?

These two research questions are addressed through two respective literature reviews, determining the methods and constructs used in design cognition research (this chapter - Chapter 3), and how dual-process theory methods and constructs align with these (Chapters 4 and 5).

The key challenges facing design cognition research were discussed in Chapters 1 and 2 and include i) the lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research. To deepen the understanding of these challenges, a mapping review of conceptual product design was conducted. Mapping reviews “map out and categorise existing literature” to characterise the scope, quantity,

and nature of research within a field, while identifying gaps and informing future research directions (Grant & Booth, 2009). Aligning with this review type, literature was gathered and categorised descriptively according to themes of theoretical framing, methodological approach, and cognitive constructs studied. These categorisations of gathered work were traced back through references to foundational texts in cognitive psychology to document the evolution of design cognition research. This enabled identification of broader patterns and gaps within the field, particularly regarding theoretical roots, methodological consistency, and ontological fragmentation.

This mapping review focuses on product design research - that is, the discipline involving the design of products concerning their functionality, usability, aesthetics, and ergonomics (Hagtvedt & Patrick, 2014). Due to similarities in the design process, research performed in adjacent disciplinary contexts (e.g. architecture, industrial design, and mechanical engineering) is often used as a foundation for product design cognition research - such work was included. Research within such adjacent fields was not included if it did not get used foundationally in product design cognition literature. The review was conducted using 6 databases (Compendex, DAAI, Embase, PsychInfo, ScienceDirect, and Web of Science). The search terms combined the domain (e.g. product design, industrial design), participants (e.g. engineers, designers), and cognitive aspects (e.g. cognition, mental). The review prioritised peer-reviewed journal articles, conference papers, and scholarly books. Studies were included where they investigated cognition in conceptual design, or proposed or evaluated methods relevant to studying design cognition. Studies were excluded where they focused exclusively on later-stage technical optimisation or manufacturing, or addressed purely computational or algorithmic systems without human cognition. Initial searches conducted in October 2020 covered studies from 2010-2020. Follow-up searches were conducted in October 2021 and March 2025 which focused on work published since the previous search.

Further, in this review, rigour and relevance are considered as criteria for evaluating the state of design cognition research. Rigour is conceptualised in alignment with the concerns outlined in Chapters 1 and 2 regarding theoretical and methodological clarity, domain of theory, ability to explain relationships between

constructs, and predictive capacity (see sections 1.1.3 and 2.2.2.6). In reviewing the literature, focus was, therefore, given to: the explicitness of construct definitions, the theoretical grounding of proposed constructs and accounts, the appropriateness of methods used to investigate cognitive phenomena, and the extent to which findings could support cumulative and comparable knowledge development across studies.

Relevance was considered as the degree to which research could contribute meaningful insight into actual design cognition and support future development of theory, methods, and practice within the field. This guided the categorisation of studies regarding cognitive constructs central to conceptual design activity, how findings related to observable design behaviour, and the balance of experimental control with representational fidelity to design practice. How gathered literature was capable of supporting cumulative, theory-driven advancement in design cognition was a guiding driver in the analysis. In particular, these criteria shaped the evaluation of existing methodological approaches, the identification of gaps relating to quantitative and mixed-method research, and the subsequent justification for work conducted in this thesis.

3.1 Views of design cognition

The majority of design cognition accounts have been developed within one of two theoretically distinct viewpoints of design (Hay et al., 2017a). These viewpoints can be described as design as search and design as exploration. Design as search and design as exploration were used to structure the initial mapping of this literature review and are, therefore, discussed in the following. Design as search views design as a rational and linear problem-solving process of search conducted within the problem space (i.e. an abstract space representing the designer's task situation). This view stems from information theory, founded in cognitive psychology, which takes an abstract view of the human mind as processing information it receives similarly to how computers process information (Anderson, 2015). Within this context, design cognition is modelled as linear process whereby the designer acts as an information processing system and is limited by their information processing capacity (IPS) (Simon, 1996; Stauffer & Ullman, 1991).

Contrastingly, design as exploration views design as an exploratory and situated process conducted through transformations between two abstract spaces: the problem space, and solution space (Maher & Tang, 2003). This perspective stemmed from situated cognition theories from cognitive psychology, which critiqued information processing theories for their limited understanding of how human thought adapts to social, cultural, and physical factors (Clancey, 1997). Situated cognition proposes that thought is intertwined with, and experienced through, the agent's environment, in what they perceive, conceive, and do (Clancey, 1997). In design, this manifests as the designers experiencing the design process as a dynamic situation wherein their perception of this situation evolves alongside their thoughts and actions (Gero & Kannengiesser, 2004).

Design, as a situated process, becomes exploratory when the problem-focus shifts and the solution space subsequently changes or expands. This view has also been modelled as 'co-evolutionary'; that is, involving parallel reasoning about the design problem and its solution (Maher & Poon, 1996). This situated and exploratory viewpoint within design research was greatly influenced by Schön's (1983) foundational work on professional practice. This work viewed design as a reflective process involving reflection-in-action (the implicit consideration of current actions), and reflection-on-action (the deliberate reflection on past actions) (Schön, 1983). The development of design as a situated process led to an extension of one of the dominant frameworks in the field - the 'function-behaviour-structure' (FBS) framework. FBS aimed to break design down into a set of foundational constructs independent from the designer, their task, and situation (Gero & Kannengiesser, 2014). It does this through three distinct concepts: function (the artefact's purpose), behaviour (how the artefact performs), and structure (the artefact's physical composition) (Gero & Kannengiesser, 2014). The extension of this to include situated aspects of design cognition resulted in the 'situated FBS ontology'. This situated ontology centred around three separate - but interacting - environments: the external world (i.e. the physical world independent of the designer), the interpreted world (i.e. the mind's perception and experience of the world), and the expected world (i.e. the imagined environment dependent on anticipated occurrences) (Gero & Kannengiesser, 2004).

3.2 Mapping constructs and accounts

The initial mapping of the literature focused on categorising work according to these viewpoints and tracing theoretical roots in cognitive psychology. This was done through aligning findings from design cognition literature with the theory and terminology found in cognitive psychology literature. Models, theories, and frameworks discussed in the literature were also mapped according to viewpoints. This initial mapping was developed visually and can be seen in Figure 3-1.

The framing of research within the viewpoints of design as search, design as exploration, or from cognitive psychology enabled the visualisation of the design research shift towards design as exploration viewpoints over time, and contextualised design research within cognitive psychology. The mapping fosters an understanding of the interconnectedness of design cognition research and cognitive psychology. Furthermore, it provides a comprehensive framework for synthesising disparate findings and identifying gaps in knowledge.

3.3 Research methods in design cognition research

To gain deeper and more concrete insights following this initial mapping process, a classification of methods and constructs in design cognition research was developed. To develop this classification, research method use in the literature was considered in more detail. This enabled a stronger foundational understanding of method use in the field considering the previously discussed challenges in research method diversity and the reliance on small scale, qualitative methods in design cognition research (Cash et al., 2019; Hay et al., 2020).

Design research can be considered behavioural research, which involves the study of psychological, sociological, and educational phenomena (Hiscock, 2003). However, in psychology, researchers often draw the more useful distinction between self-report, behavioural, and physiological experimental methods (Cozby, 2009). Within this distinction, self-report measures involve the participant reporting on aspects such as their feelings and judgements through methods including verbalisation, surveys, and rating scales (Hiscock, 2003). Behavioural measures are distinguished as direct observations of behaviour (Cozby, 2009). Lastly, physiological measures assess bodily outputs such as heart-rate monitoring (Cozby, 2009). This includes neurophysiological measures relating to brain outputs from brain scanning and imaging.

Self-report, behavioural, and physiological measures have seen varying application and extent of use in conceptual design cognition research. Categorising literature according to these distinctions facilitates a deeper understanding of method use, the capacity and limitations of different methods, and the triangulation of research. A summary of findings from the literature according to self-report, behavioural, and physiological measures is given in the following subsections.

3.3.1 Self-report measures

Self-report measures, where the participant reports on their behaviour, dominate in design cognition research. Such methods include surveys, rating scales, and the most notable regarding design cognition - protocol analysis (Hay et al., 2017a). Protocol analysis examines the designer's mental processes through the verbalisation of their

thoughts (van Someren et al., 1994). Many design cognition research methods originated in cognitive psychology - protocol analysis being an example this, with Ericsson and Simon (1993) developing the method's most influential framework. In design research, protocol data is gathered from video and audio recordings of designers that are then transcribed, encoded using a coding scheme, and analysed for insight into the designer's cognition (van Someren et al., 1994). Alongside verbal reports, given during (concurrent) or after (retrospective) the task, behavioural data from sketches and motor actions can be analysed (Hay et al., 2017a).

Self-report measures, including protocol analysis, have provided valuable measures of attitudes, emotions, intended behaviour, cognitive products, and other perceptual constructs (Haeffel & Howard, 2010). They tend to be cost-effective and easy to perform (Haeffel & Howard, 2010). However, they have flaws that are hindering the progression of design cognition research. The degree of insight required by the participant is one such limitation as it can affect the accuracy of self-report measures and should be minimised (Haeffel & Howard, 2010). Protocol analysis does well in minimising this influence as it does not require a high level of self-awareness from the participant i.e. the voicing of the participant's thoughts does not require them to reflect on why they are thinking or acting the way they are. Protocol analysis also falls short in capturing nonconscious thought, and the intensive process of extracting conclusions from qualitative data often resulting in small-scale studies and difficulty in generalising results (Dinar et al., 2015; Hay et al., 2017a). Additionally, research into the neurophysiology of the method has shown an increase in required neurocognitive resources, and changes in sketching (Shealy et al., 2023). The various coding schemes used for protocol analysis also obstruct result comparisons and are contingent on the subjective nature of the reporting and analysis (Gero & Milovanovic, 2020). However, it remains one of the few methods capable of providing real-time insight into a designer's thoughts. While the historic dependency of design cognition research on protocol analysis is apparent, other methods are becoming increasingly common.

3.3.2 Behavioural measures

Direct observations of behaviour have also recently seen increasing use. In design, output-based behavioural experiments are common. This involves analysing the outcome of a design task and making inferences about the cognitive processes involved (Gero & Milovanovic, 2020). Such studies use a control and an experimental condition, with the outcomes being analysed comparatively (Gero & Milovanovic, 2020). Output-based studies applying standardised psychometric tests (often used in cognitive psychology research) have also been reported in recent years (e.g. Khorshidi et al., 2014). It has been proposed that using standardised measures, along with greater standardisation of conventional design cognition research methods (e.g. protocol analysis coding schemes), could improve generalisability, facilitate meta-analysis, and increase scientific rigour in the field (Cash, 2018; Hay et al., 2020).

In addition to output-based behavioural experiments, social science methods have been used to study design cognition. While research on collaborative design cognition has used ethnography methods, the study of individual designers using such methods has mostly employed case studies (Schön, 1984). However, reviewing the gathered literature indicated that the use of such methods is less common than other behavioural and self-report methods.

3.3.3 Physiological measures

Physiological measures relate to bodily outputs such as heart-rate monitoring (ECG), eye-tracking, electro-dermal activity (EDA), and emotion tracking (Cozby, 2009; Gero & Milovanovic, 2020). Neurophysiological measures, which concern brain outputs, are a subset of physiological measures including functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG). While physiological outputs can be measured directly, they do not inherently reflect cognitive processes and must be interpreted as an indirect correlate of these processes (Gero & Milovanovic, 2020).

In the past five years, the use of physiological measures in design cognition research has grown rapidly. Eye-tracking has provided insight into fixation (Starkey et al., 2018; Wu et al., 2023), divergent/convergent thinking (Colombo et al., 2020),

cognitive load (Cass & Prabhu, 2023), and reasoning (Nelius et al., 2020). Heart rate monitoring (ECG) has also been applied (e.g. to study designer's mental effort and stress (Nguyen & Zeng, 2014)), although far less extensively. Neurophysiological measures - used to study how brain areas support cognitive processes (Alexiou et al., 2009), are also gaining popularity in design cognition research. However, despite discoveries in the early 1990's leading to the invention of fMRI and fNIRS (Ferrari & Quaresima, 2012), and the first recorded human EEGs in the 1920's (St. Louis & Frey, 2016), its use within the discipline has only recently received greater focus. fNIRS research has shown that design differs from general problem solving and involves distinct brain areas (Alexiou et al., 2009), cognitive differences between novice and expert designers have been examined (Hu, Shealy, & Milovanovic, 2021), and neurocognitive feedback has been explored as a means to sustain idea generation over time (Hu, Shealy, Milovanovic, et al., 2021). EEG studies have examined visual reasoning (Vieira et al., 2021; C. Y. Wang, 2020; Yao et al., 2017), divergent/convergent thinking (Colombo et al., 2020), logical reasoning (Göker, 1997), mental effort (Nguyen & Zeng, 2010), and decision making (Liu et al., 2018). fMRI studies have given insight into the neural basis of design (Alexiou et al., 2009; Campbell et al., 2024; Hu et al., 2023), and analogical reasoning (Goucher-Lambert et al., 2019). fNIRS has also supported divergent/convergent dual-process theories (Milovanovic et al., 2021).

Design cognition researchers have also explored which physiological measures can be used simultaneously, such as eye-tracking and EEG (Colombo et al., 2020), and ECG with EEG (Nguyen & Zeng, 2014). Design research has also applied mixed methods approaches using protocol analysis with select physiological measures, namely, eye-tracking (Nelius et al., 2020; Yu & Gero, 2018), and EEG (Göker, 1997; Vieira et al., 2023). However, the recent introduction of physiological measures to the field continues to pose challenges in interpreting results and inferring implications for design cognition theory (Hay et al., 2020). Hay et al. (2022) discussed challenges facing fMRI studies in design cognition; they identified the development of experimental protocols, establishing a common ontological foundation, the identification of areas of neural activation during design, and managing methodological constraints as key challenges for future research. Many of these

challenges have parallels affecting other physiological and neurophysiological measures.

Beyond the diversity of methods used in design cognition research, these approaches also differ in the forms of validity they support and the limitations they introduce. Self-report measures provide valuable often qualitative access to subjective experience and reflective thought but face challenges regarding construct validity and introspective accuracy, particularly when studying nonconscious or automatic cognition. Behavioural measures can strengthen internal validity through greater standardisation and experimental control, yet may reduce ecological validity if tasks become detached from naturalistic design activity. Physiological and neurophysiological measures offer increasingly precise quantitative indicators of attentional, affective, and neural correlates of cognition, but introduce challenges of interpretive validity, as physiological outputs are indirect indicators of cognitive processes rather than direct measures of thought itself. Consequently, quantitative design cognition research requires careful alignment between theoretical constructs, operationalisation, and interpretation. These challenges reinforce the importance of theory-driven method development, triangulation across multiple data sources, and balancing experimental control with ecological validity when advancing design cognition research.

3.4 Design cognition constructs

Having outlined the viewpoints and methods used in design cognition research, an overview of the constructs studied and their theoretical roots in cognitive psychology is provided. As discussed previously, constructs in this context refers to the cognitive processes and mental representations that are theorised to be involved in design activities. Constructs and their potential relationships are formalised in accounts, i.e. frameworks, theories, and models. The majority of design cognition accounts have been developed within one of the two discussed key viewpoints on design - design as search and design as exploration (Hay et al., 2017b).

While the initial focus on viewpoints in design research was crucial to understanding shifts in research paradigms, the developed classification from this

review focused on research method use, cognitive process, and theoretical roots. This classification added clarity and provided a basis for ensuring greater scientific rigour in subsequent experimental work. By formalising the theoretical roots of conceptual design cognition constructs, it was ensured that subsequent work was conducted with a comprehensive understanding of the foundational paradigms and theory underpinning the field. This review tackles key issues identified within the field, fostering scientific rigour, greater mutual intelligibility between design cognition and cognitive psychology research, and enabled diversification of methods for this work.

This section classifies design cognition research into nine main cognitive processes that were identified in the literature. These classifications were derived from conventions and terminology taken from cognitive psychology (Anderson, 2015; Goldstein, 2019) that were also discussed within the design cognition literature:

- Reasoning
- Decision-making
- Knowledge
- Memory
- Metacognition
- Executive functions
- Attention
- Visual perception
- Mental imagery

Several papers gathered in this review focused not on cognitive processes but on cognitive strategies, which may be interpreted as a set of cognitive processes engaged to move towards a goal. This includes problem decomposition (dividing a problem into subproblems) (Song et al., 2016); and problem structuring (defining the problem space through knowledge retrieval) (Bilda & Gero, 2007). Another focus of design cognition research that could be viewed as a cognitive strategy is the duality of divergent and convergent thinking - terms coined by Guilford (1956). Divergent thinking in design is an intuitive, associative process that can generate a wide variety of ideas (Gabora, 2010). In contrast, convergent thinking is an analytic process that consolidates knowledge to move towards a solution (Gabora, 2010). The role of divergent and convergent thought has been researched in design and cognitive psychology across cognitive processes such as attention, reasoning, and memory. While cognitive strategies often feature in design cognition research, the focus of such studies was determined to be too high-level when examining the roots of cognitive constructs, at the level of cognitive processes. Therefore, they were not included in the categorisation.

It is not always clear how design cognition constructs relate to the well-established constructs and accounts of cognition in cognitive psychology. In the following subsections, the fundamental design cognition constructs identified through the literature review are discussed and how they align with cognitive psychology in both terminology and theoretical origin is illustrated.

3.4.1 Reasoning

The cognitive processes of reasoning, decision-making, and judgement, each have their theoretical roots in a different normative theory (Hardman & Macchi, 2003). Reasoning, or the process of making inferences, stems from the normative theory of logic; decision making, or the process of choosing amongst options, from utility theory; and judgement, or determining the probability of uncertain outcomes, from probability theory (Hardman & Macchi, 2003). However, much cognitive psychology research since has focused on the factors behind why these rational norms are often violated (Hardman & Macchi, 2003). This theme has presented in design cognition research through investigating biases and heuristics (Daly et al., 2010; Yilmaz &

Seifert, 2011). While reasoning and decision-making are explicitly studied in design cognition research, judgement is often indistinctly grouped with these two processes and will, therefore, be discussed within the reasoning and decision-making sections.

Reasoning processes are central to conceptual design (Ball et al., 2004). Design reasoning has been elaborated as the lines of thought, transformations of information, questioning, and inferences that lead to conclusions being drawn beyond the designer's given information (Elias & Dasgupta, 2005; Park et al., 2006). In design, reasoning research has focused on logical reasoning, analogical reasoning, visual reasoning, dual-process reasoning, heuristics, and biases. While such research has mostly used protocol analysis, use of physiological measures is growing.

3.4.1.1 *Logical reasoning*

Logical reasoning processes - deductive reasoning (inference from the logical result of multiple true propositions), abductive reasoning (inference of a cause from an effect), and inductive reasoning (probabilistically true inference based on evidence) have been discussed in design cognition research since the 70's (Bhatt et al., 2021; Goldstein, 2019; March, 1976; Stauffer & Ullman, 1991). They each play important roles in the design process. In design, deduction is considered to occur after the proposition of something novel whereby it decomposes and predicts how the proposition would perform based on characteristics emerging from analysis (Cramer-Petersen et al., 2019). Deduction has been shown as the most common form of reasoning in design, often following instances of abduction (Cramer-Petersen et al., 2019). Abduction, a concept subject to varying definitions in design, has been framed as hypothesis generating, through often intuitive, subconscious processes (Koskela & Kroll, 2020; Kroll & Koskela, 2023). In this, the relevance of abduction in conceptual design, a process of generating ideas, can be seen. Indeed, abduction is considered to be the key mode of reasoning in design (March, 1976). Inductive reasoning research in design has emphasised how knowledge from a previous problem-solving experience can assist solving a new problem. This is termed analogical reasoning, which, in design, has been studied through assessing the distance between source and target of this knowledge between experts and novices (Ozkan & Dogan, 2013). Experts are known to prefer short analogical distances while novices rely on longer distances

(Ozkan & Dogan, 2013). As with much recent design cognition research, analogical reasoning design research has also focused on the differences between implicit, intuitive aspects, and explicit, effortful aspects of cognition (here termed ‘schema-driven’ and ‘case-driven/based’ analogical reasoning respectively) (Ball et al., 2004; W. Wang & Zhao, 2006).

3.4.1.2 *Visual reasoning*

Following the definition of reasoning as drawing conclusions beyond the given information, the information involved in visual reasoning is visual information e.g. a sketch (Park et al., 2006). While differing terminology is used to discuss visual reasoning processes in design (Park et al., 2006; Suwa et al., 2000), they largely refer to the same three processes: visually perceiving what is before them (e.g. a sketch), forming a judgement on this perception through the discovery of intended and unintended consequences, and acting on this judgement to imagine a new solution. This shows the close involvement of visual perception and mental imagery processes in visual reasoning. Visual reasoning abilities are central to the design process and have been connected to creativity and diversity in design concepts (Goel, 1995b; Park & Kim, 2007). Research on visual reasoning emphasises the ‘situated’ aspect of cognition - in that the designer takes part in a ‘reflective conversation’ (Schön, 1984) with the information. However, such research shows that information processing views are not entirely conflicted with situated cognition (a design cognition framework linking the views has been proposed (Haupt, 2015)). Rather, that situated views emphasise aspects that information processing views tend to neglect and decontextualise (Heylighen & Nijs, 2014)).

3.4.1.3 *Dual-process theories of reasoning*

Another theory founded in cognitive psychology that has recently entered design cognition research is dual-process theory (DPT). DPT, sometimes referred to as dual-system theory, is a widely recognised and studied theory of human reasoning and judgement within cognitive psychology (Evans & Stanovich, 2013). At a simplistic level, the theory divides cognition into: autonomous and intuitive processing (Type 1), or reflective and effortful processing (Type 2) (Evans & Stanovich, 2013). While DPT

is widely accepted within cognitive psychology, it is only beginning to have a wider impact on design research. Dual-process models of creative thinking are gaining traction (Kannengiesser & Gero, 2019; Sowden et al., 2015), a ‘dual-process ideation model’ of design cognition has been recently proposed (Gonçalves & Cash, 2021), intuition and unconscious processing in design has been studied (Badke-schaub & Eris, 2014), tests used to measure tendencies in dual-process thinking have been applied to designers (Tonetto et al., 2021), and design representations have been assessed through a DPT lens (Cash & Maier, 2021). In design, both Type 1 and 2 thinking have been linked to the drivers of novelty alongside errors and biases in judgement (Gilhooly et al., 2015). Furthermore, initial work has aligned DPT with design ontology (Kannengiesser & Gero, 2019). Current DPT design research is preliminary and has consulted only a few of the many DPT models from cognitive psychology. Future design cognition research in DPT faces challenges regarding intradisciplinary fragmentation between reasoning research and creativity research in cognitive psychology with calls from within cognitive psychology to align these areas (Barr, 2018).

3.4.2 Decision making

Conceptual design cognition greatly relies on decision making processes. Decision making can be defined as the processes that consider alternatives and select one alternative under the presence of uncertainty and through consideration of context, preferences, and boundaries (Anderson, 2015). In design, this can refer to the selection, or dismissal, of concepts over other concepts (Hay et al., 2017b). The timing of decision making, when selecting concepts, has also been tied to the creativity of solutions (M. H. Kim et al., 2007). The reliance on subjectivity in decision making has been linked to conceptual design considerations such as functional requirements and customer needs which rely primarily on human preference (Lu & Liu, 2011). The subjectivity in conceptual design also relates to intuition. However, early theories of decision making developed in cognitive psychology consisted of normative descriptive models that assumed the decision maker not to rely on intuition, but to be an entirely rational information processing system (Tversky & Kahneman, 1992). Such models described the decision maker as taking a probabilistic approach (Badke-

schaub & Eris, 2014). That is, that the decision maker would assess the options and information, and choose the alternative that provides the most utility (Badke-schaub & Eris, 2014). These theories ultimately failed and are now largely disregarded as ways to describe decision making (Tversky & Kahneman, 1992). Simon (1972), in his theory of 'bounded rationality' discussed how rather than making optimising decisions, designers make satisficing decisions. This results from designers not being given alternative concepts (as solely rational decision-making models assume), but rather that they generate and develop their own options (Simon, 1972).

3.4.3 Knowledge and memory

Knowledge and memory are another two key constructs in design cognition. Knowledge can be defined as information and beliefs stored in memory (Rumelhart & Ortony, 1977), and memory as the cognitive processes that store and retrieve this information after its presentation (Goldstein, 2019). The close relation of these constructs means they are most easily discussed together. The idea that designers possess more knowledge than they can express is often discussed (Schön, 1988). Knowledge held by designers that can be expressed directly through words is referred to as explicit knowledge (Schön, 1988). Contrastingly, implicit knowledge, or tacit knowledge, cannot be articulated and refers to the designer's intuition and understanding gained through experience (Schön, 1988). These types of knowledge are often termed declarative (explicit) and procedural (implicit); again, stemming from formalisations made in cognitive psychology (Anderson, 1976). The knowledge gained through experience also results in different application, with experts using more structured and goal-directed knowledge compared to novices (Christiaans & Dorst, 1992).

Early conceptualisations of memory in cognitive psychology distinguished between long- and short-term memory (Waugh & Norman, 1965). Long-term memory holds information over extended periods of time (minutes to years) and holds both declarative and procedural knowledge (Goldstein, 2019). Long-term memory is also theorised to hold schemas - abstract knowledge structures that constrain and influence the problem-solving process (Chan, 1990). Schemas function as the automatic recognition of a category of previously experienced problems from which the previous

solution procedure is abstracted and applied to a current similar problem (Chan, 1990). Schemas hold both declarative and procedural knowledge of how to classify and best solve problems in each group (Ball et al., 2004).

Declarative knowledge can be stored in episodic or semantic memory (“memory for experiences” and “memory for facts” respectively) (Goldstein, 2019). These memory processes have been identified as a direction for future research with neither having been widely researched in design cognition (Hay et al., 2017b). However, recent research has investigated the role of memory in brainstorming (Shen et al., 2023; Zou et al., 2024). Differences in episodic and semantic memory use has been shown across educational background with industrial designers relying more on episodic memory compared to greater semantic memory use in mechanical designers (Zou et al., 2024). Furthermore, memory retrieval has been shown to act both as a stimulus for concept generation and to reinforce design fixation (Shen et al., 2023). In investigating memory and association processes in design, both the quantity and the sequence of different cognitive processes have been tied to creativity levels (Yin & Childs, 2024).

Semantic processing, a process connected to semantic memory, is the method by which stored information on the attributes of concepts is retrieved from this memory, acted upon, and expressed through language (Martin & Chao, 2001). In design, semantic processing has been studied through the designer’s interpretation of meanings from stimuli e.g. words describing artefacts, and sketches (Suwa et al., 1998; Trinh & Elverum, 2019; Yuan et al., 2018).

Initial research in cognitive psychology on short-term memory (memory of the previous 15-30 seconds) focused on its storage capacity and timeframe (Goldstein, 2019). This led to the development of Baddeley and Hitch’s 1974 model of working memory (later developed in Baddeley et al., 2011) - a concept that replaces short-term memory and instead proposes a multi-component model that aims to better explain complex cognition (Baddeley & Hitch, 1974). Few attempts have been made to reconcile this model within design (e.g. Bilda & Gero, 2007). However, gaps in design cognition research regarding executive control mechanisms reveal an apparent need for future consideration of such control mechanisms as discussed in Baddeley’s model.

This links to the discussed potential in DPT accounts for the field regarding how Type 1 and Type 2 processing is controlled.

3.4.4 Metacognition

Another area of cognition research that has only recently received increased interest regarding design is metacognition, despite it being identified as an essential component of creativity for some decades in cognitive psychology literature (Ball & Christensen, 2019). Metacognition, originally coined in the mid 70's by Flavell (1979), refers to the cognitive processes that facilitate the ongoing supervision and regulation of thought to achieve efficient cognitive processing (Ackerman & Thompson, 2017; Flavell, 1979). In other words, metacognition is thinking about thinking (Flavell, 1979). In design, metacognitive processes are essential in managing the complexity of problem solving, concept generation, evaluation, and development (Ball & Christensen, 2019).

A focus of metacognitive research in cognitive psychology has been metacognitive reasoning (Ackerman & Thompson, 2017). Such research has influenced similar design cognition work. In particular, the role of uncertainty perception and heightening uncertainty as metacognitive triggers for regulating the design process have been used to model the progression of design activity (Ball & Christensen, 2019; Cash et al., 2023; Cash & Kreye, 2017, 2018). Furthermore, in design education, teaching metacognitive skills have been shown to increase and maintain higher levels of creativity (Hargrove, 2013).

3.4.5 Executive functions

Similarly to metacognition, executive functions are a set of cognitive processes that have recently entered design cognition research (Hay et al., 2017b, 2020; Yao et al., 2017), despite being discussed in cognitive psychology for some decades (Karbach & Kray, 2016). The term refers to the cognitive processes involved in controlling behaviour according to changes in environment which is required when intuitive and automatic processes are insufficient or impractical (Karbach & Kray, 2016; Roebbers & Feurer, 2016). Within cognitive psychology there is a general consensus on three 'core' executive functions: working memory, cognitive flexibility (ability to shift

mental task and content), and inhibition (ability to ignore distractions and focus attention) (Roebbers & Feurer, 2016). Similarly to metacognition, executive functions play a role in monitoring, interpreting, and regulating cognition (Roebbers & Feurer, 2016). Despite certain executive functions being studied in design research (e.g. working memory (Bilda & Gero, 2007)), executive function research in design cognition literature is even more limited than that of metacognition in the same context (Hay et al., 2020).

3.4.6 Attention

Attention can be considered as the capacity to focus on certain stimuli when simultaneously processing additional things is impossible (Anderson, 2015). In cognitive psychology, the defocusing and focusing of attention has been linked to divergent and convergent thought respectively (Gabora, 2010). This stems from associative thinking being facilitated by defocusing attention, while the focusing of attention facilitates analytic thought (Gabora, 2010). While there are parallels with DPT, the concepts do not map directly onto one another. However, studying the relationship between divergent and convergent thinking regarding attention through a DPT lens invites future design cognition research. The ability to shift attentional focus has also been related to an individual's creativity (Gabora, 2010). This aligns with current DPT views that link creativity to the ability to switch between Type 1 and 2 processing (Gabora, 2010).

Another area of attention research in design cognition investigates how designers overcome mental blocks and impasses during design. Such blocks can be considered a cognitive bias - consistently occurring errors in cognition that form an inaccurate view of reality (Nelius et al., 2020). In design research, these blocks are often referred to as fixation - an illogical adherence to a perceived set of limitations or ideas during while designing (Jansson & Smith, 1991). These restrictions can block finding a successful solution and often lead to limiting creativity. Research in design has investigated fixation on the function of an artefact, a problem-solving approach or solution, inspiration sources, mitigation, and being limited by emotional, cultural, and environmental factors (Cai et al., 2010; Cheng et al., 2014; Jansson & Smith, 1991). Although fixation can hinder the design process, it can also foster inspiration (Starkey

et al., 2018). In line with recent research into nonconscious aspects of design, initial work regarding this in fixation has used physiological methods (Starkey et al., 2018).

3.4.7 Visual perception and mental imagery

Visual perception and mental imagery are cornerstones of conceptual design cognition. The two are closely related cognitive processes and play a key role in absorbing external information and imagining new ideas. Visual perception can be defined as the cognitive process of extracting and recognising visual information entering through the eye (Anderson, 2015). Contrastingly, mental imagery is processing involving the recreation of perceptual information without any external source of this information present (Anderson, 2015; Goldstein, 2019). In conceptual design cognition research, the two are often investigated together. Such studies have examined aspects such as the effects of visual stimuli, emotional and visual mental imagery, vividness of mental imagery, the effects of tools for external representation on mental imagery, the interplay of sketching and mental imagery, and interpreting visual perceptions through metaphor (Chen et al., 2018; Chu et al., 2017; Edgecomb et al., 2024; Hart & Hay, 2022; Tedjosaputro et al., 2018). Indeed, the multiple viewpoints through which mental imagery is research have been defined in a framework (MacFie et al., 2023). Although protocol analysis has remained dominant in visual perception and mental imagery research in design, newer methods to the field - such as eye-tracking, have recently provided further insight (Yu & Gero, 2018).

3.5 A classification of methods and constructs

The findings of this review were developed into a visual classification and timeline of the research methods, constructs, and theoretical roots discussed in conceptual design cognition literature. This classification, shown in Figure 3-2, shows the accounts of the theoretical roots (left); the influence of these accounts on the study of cognitive processes of conceptual design (centre); and a timeline of the empirical studies investigating these processes and the type(s) of research method used (right). Each dot shows the use of a method to study a cognitive process in the literature using a self-report (green), behavioural (orange), or physiological (red) measure. Studies using a mixed methods approach are denoted by a halved dot coloured in each half according to the methods used.

This classification conveys several observations about the state of design cognition research and its future. Some themes emerged, with dual-process theory, memory, and mental imagery research being the most researched phenomena in the past five years. In the sample reported in this classification, 53% used self-report measures, 37% physiological, 22% behavioural, and of these 13% used mixed methods. Until recently, the domination of self-report measures was even greater.

Prior to 2016 the percentage of studies using self-report measures was 57%, 16% used physiological, 32% used behavioural, and of these, 5% used mixed methods. This shows signs of a considerable shift in design cognition research. A greater emphasis on scientific rigour has seen increasing use of physiological measures in addition to traditional design cognition methods like protocol analysis. However, behavioural methods have fallen behind, suggesting a lack of behavioural methods that support the shift towards greater scientific rigour. Indeed, a lack of suitable tests and metrics has been noted in design research (Hay et al., 2017a). Development of such tests and metrics, aligning with the behavioural methods used in cognitive psychology should be a focus of future design cognition research to ensure a balance of methodological approaches can be maintained. Mixed method approaches - combining self-report, behavioural, and physiological measures are also increasingly used. However, relatively few studies reported in this review followed this approach. This reflects the continued tendency of design cognition research to rely on single methods despite calls

from authors to use more mixed methods. Continued efforts towards mixed methods approaches could allow the field to harness the advantages of triangulating findings across methods and data sources and address subjectivity in protocol analysis. The combination of behavioural methods with physiological and neurophysiological methods could also aid in building connections between cognition and brain activity.

The complex array of accounts depicted in Figure 3-2 shows what could be considered both healthy pluralism and debate. However, it also shows that design cognition constructs can largely be aligned with current knowledge in cognitive psychology. In accordance with design cognition researchers promoting the alignment of these two fields, using more consistent terminology like that used in this classification would aid in mutual intelligibility between the fields, and ease access to knowledge in cognitive psychology. Furthermore, such efforts would provide a basis for the wider reach of design cognition research such that knowledge would not only transfer from cognitive psychology to design cognition but vice versa. Recent advancements in DPT design cognition work also show promise for building a wider framework within which cohesion in design cognition research can be built.

This classification provides an overview, rather than great depth, regarding each of the identified constructs. It was used as a starting point to understand research methods, theoretical origins, and terminology to use regarding conceptual design cognition phenomena.

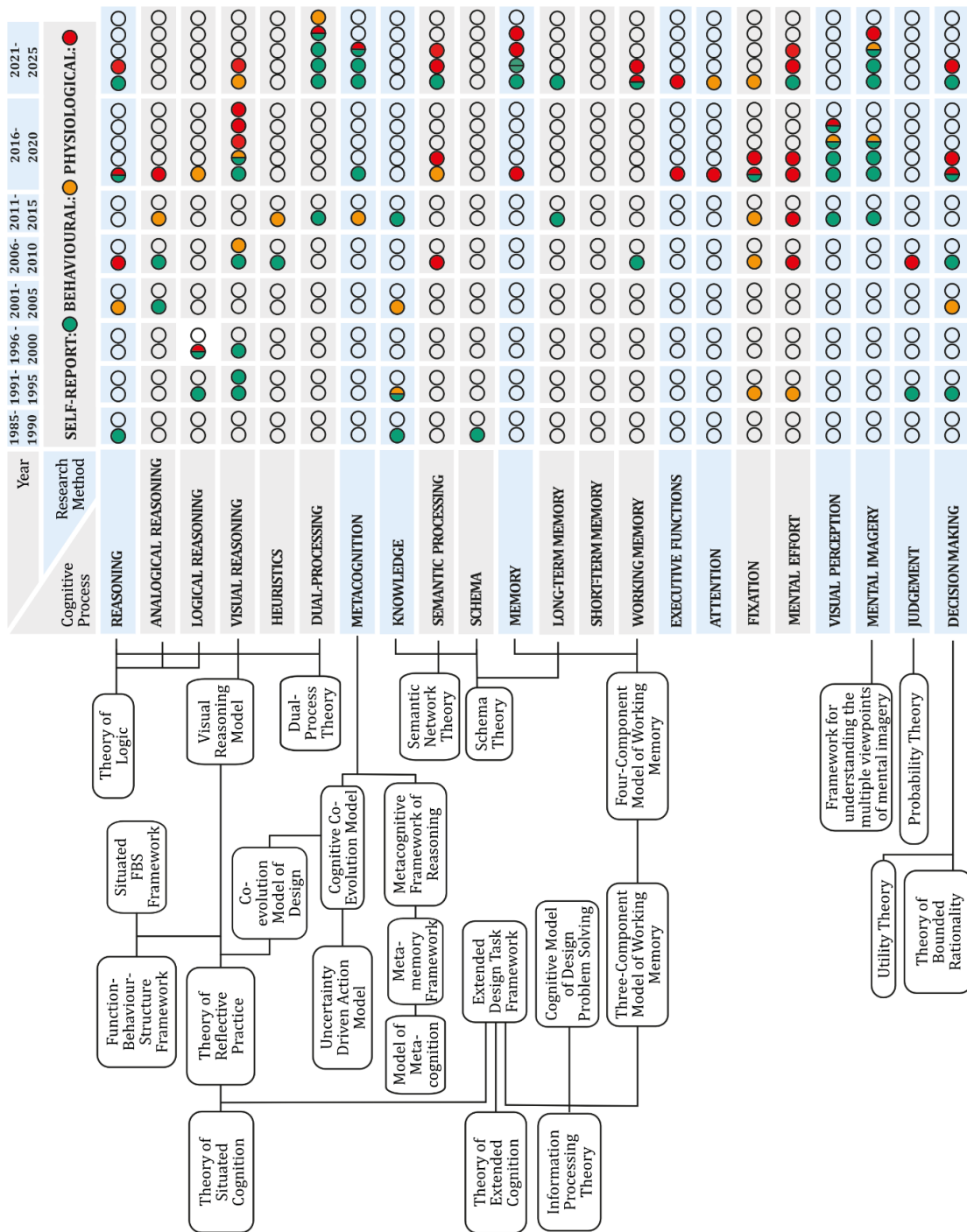


Figure 3-2 - A timeline (1985-2025) of the cognitive processes, theoretical roots, and research methods in conceptual design cognition research on individual designers - Adapted from Paper A

3.6 Summary

This review of conceptual design cognition research focused on constructs and methods by tracing the disciplinary roots of design cognition in cognitive psychology. The literature shows the growing use of physiological, behavioural, and mixed methods use which shows initial progress regarding the drive to align design cognition research with cognitive psychology. However, physiological and behavioural measures present their own challenges for interpreting results (Gero & Milovanovic, 2020). Much room remains for harnessing the full potential of recently applied methods, methods yet to be applied, and methods yet to be combined in a mixed-method approach. The drop in recent years of behavioural method use supports claims that there are a lack of appropriate tests and metrics for studying design cognition (Hay et al., 2017a). Despite this, the trend towards diversifying methods shows promise for closing this knowledge gap between cognitive psychology and design cognition. As design research makes this shift, the support to enable this work through the development of such tests and metrics is a central challenge for the field. More recent cognitive constructs and theory to enter design cognition research from cognitive psychology (e.g. metacognition, executive functions, and dual-process theories) have also been identified as key to developing the field. This classification assisted the framing of subsequent work through providing an understanding of method diversity, easing access to foundational paradigms, and highlighting gaps in current research.

4 A REVIEW OF DUAL-PROCESS THEORIES OF REASONING FOR DESIGN COGNITION RESEARCH

In Chapter 3 the current landscape of design cognition research was reviewed and categorised according to design cognition constructs and research methods. This review highlighted the previously discussed challenges facing design cognition research of i) the lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research. Given the increasing calls for theory-driven research in design, suggestions for tackling these challenges have appealed to introducing and aligning with the research methods, ontology, and theory from the more established field of cognitive psychology (Cash, 2018; Chakrabarti & Blessing, 2014; Hay et al., 2020). One such well-established theory with reliable methods identified in Chapter 3 is dual-process theory (DPT)(see Section 3.4.1.3). Indeed, this has been identified in recent work and dual-process theory research in design has increased dramatically in the last five years being the most researched phenomenon in that time period from the literature reviewed (see Figure 3-2). DPT could support increased consistency in design cognition research which would improve accessibility to design research, knowledge transfer with adjacent fields (Hevner, 2007), the ability to synthesise research, generalisability of conclusions, and work comparison (Hay et al., 2020).

DPT was developed in cognitive psychology and categorises cognition into two types of processes: intuitive, autonomous processing, and reflective processing that burdens limited executive cognitive resources (De Neys, 2018b; Evans & Stanovich, 2013). The application of DPT in design cognition research has many potential benefits but introduces its own challenges. Adopting theories from adjacent fields may come with an incomplete understanding of the underlying principles, resulting in limitations (Blessing & Chakrabarti, 2009). Additionally, staying updated on knowledge and theoretical developments is crucial when consulting unfamiliar disciplines. Dual-process theorists propose different models of the theory, posing challenges in determining suitability for design research goals, synthesising research across models, and identifying relevant DPT debates for design. Furthermore, DPT understanding is hindered by the noise of critiques and clarifications scattered over decades of papers, which has resulted in a flawed, culturally perceived version of the theory (Evans, 2012).

Considering these challenges of applying DPT to design contexts, it is important to properly navigate and situate this work within the differences in formalisations of DPT, particularly the semantics that have obscured some of the theory's key advancements. One such example is the fragmentation of terminology, particularly the use of the terms System 1 and System 2 as an alternative to Type 1 and Type 2. The System terminology became popularised at the end of the 20th century (Stanovich, 1999) and continues to be used by certain authors (De Neys, 2018a; Kahneman, 2011). However, several DPT theorists have moved away from the use of 'systems' in favour of 'types' arguing that the former conjures the idea that each subset of processing is generated by a single brain system rather than multiple brain systems - an unlikely prospect that has the potential to contribute to DPT misconceptions (Evans, 2011; Stanovich et al., 2014). While both terms are still widely used, to avoid bringing such misconceptions about two distinct brain systems into design research, this thesis will use the terms Type 1 and Type 2.

Despite challenges, DPT offers a potential new design research framework with its diversity of the theory offering flexibility. Design research may even aid in clarifying DPT debates and help drive the theory forward. Ultimately, integrating DPT into

design cognition research has the potential to address current challenges, enhance consistency, provide established methods, and improve accessibility and knowledge transfer in design research. A review of DPT research in cognitive psychology as it relates to design research ensures rigour and appropriate contextualisation for subsequent work. In alignment with considerations thus far, rigour was operationalised in this review through situating dual-process theory within its contemporary theoretical context, including distinctions between competing models, terminology, and ongoing debates within cognitive psychology. Relevance was operationalised as the extent to which DPT constructs, methods, and explanatory mechanisms could plausibly align with and inform conceptual design cognition research. The review, therefore, prioritised theoretically influential and methodologically established DPT literature with clear implications for design reasoning, representation, creativity, and cognitive conflict.

This review followed a snowball literature review process, whereby a set of papers was selected through conducting forward and backward citation searches based from the initial conceptual design cognition review sample to identify relevant papers (Wohlin, 2014). This set of key papers was reviewed to determine the current state of DPT design research from its theoretical foundations.

4.1 Models of dual-process theory

For centuries, theories that divide thought into two distinct categories of fast intuition and slow reflection have permeated writing and culture. This can be traced as far back as Aristotelian ideas dividing the mind (viewed as rational) from the body (viewed as the source of emotional thought) (Evans, 2010). Prominent cognitive psychologists of the late 20th century developed more refined ideas of the dual-processing nature of thought which are now held in wide academic regard (e.g. Wason & Evans, 1974) and have snowballed into a popular cultural concept (e.g. Kahneman, 2011).

There are three main views of DPT - the default-interventionist view (also called

the serial model), the parallel processing model, and the hybrid model. These views have been summarised in Table 4-1 outlining the primary difference between the models: order of processing; and the definitions used by each theorist. A sample was taken of the most prominent authors of each model.

Table 4-1 - The main models of DPT and prominent theorists' definitions of Type 1 and Type 2 processing (Adapted from Paper B)

Debate	DPT Model					
	Default-interventionist		Parallel processing		Hybrid model	
Order of processing	Type 1 processing provides an intuitive response that may be subsequently moderated by Type 2 processing		Type 1 and Type 2 processing occur in parallel with both responses competing		Type 1 generates two types of response: heuristic and logical. Type 2 may then moderate the response	
Author	Evans, 2019	Kahneman, 2011	Handley & Trippas, 2015	Trippas et al., 2017	De Neys, 2018a	Pennycook et al., 2015
Definition of Type 1 processing	Intuitive autonomous responses or judgements accompanied by a feeling of rightness.	Automatic, quick, with little or no effort and no sense of voluntary control.	Quick, effortless, high capacity, and autonomous.	Autonomous,	Fast, effortless.	Autonomous and do not require working memory.
Definition of Type 2 processing	Slow, reflective, and which engages working memory.	Attentional allocation to effortful mental activities. Associated with subjective experience of agency, choice, and concentration.	Slow, effortful, low capacity, reliant upon working memory resources, and therefore slow.	Requires working memory.	Slow, effortful, burdens limited executive cognitive resources.	Deliberative and require working memory.

While there are commonalities between DPT models, the key difference is the order in which Type 1 and Type 2 processing occur. The dominant model in the field is the default-interventionist account, whereby Type 1 processing occurs automatically and provides an intuitive response that may subsequently be moderated by Type 2 processing (Evans, 2018). While such accounts consider Type 2 processing to be always engaged, at least at a low level, the first role of Type 2 processing is to determine if the intuitive response is justified (Evans, 2018).

In contrast, the parallel processing model proposes that both Type 1 and Type 2 processing operate simultaneously to generate competing responses (Trippas et al., 2017). Here, the task complexity determines the given response, with logical judgments superseding belief judgements in simpler cases (Trippas et al., 2017).

Hybrid models take a middle ground between these views, proposing that Type 1 processing can give two potential intuitive responses (which may then be moderated by Type 2 processing) (De Neys, 2018a). These two responses are referred to as the logical intuitive response (founded in basic logic and probabilities) and the heuristic intuitive response (founded in associations) (De Neys, 2018a). The view ultimately proposes that Type 1 processing can generate normatively correct responses both through basic logic and bias (De Neys, 2018a).

Much of the debate between these models has been driven by studies showing that logical and belief-based responses can occur in parallel (De Neys, 2012; Handley et al., 2011; Trippas et al., 2017). However, such studies use simple reasoning tasks for which Type 1 processing could automatically process the simple logic (i.e. Type 1 processing could produce both the logical and belief-based responses) (Evans, 2019). Additionally, such simple reasoning tasks differ from the challenging and novel paradigmatic tests used in DPT research which require the use of Type 2 processing to solve (Evans, 2019). The hybrid model that proposes that Type 1 processing can generate both logical and heuristic response does not contradict the default-interventionist view. Rather, it places an emphasis on this Type 1 capacity that is often missed when the ‘received theory’ is mistakenly observed. This is the normative fallacy of the ‘received theory’, whereby Type 1 processing is assumed to generate fast and careless conclusions based on prior beliefs, while Type 2 processing leads to

normatively correct answers from effortful reflection (Evans, 2018). However, intuitive answers can be correct through a fortunate guess, learned associations, or a useful heuristic (Evans, 2018). Considering this, Type 1 is perfectly capable of providing normatively correct answers within both the default-interventionist and hybrid models. Considering these perspectives, this work situates itself within the default-interventionist account.

The different DPT models are layered with varying defining features of Type 1 and Type 2 processing used by dual-process theorists (see Table 4-1). Certain features considered defining by some, are considered correlates by others (Evans & Stanovich, 2013). Commonly considered correlate features of Type 1 and Type 2 processing are: fast and slow, conscious and nonconscious, and belief-based and normative, respectively. These correlations often manifest in DPT research as fallacies which will be contextualised within design research (see Section 4.3).

4.2 Dual-process theory design research

While DPT is widely accepted within cognitive psychology, it is yet to make a wider impact on design research. However, dual-process theory research on creativity (a key component of design cognition) within cognitive psychology is more extensive (e.g. Gabora & Ranjan, 2013; Howard-Jones, 2000; Rominger et al., 2019). Dual-process models of creative thinking are gaining traction (Kannengiesser & Gero, 2019; Sowden et al., 2015), and a ‘dual-process ideation model’ of design cognition has been recently proposed (Gonçalves & Cash, 2021). In design, both Type 1 and 2 processing play important roles in conceptual design (Sowden et al., 2015) and have been linked to the drivers of novelty alongside errors and biases in judgement (Gilhooly et al., 2015). Furthermore, initial work has aligned DPT with design ontology (Kannengiesser & Gero, 2019). Current DPT design cognition research is preliminary and only a few of the many variations and models of DPT in cognitive psychology have entered design cognition research.

Models of creative cognition often divide creativity into two types of processes,

often one more intuitive and one more analytical. For example, thinking categorised as divergent and convergent (Guilford, 1956), associative and analytic (Gabora, 2010), reflection-in-action and reflection-on-action (Schön, 1984), generation and exploration (Finke et al., 1992), schema-driven and case-driven (Ball et al., 2004; W. Wang & Zhao, 2006), or flexibility and persistence (Nijstad et al., 2010). Indeed, many of these conceptualisations of cognition have been cornerstones of design research (e.g. divergent and convergent thought (Dorst, 2011; Goldschmidt, 2016)), continuing the pattern of theory migration from cognitive psychology to design cognition research established in the review of design cognition constructs. While these divisions of cognition from creative cognition research frequently use language associated to DPT, they can rarely be mapped to Type 1 and Type 2 processing directly. However, creative cognition research has shown that both Type 1 and Type 2 thinking have important roles in generative and evaluative stages of the design process (Sowden et al., 2015). Within what Gilhooly et al. (2015) referred to as insight problems (i.e. problems necessitating changes in representational spaces) and creative problems (i.e. those requiring novel solutions), Type 1 processing has a positive impact towards generating novel solutions that may otherwise be unreachable through solely Type 2 analytic processes (Gilhooly et al., 2015). Furthermore, the ability for flexibly switching between these modes (referred to as ‘contextual focus’ (Gabora, 2010) or ‘mode-shifting’ (Pringle & Sowden, 2017)) has been determined as a driver for creativity.

Despite a rich history concerning the duality of cognition in design research, DPT has only recently entered the discipline. This initial DPT driven design research has resulted in a dual-process ideation model with useful insights into the design process regarding potential ratios of Type 1 and Type 2 processing during idea development (Gonçalves & Cash, 2021). In addition, an alignment of DPT with design ontology has provided useful instances where dual-processing can be considered e.g. fixation (Kannengiesser & Gero, 2019). Contrasting design representations (sketching and gestures) through a DPT lens has shown the effect of mismatching representations on the design process (Cash & Maier, 2021). Furthermore, iterative loops of the design process have been mapped through tracing Type 1 and Type 2 thinking with Linkography (Moore et al., 2016).

However, these existing studies rely primarily on speculative assumptions based on dual-process theory. For example, it is often assumed that concept generation will be dominated by Type 1 processing while concept evaluation will feature a greater proportion of Type 2 processing (e.g. Moore et al., 2014). This is likely to be true due to the associative nature of both concept generation and Type 1 processing, and the analytic nature of both concept evaluation and Type 2 processing. However, these assumptions lack the necessary scientifically rigorous foundation in design research with which specific instances of Type 1 and Type 2 thoughts can be confidently identified. This can minimise the impact of such work and lose nuance in how Type 1 and Type 2 thinking are used in each stage of the design process.

4.3 DPT Research paradigms and design research paths

To build the case for conducting more rigorous DPT-driven design research, these intuitive assumptions in design research must be broken down and the research methods used in DPT research must be understood. As research on DPT has evolved, a set of tailored paradigms have emerged within the cognitive psychology discipline. The three types of measures outlined in Section 3.3 are used to guide the discussion of these paradigms and their relevance for the subsequent research. That is, self-report (participants' own descriptions of their cognition), physiological (assessing bodily outputs), and behavioural (direct observations of behaviour) measures (Cozby, 2009; Hiscock, 2003). This division also aids in facilitating triangulation of research - a fundamental driver of theory building and testing (Cash, 2018). In what follows, the paradigms from cognitive psychology and design cognition research found in the literature are discussed. Furthermore, the debates of dual-process theorists and the consequences of these in design research are contextualised within the discussion of these paradigms.

4.3.1 Self-report measures of DPT

4.3.1.1 *Rating scales*

Self-report measures have seen extensive use in DPT research in cognitive psychology. For example, confidence measures have been used as nonverbal measures of cognitive conflict detection. Conflict is an important phenomenon within DPT and refers to a discrepancy between two generated responses e.g. a logical and heuristic Type 1 response (Type 1-Type 1 conflict) or a Type 1 and Type 2 response (Type 1-Type 2 conflict) (Evans, 2019; Pennycook et al., 2015). Studies have shown that in reasoning tasks where the intuitive response conflicts with the normative response, participants report a decrease in confidence (De Neys et al., 2011). Further, when participants are asked to report liking ratings (a Likert scale assessing how liked something is) they assign higher ratings in syllogistic reasoning tasks with believable conclusions than unbelievable conclusions. These studies have demonstrated the importance of metacognition (processes that monitor ongoing thoughts and allocate cognitive resources (Ackerman & Thompson, 2017)) in relation to conflict detection, decision-making, and processing effort (Evans, 2019).

A recent appeal for a narrower definition of Type 1 processing has suggested that “autonomous” is too broad a definition (Evans, 2019). To address this, Evans (2019) proposes that while Type 1 processes do not burden executive resources or working memory, they do post their products into working memory. It is also proposed that this output is accompanied by a metacognitive ‘feeling of rightness’ (FOR) - a sense of the correctness of a generated response (Evans, 2019; Thompson et al., 2011). A low FOR reflects high levels of uncertainty in a response which can trigger the intervention of Type 2 processing.

Feelings of rightness have been previously discussed in design (Ball & Christensen, 2019; Moore et al., 2014), and are hypothesised to be an indicator of Type 2 engagement (Thompson et al., 2011). That is, a low FOR triggers a greater extent of Type 2 analytic reasoning (Thompson et al., 2011). FOR can also be assessed using a self-report rating scale (e.g. Thompson et al., 2011). This could, for instance, be used in a context where designers are asked to assess their FOR about each newly generate concept. Assessing feeling of rightness in the design process could provide another

route to exploring the applications of DPT in design cognition research.

These discussions of metacognition in DPT are a reflection of the ongoing ‘control problem’ debate. That is, what type of processing determines the engagement of Type 2 resources. Does Type 1 intuition reflect on its own response to determine if increased scrutiny is needed? Or, does Type 2 processing act as a judge between its own response and the preceding Type 1 response? Some theorists have indeed taken this view e.g. (Kahneman, 2011). However, such positions posit, as Evans (2019) puts it - that one of the two processing types is both a referee and a participant. An alternative account from Evans (2019) proposes that Type 2 engagement levels are determined by the degree of critical effort set. These processes are not a product of Type 1 or Type 2 processing. Instead, the concept of ‘Type 3’ processes is put forward - defined as “preconscious monitoring and control processes” (Evans, 2019). The role of which is to redirect attention, increase the effort of engagement with a task, and convene the required cognitive processes required for Type 2 engagement with a task (Evans, 2019). FORs are an example of what Evans (2009, 2019) has termed Type 3 processes.

4.3.1.2 *Protocol analysis*

Protocol analysis, whereby a person’s cognition is examined through the verbalisation of their thoughts (van Someren et al., 1994), is one of the dominant self-report measures within design research. Verbal protocols have also been used since the early years of DPT research in cognitive psychology (Cokely & Kelley, 2009; Evans et al., 1983; Verschueren et al., 2005). Verbal protocols are thought to reflect the ongoing contents of working memory (Ericsson & Simon, 1980), and therefore, reflect Type 2 processes (directly) and Type 1 processes (indirectly) (Evans, 2007b). However, there are inherent limitations to studying DPT phenomena through protocol data. That is, Type 1 processing, due to its automatic nature, cannot be accurately reported verbally. Further, verbal protocols are serial, and may limit the expression of competing logical and heuristic Type 1 responses.

Considering the extensive use of protocol analysis in design cognition research, its application to DPT-driven design research was an intuitive step. Indeed, recent design research has seen an exploration of protocol coding schemes based on DPT concepts

(Gonçalves & Cash, 2021; Vieira et al., 2022, 2023). Through drawing on Evans' (2019) concept of Type 3 processes (see section 4.3.1.1), Vieira et al. (2022, 2023) approach protocol analysis in DPT design research by proposing a 'Triple Process Theory' (Vieira et al., 2022, 2023). Triple Process Theory proposes a basis for a protocol analysis coding scheme by categorising cognitive processing as spontaneous, deliberate, or metacognitive. Here, generation can be considered spontaneous or deliberate based on if verbalisations of ideas are either 'automatic, rapid, and effortless' or 'controlled, analytical, and including details or explanations', respectively. Clear parallels are being drawn here between Type 1 and 'spontaneous' thought and Type 2 and 'deliberate' thought. Indeed, similar reasoning is proposed by Moore (2014, 2016) to categorise different statements as indicators of Type 1 or Type 2 processing. However, it seems that such categories may also be subject to critiques of previous work. For example, the first role of Type 2 processing in generating reasons and justifications to rationalise intuitive responses (Evans, 2019). In protocol analysis, this could appear as a response seemingly developed through Type 2 reasoning which could be retrospective analysis of a Type 1 response. However, the framework does offer a promising step towards creating research methods for analysing design through a DPT lens.

The investigations of DPT in design have gone beyond standard protocol analysis with Gonçalves and Cash (2021) using protocol analysis and linkography. Within this research, consciousness was used to distinguish Type 1 and Type 2 processing (Gonçalves & Cash, 2021). In DPT research, a distinction is often made between the nonconscious nature of Type 1 processing and the conscious nature of Type 2 processing. The problematic nature of these correlates being held as defining features has been widely discussed (Evans & Stanovich, 2013; Gronchi & Giovannelli, 2018). There are obvious challenges for understanding Type 1 nonconscious processes through self-report measures. This is particularly important in the context of protocol analysis. While, as discussed, Type 1 processing cannot be accurately verbalised, the result of this processing can be verbalised. That is, a lack of verbal acknowledgement of a design move holds potential for Type 1 attribution, but interpreting verbal acknowledgement of a design move as inherently a Type 2 process risks unwarranted attribution of design moves. This is furthered by the rationalising function of Type 2

processing. Despite this, the consciousness of each process does reveal itself differently. In Type 1 processing, only the result of the processing can be considered consciously (Gronchi & Giovannelli, 2018; Sloman, 2002). Contrastingly, Type 2 processing involves both conscious awareness of the process and the result (Gronchi & Giovannelli, 2018; Sloman, 2002). Type 2 processing is also dependent on unconscious processes such as the delivery of relevant contextual information (Evans, 2010).

4.3.2 Behavioural measures of DPT

4.3.2.1 Cognitive constraints

Behavioural measures have been the primary tool of DPT investigation in cognitive psychology. A common DPT behavioural method involves applying cognitive constraints to influence the type of processing used in a study response. This is often done by loading the participants' working memory - an individual's capacity to temporarily store and manipulate information to support ongoing cognitive activities (Baddeley et al., 2011; Logie et al., 2021). Working memory is a defining feature of many definitions of Type 2 processing (see Table 4-1). Within the dual-process account, loading working memory should interfere with the participants' ability to engage Type 2 processing as these limited resources are already occupied by effortful cognitive tasks such as counting aloud. Such experiments have indeed shown that logic-based responding decreases as working memory load increases (Baddeley et al., 2011). In other words, when participants have a loaded working memory, they rely more on Type 1 processing. In design, possible applications of this method may involve asking participants to count aloud while completing a design task, such as ideation.

Another method of inducing a greater reliance on Type 1 processing is through constraining the time available for a participant to provide a response to a reasoning task. Reducing available time decreases the likelihood of Type 2 intervention (Evans & Curtis-Holmes, 2005). This factor often follows the 'two-response paradigm' (Ball et al., 2018; Thompson et al., 2011) whereby participants are given a task with both a time constraint and no time constraint. Such paradigms have shown an increase in

responses based on various Type 1 biases (Evans & Curtis-Holmes, 2005; Roberts & Newton, 2001; Thompson et al., 2011).

Cognitive constraints could provide a useful framework to investigating DPT phenomena in design. Reducing available time for tasks could highlight the role of Type 1 processing while revealing the results of constraining Type 2 processing. Such paradigms rely on a fast response when reducing available time and allowing for slower responses when time is unconstrained. However, this paradigm is not an absolute determinant of Type 1 and Type 2 processing and it should be noted that fast responses are mostly based on Type 1 processing.

DPT research often utilises the correlation of fast processing with Type 1 processing due to its automatic and intuitive nature, while slow processing is correlated with Type 2 processing as more effortful and reflective thought. While this is often the case, a process being quick does not necessitate the use of Type 1 processing. Type 1 processing forms associations through experience, while Type 2 processing can learn heuristics and rules-of-thumb which must be explicitly applied but can be done so quickly (Evans, 2011). These shorthands are tempting tools to roughly identify the processing types, but are considered fallacies of the theory (Evans, 2012). These fallacies have already featured in initial DPT-driven design cognition research. For example, defining Type 1 and Type 2 as “fast” and “slow” processing, rather than correlating with these characteristics, has featured in recent DPT-driven design research (Cash & Maier, 2021; Gonçalves & Cash, 2021; Kannengiesser & Gero, 2019; Moore et al., 2016). Such tendencies may place limitations on the current conclusions of DPT design research. Additionally, drawing links between ‘fast’ design processes like concept generation, and ‘slow’ design processes like concept evaluation with Type 1 and Type 2 processing (e.g. Kwon & Goucher-Lambert, 2025), risks losing the nuance of both design and DPT. Evans (2020) worded it succinctly regarding this nuance stating that there are two processing forms - “Type 1 which is intuitive and typically quick, and Type 2 which is reflective and typically slow”.

Alongside differences in treating fast/slow as defining features or correlates of DPT, there is, much debate between DPT theorists regarding working memory - a key variable in cognitive constraint paradigms. Evans and Stanovich (2013) proposed that

working memory should be the defining feature of Type 2 processing. Evans (2018) even considers the study of working memory and Type 2 processing to be one and the same. However, such perspectives have been criticised considering the various definitions and models of working memory alongside recent evidence of an unconscious engagement of working memory. There are arguments that posit working memory to be a continuum, with more nuance than simply being engaged or not engaged (De Neys, 2021; Soto & Silvanto, 2014). Despite such evidence, De Neys (2021) argues that deliberate thinking can still be conceptualised as requiring greater executive control than intuitive thought. While certain defining features of dual-process theories are under constant criticism, De Neys (2021) also believes these debates to be somewhat irrelevant to the progression of psychological theories. Understanding the quantitative or qualitative nature of Type 1 and Type 2 processing is not necessary to gain insight into our psychology (De Neys, 2021). Some parallels can be drawn from De Neys (2021) to consider the future DPT design research: knowing if Type 1 and Type 2 processing are a continuum or discrete categories is irrelevant to determining whether a dominance of analytic thought leads to more optimal design evaluation than intuitive thought, whether designers are more susceptible to bias when intuiting more, if there are design processes that perform better with more intuition or less, which cues in the design process trigger the switch to more analytic processing, and whether we can optimise designer's reasoning through tools that encourage more or less intuitive or analytic processing. Indeed, it is this approach that is taken in this work - that determining whether working memory is discrete or a continuum is irrelevant to advancement. Rather the focus is on defining Type 2 processing as requiring greater executive control than Type 1 processing. Determining a resolute answer to such debate fell beyond the scope and requirements of this thesis.

4.3.2.2 *Heuristics and biases*

Thus far, several methods commonly used in DPT research have been discussed. However, the dominant research method in DPT research centres around the concept of cognitive bias, first investigated in the heuristics and biases program initiated by Tversky and Kahneman (1974). This paradigm led to a vast wealth of research on the

systematic errors made by people when selecting actions and assessing probabilities (bias) and the reasons behind why people often make these errors through applying mental shortcuts (heuristics) (Stanovich et al., 2016). The study of dual-processing in cognitive psychology is conducted almost exclusively by giving participants written tasks that either do, or do not, require the engagement of Type 2 processing to provide the correct response. Specifically, tasks that induce biased responses detangle the intricacies of Type 1 and 2 interactions during reasoning processes. The performance on these tasks is then assessed and contrasted with a variety of measures.

The most commonly used method for engaging Type 2 reasoning is inducing belief bias: the phenomenon that, when presented with an argument, people will find a conclusion acceptable if the conclusion aligns with their existing beliefs, regardless of its logical validity (Ball et al., 2018). That is, people tend to focus on pre-consciously cued beliefs, and maintain the conclusion drawn from these beliefs, without considering alternatives. Presenting participants with reasoning tasks that induce a discrepancy between the belief-based and logic-based responses (i.e. causing a cognitive conflict (Evans, 2007b)) has been the archetypal case for identifying Type 2 thinking in DPT research and for developing the theory (Evans, 2008). The paradigmatic test that illustrates this concept of conflict and belief bias involves giving participants a syllogism (deductive reasoning task) and asking them to assess its logical validity (Evans, 2008). An example from Handley and Trippas (2015) of such a syllogism is:

All living things need water

Roses need water

Therefore, roses are living things

1. The conclusion is valid (incorrect)
2. The conclusion is invalid (correct)

Both the validity (if the conclusion is true following the premises) and the believability (if the conclusion aligns with the participant's beliefs) of such syllogisms can differ (Evans, 2008). In the above examples, the conclusion is invalid but believable (i.e. a belief-logic conflict).

Alongside syllogisms, researchers use deductive reasoning tasks intended to measure the tendency of a participant towards Type 2 processing to override an intuitive response (Pennycook, 2018; Toplak et al., 2014). The most famous of which is the “bat and ball problem” developed by Frederick (2005) as part of the Cognitive Reflection Test. The problem is as follows:

A bat and a ball cost \$1.10 in total. The bat costs \$1.00 more than the ball.

How much does the ball cost? _____ cents

It is easy to see the intuitive answer to the question (10 cents), but it is also, after some reflection, easy to determine the correct answer (5 cents). Such reasoning tasks follow a similar premise to logical syllogisms whereby there is a “lure” that induces conflict between an incorrect intuitive response and the correct response that is gained with Type 2 processing.

The Cognitive Reflection Test is also thought to be a measure of a factor that could be critical to developing DPT design research - rational thinking disposition (sometimes referred to as cognitive style (Trippas et al., 2015)). That is, the inherent tendency of each individual to have different reliance on Type 1 or Type 2 processing (Stanovich et al., 2016; Trippas et al., 2015). This too is included in Evans' (2019) term - Type 3 processes (see Section 4.3.1.1). Alongside inherent tendencies, the employment of Type 1 or Type 2 processing is influenced by the context. An expert designer may be more likely to rely on Type 1 processing in many situations where a novice would respond with Type 2 due to processes learned to automaticity over time. Additionally, each phase of the design process may also be dominated by a Type 1 or

Type 2 response. Investigating the rational thinking disposition of designers and how this plays out in different design contexts may be crucial to the development of design tools and methodology to aid and cater to individual designer needs.

Many early experiments in the heuristics and biases approach in cognitive psychology centred around the idea that Type 1 generates fast and careless conclusions based on prior beliefs, and that Type 2 processing leads to normatively correct answers from effortful reflection (Evans, 2018). However, awareness that both Type 1 and Type 2 processing can generate belief-based and logical responses is an important consideration for design research in the area. Indeed, intuitive answers can be correct through a fortunate guess, learned associations, or a useful heuristic and more recent efforts have been made to emphasise that Type 2 processing can be a cause of just as much bias as Type 1 processing (Evans, 2018). Namely, two fundamental types of bias can be linked to each of the processing types:

- The fundamental heuristic bias:
 - o The selective focusing on pre-consciously cued relevant information during Type 1 processing.
- The fundamental analytic bias:
 - o The maintenance of a hypothesis in Type 2 processing without considering alternatives.

(Evans, 2018).

How such biases play out during the design process may differ to that shown in reasoning research in cognitive psychology. While Type 1 processing has often been connected to errors in judgement in decision making and reasoning tasks, it has also been connected to novel solutions in creativity research (Gilhooly et al., 2015). Indeed, intuition can be a powerful driver of good solutions honed through the accumulation of experience (Badke-schaub & Eris, 2014). Furthermore, in contrast to the absolute nature of paradigmatic DPT tasks, design operates through a satisficing nature (Simon, 1972)(see Section 3.4.2), whereby designers generate and develop their own solutions

rather than assessing given alternatives. Therefore, there are multiple solutions to satisfy any given design problem, not a singular correct answer. However, there are incorrect or unsatisfactory design solutions. Given this nature of design, a key avenue for DPT design research, and, indeed, this thesis, is how the respective biases of Type 1 and Type 2 processing play out within the design process.

4.3.3 Physiological measures of DPT

As with the increasing application of physiological measures in design cognition research at large (see Section 3.3.3) - DPT research has also explored the use of such measures. Particularly, physiological measures have been used to investigate DPT conflict between responses on reasoning tasks. For example, skin conductance response research has shown that autonomic arousal is tied to the detection of a conflict between a logical and intuitive response (De Neys et al., 2010). Interestingly, a participant may detect this conflict and still decide to respond with an incorrect intuitive response to a reasoning task. Therefore, supporting that the participant's cognitive ability and individual tendency to engage Type 2 processing determine the likelihood of high Type 2 engagement. Relating this to design research, the use of skin conductance measures poses many challenges. Autonomic arousal can be caused by various stimuli and contextual factors which makes it an unlikely choice for in-situ DPT design research. However, the method could be applied within more traditional cognitive psychology paradigms such as used by De Neys et al. (2010).

Eye tracking has also been successfully applied in DPT research. Research has shown that participants spend more time looking at the given problem in conflict reasoning tasks over no-conflict tasks (Purcell et al., 2021). This indicates that the length of gaze and the objects of this gaze can be indicators of Type 2 processing depth and engagement (Purcell et al., 2021). Furthermore, eye-tracking has been used to investigate the differences in expertise through a DPT lens (Gegenfurtner et al., 2011; Warren et al., 2018). Such research has shown experts have a greater dependency on Type 1 processing regarding the process of visual information than novices.

EEG recordings are a more recent addition to methods in DPT research. Banks and Hope (2014) used EEG measurements to investigate belief bias. They found that EEG

measurements during belief bias conflict problems suggested that parallel models of dual-processing were more correct than serial models (e.g. default interventionist). However, this work is open to the same limitations pointed out by Evans (2019) regarding the use of simple reasoning tasks for which Type 1 processing could automatically process the simple logic (i.e. Type 1 processing could produce both the logical and belief-based responses). Indeed, although using a different reasoning task, later work conducted by Bago et al. (2018) used EEG to determine that early conflict detection on base-rate problems suggested that Type 1 processing was capable of processing both belief-based and simple logic-based responses. These base-rate tasks are another traditional behavioural measure task used in DPT research typically involve presenting participants with scenarios requiring a judgement based on both statistical base rates (such as the prevalence of certain traits or events within a population) and specific case information. These tasks are subject to the familiar biases of Type 1 and Type 2 processing (see Section 4.3.2.2), for example:

“In a study 1000 people were tested. Among the participants there were 995 nurses and 5 doctors. Pat is a randomly chosen participant of this study. Pat is 34 years old and lives in a beautiful home in a posh suburb. Pat is well spoken and very interested in politics and invests a lot of time in his or her career. Which of the following is more likely?

1. Pat is a nurse (logical response)
2. Pat is a doctor (heuristic response)

(Handley & Trippas, 2015)

While physiological measures are seeing a rapid increase in use in design research as a whole (see section 3.5), they have yet to be used in initial DPT driven design research. However, the discussed paradigms in physiological cognitive psychology research could help detangle Type 1/Type 2 processing ratios in design tasks.

4.4 Summary

There is great potential for DPT application in design research. However, the frequent use of Type 1 and Type 2 correlates as defining features indicates the need for caution in design research applying DPT. While Type 1 or Type 2 distinctions such as fast/slow, conscious/nonconscious, and belief-based/normative are tempting shorthands to roughly identify the processing types (Evans, 2012), this simplification risks losing the details of how the two processing types interact in the design process. Indeed, several of these correlates have been used in initial DPT design research to identify processing type. While such associated features may give broad insight into the workings of dual-processing in design - ensuring conclusions are built on a scientifically rigorous and theoretically grounded foundation is crucial.

The exploration into self-report, behavioural, and physiological measures following on from the work in Chapter 3 reveals the current work and potential for adapting DPT methods from cognitive psychology to design. Such work would benefit from the established high degree of internal validity. The nature of design, however, presents unique challenges for DPT research.

The rigour seen in DPT research is aided by the archetypal constrained scope typical of cognitive psychology research. In contrast, design research has excelled at naturalistic paradigms and practice-based research. How these two approaches can be combined to support the lack of theory development and impact in design research is a challenge. Indeed, cognition itself, by its nature, a complex topic to study. It has been compared to trying to studying your blind spot, in that “as soon as you look at it, it shifts” (Sloman, 2015). A clear example of this in design research is the dominance of ‘think aloud’ methods (protocol analysis) which, by the nature of verbalising their thoughts, changes the thought itself (Hay et al., 2017a; Mega & Volz, 2014). Not only is cognition difficult to study even in highly controlled and scoped experiments, the complexity of design adds yet further challenges. Design is non-linear, and highly iterative. It centres around problems often discussed as being complex and ill-defined (Buchanan, 1992; Goel, 1995a; Ho, 2001; Simon, 1973). This stems from the concept of ‘wicked problems’ (Rittel & Webber, 1973) which describes such problems as: essentially unique; poorly formulated; having no clear end point; resulting in only

satisficing solutions - rather than true or false solutions; and influenced by the conflicting values of stakeholders. It is this complexity that differentiates design problem solving from more general problem solving where the problem can be considered 'well-defined' (Ball & Christensen, 2019).

These challenges must be overcome to adapting the discussed established DPT methods to design research. For example, psychometric measures may assist in creating a solid foundation of theory for DPT-driven design research and assessing individual differences in designers. Within this it must be determined which cognitive processes can be assessed using the well-established battery of tests from cognitive psychology, and for which must we develop tailored psychometric tests targeting cognitive processes that are design-task-dependent.

The design process itself must also be measurable. Challenges here could present in a designer's tendency to engage rational thinking being tested, but the application of this tendency being different during concept generation (when critical analysis is discouraged) and concept evaluation (when critical analysis is necessary). Susceptibility to cognitive biases may also change throughout the design process, as may tendency to act on uncertainty or preference of communication style, among others. Utilising experimental paradigms from cognitive psychology reasoning research in design will not solely explain the wider workings of design cognition. Therefore, to conduct DPT-driven design research, how the design context influences cognition must also be considered.

This dynamic nature of design, and the lack of solid foundational theory for applying DPT in design research, suggests that the identification of exact instances of Type 1 and Type 2 processing appears to be beyond current reach. An approach that is more likely to support the building of such a foundation is the identification of patterns of Type 1 and Type 2 processing. While psychometric testing holds potential for investigating individual differences in dual-processing for designers, connecting such differences to the presentation of known dual-processing biases may well be a route to identifying such patterns in design cognition. Indeed, DPT research in cognitive psychology has relied heavily on cognitive biases to explore the roles of Type 1 and Type 2 processing. The fundamental biases of Type 1 and Type 2

processing (the fundamental heuristic bias and the fundamental analytic bias) could be an aspect of such foundational theory that can be linked to design.

Through this chapter a clear gap has been identified for more rigorously founded experimental work applying DPT to investigate cognitive phenomena in design research. However, design is not as simple as paradigmatic reasoning tasks used in cognitive psychology. Following this, there is also a gap for theory to support this experimental work in design.

5 RESEARCH FOCUS

Chapters 3 and 4 revealed several persistent challenges that hinder progress in design cognition research, highlighting three key issues that are key to strengthening the field's theoretical and methodological foundations:

- i) The lack of alignment of design cognition with established ontological and methodological standards.
- ii) The absence of suitable tests and metrics for studying design cognition
- iii) The lack of combining quantitative and qualitative methods in design cognition research

(Cash et al., 2019; Dinar et al., 2015; Hay et al., 2017a, 2017b, 2020)

It was identified that through applying theory and methods from more established fields, these challenges could be addressed. Particularly, DPT emerged as a promising route to progressing the field of design cognition. In tackling these challenges, the literature called for improvements in ontological consistency, accessibility to design research, knowledge transfer with adjacent fields, the ability to synthesise research across disciplines, ecological validity of research, significance and generalisability of conclusions, and ability to comparison research findings. These conclusions were synthesised using the DRM technique of a Reference Model (Figure 5-1).

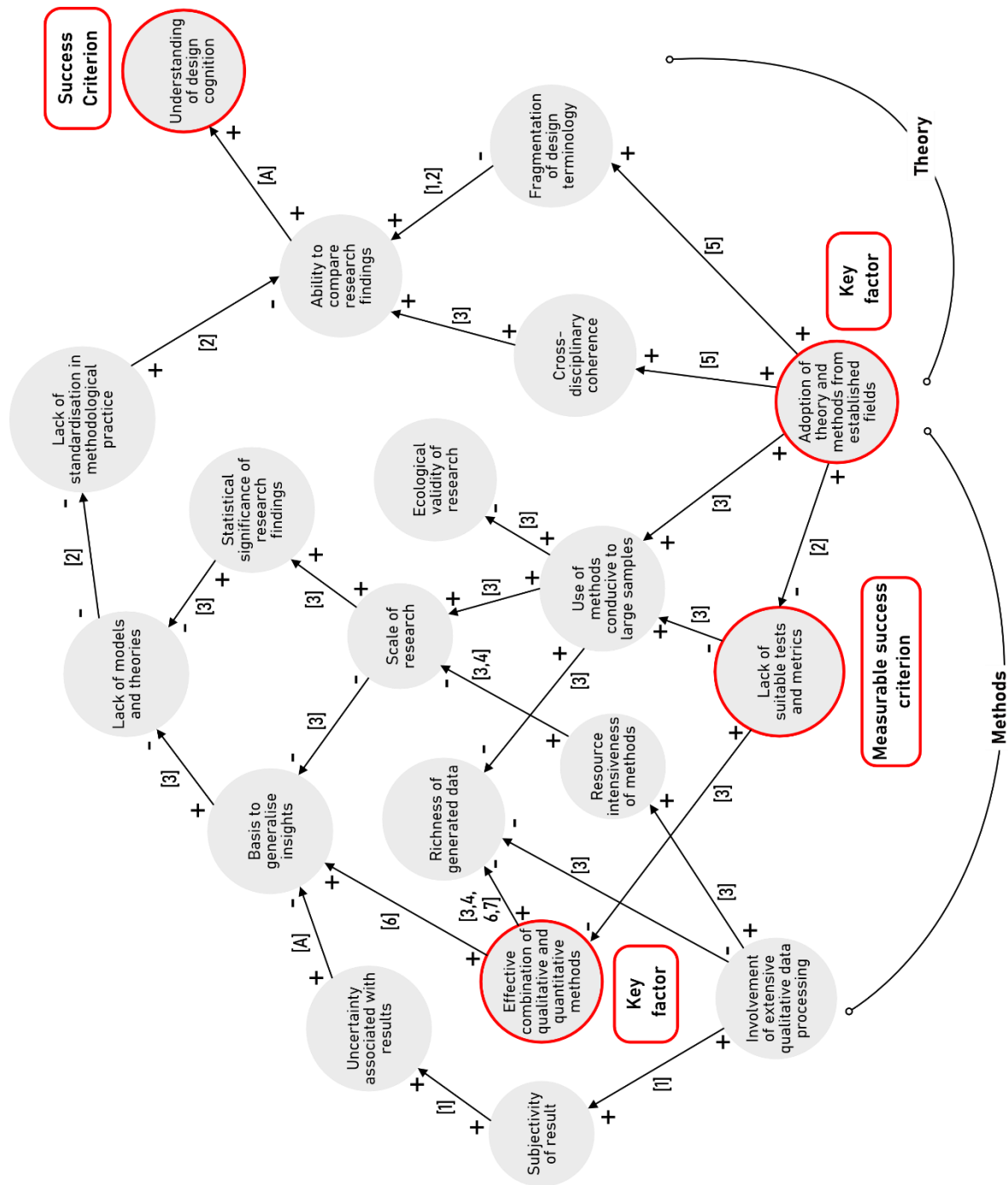


Figure 5-1 - Reference Model of the existing situation

[1] Hay, L., Duffy, A. H. B., McTeague, C., Pidgeon, L. M., Vuletic, T., & Grealy, M. (2017). Towards a shared ontology: A generic classification of cognitive processes in conceptual design. *Design Science*, 3(7). <https://doi.org/10.1017/dsj.2017.6>

[2] Hay, L., Cash, P., & McKilligan, S. (2020). The future of design cognition analysis. *Design Science*, 6(<https://doi.org/10.1017/dsj.2020.20>)

[3] Hay, L., Duffy, A. H. B., McTeague, C., Pidgeon, L. M., Vuletic, T., & Grealy, M. (2017). A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. *Design Science*, 3. <https://doi.org/10.1017/dsj.2017.11>

[4] Dinar, M., Shah, J. J., Cagan, J., Leifer, L., Linsey, J., Smith, S. M., & Hernandez, N. V. (2015). Empirical Studies of Designer Thinking: Past, Present, and Future. *Journal of Mechanical Design, Transactions*

[5] Cash, P., Daalhuizen, J., Valgeirsdottir, D., & van Oorschot, R. (2019). A theory-driven design research agenda: Exploring dual-process theory. *Proceedings of the International Conference on Engineering Design, ICED, 2019-Augus(AUGUST)*, 1373–1382. <https://doi.org/10.1017/dsi.2019.143>

[6] Shah, S. K., & Corley, K. G. (2006). *Building Better Theory by Bridging the Quantitative – Qualitative Divide* *. December. <https://doi.org/10.1111/j.1467-6486.2006.00662.x>

[7] Cash, P. J. (2018). Developing theory-driven design research. *Design Studies*, 56, 84–119. <https://doi.org/10.1016/j.destud.2018.03.002>

The Reference Model provides a structured synthesis of knowledge extracted from the literature reviews, capturing key methodological and theoretical challenges in design cognition research. While the first literature review served as the foundation for structuring the existing insights and identifying challenges (Chapter 3), the second literature review (Chapter 4) deepened the theoretical basis for the empirical studies and helped refine the scope of investigation. The Reference Model represents a comprehensive picture of the existing state of design cognition research, which helped to determine areas that required further investigation.

The network of the Reference Model outlines influencing factors of the existing situation in design cognition research, providing an overview of critical dependencies and relationships. Each factor represents an aspect of the research environment that has a measurable or observable impact on design cognition research. These factors are linked to each other to show how these influences exist. That is, they represent statements about the current or desired situation. The symbols - '+', '-', '0', describe how each factor directionally affects another e.g. that less ('-') 'fragmentation of design ontology' leads to greater ('+') 'ability to compare research findings' or no effect - '0'. (see Figure 5-1). (Blessing & Chakrabarti, 2009)

Two key factors were identified that document two of the challenges discussed throughout Part 1 of this thesis. From Figure 5-1, it can be seen that these factors play an important role in shaping how design cognition research is conducted and evaluated: the adoption of theory and methods from established fields, and the effective combination of quantitative and qualitative methods. The success criterion established in this model is "Understanding of design cognition", which serves as the benchmark for measuring improvements in the research domain. The measurable success criterion - the 'Lack of suitable tests and metrics' is captured in the last of the main challenges discussed throughout. It is this criterion on which the success of this work will be qualitatively measured.

By explicitly mapping influencing factors and their interrelationships, this Reference Model provides both a theoretical foundation and a practical guide for advancing research in design cognition. The key factors and criterion are all linked, directly or indirectly to a root node of the 'adoption of theory and methods from

adjacent fields’ - it is here that the potential of DPT emerges. How it will be adopted is approached in this chapter.

5.1 Cognitive bias and conflict

Through reviewing existing DPT research in cognitive psychology and the initial DPT-driven design cognition research, several directions for this work were revealed. Specifically, the dominant DPT research paradigm used in cognitive psychology of assessing bias was identified for potential application in design. Furthermore, it was determined that the concept of cognitive conflict could be crucial to determining how Type 1 and Type 2 processing play out in the design process.

The concepts of bias and conflict are intrinsically linked within DPT. That is, conflict arises when facing a task that generates two different responses - at least one of which is likely to be the product of cognitive bias. Intuitive responses from Type 1 processing may contradict reasoned judgements generated by Type 2, or when conflicting information challenges preconceived notions held by either processing type. Type 2 can then be engaged to resolve this conflict by critically evaluating information, applying logical reasoning, and potentially revising initial judgements.

As discussed in Chapter 4 (section 4.3.2.2.), traditional reasoning tasks from cognitive psychology assess conflict through inducing a discrepancy between the belief-based and logic-based responses (Evans, 2007b). The paradigmatic test illustrating this concept of conflict was also reviewed through an example from Handley and Trippas (2015) (section 4.3.2.2). In this syllogistic reasoning task, the belief-based response (conclusion is valid) is considered the ‘lure’ answer, given that the correct response is that the conclusion is invalid. This task follows syllogistic logic. That is, a major premise, a minor premise, and a conclusion.

This was taken as the basis of the methodological bridge built in this thesis from cognitive psychology dual-process theory and methods to design research. There is a correct and incorrect answer in such reasoning tasks. However, as previously discussed, design operates through a satisficing nature (Simon, 1972), whereby

designers generate and develop their own solutions rather than assessing given alternatives. While there are multiple correct solutions, there are also incorrect or unsatisfactory design solutions. Considering this, we must determine a basis on which to conceptualise the ‘lure’ and ‘correct’ responses of design to assess DPT concepts.

5.2 A theory of FBS conflict

In this section a novel theory of dual-processing conflict in design will be proposed. To found this theory, deductive reasoning tasks used in DPT research were considered. Such tasks can be broken down into discrete components - the premises, and the conclusion. Here it is proposed that the ‘function-behaviour-structure’ (FBS) framework, emerging from initial literature searches (section 3.1), can function similarly in design to the premises of such tasks. The following breaks down the a priori logic used to develop this theory.

5.2.1 The FBS Framework

The FBS framework breaks design down into three foundational constructs: function (the artefact’s purpose), behaviour (how the artefact performs), and structure (the artefact’s physical composition) (Gero & Kannengiesser, 2014). This foundational nature of the framework led to its use as the basis for the novel theory of dual-processing conflict in design. Here, the framework and its developments are discussed within this context.

The FBS framework has been fundamentally criticised within design research. These concerns have addressed inconsistent definitions across publications on the framework, and the incompatibility of posing FBS as both a descriptive and prescriptive model of design (Vermaas & Dorst, 2007; Zhang et al., 2011). To account for such criticisms, this work uses the above definitions, and takes FBS as a descriptive base for deconstructing design into discrete concepts. The resulting hypothesis is that a cause of cognitive conflict can be derived from the FBS framework whereby the perceived validity of a design concept is a driver of the design process. That is, that an influencing factor of this validity is dependent on the alignment of the perceived

function, behaviour, and structure of the concept. To untangle this proposed connection with FBS, it must be considered in more detail. This is aided by a graphical depiction of the framework (see Figure 5-2).

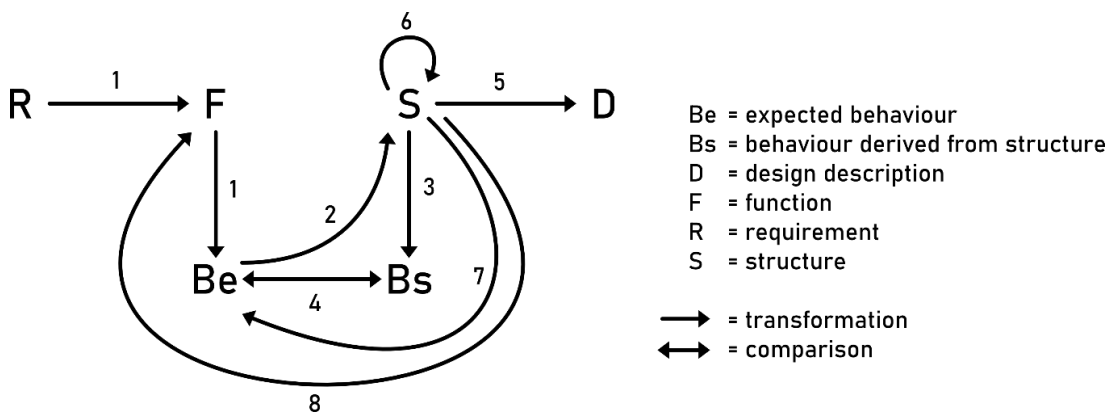


Figure 5-2 - The FBS framework (redrawn from Gero and Kannengiesser (2014))

Beyond the core FBS constructs already defined, the framework proposes two separate categories of behaviour (B): expected behaviour (Be) and the behaviour derived from structure (Bs) (Gero, 1990) (see Figure 5-2). The expected behaviour is how the designer intended the artefact to operate, which may differ from the resulting behaviour produced from its structure (Gero & Kannengiesser, 2014). Additionally, the set of requirements are denoted by ‘R’, and a description of the artefact is denoted by ‘D’. The designer, through using their experience, creates links between the function, behaviour, and structure of a design artefact. The proposed set of transformations possible between these three main ontological constructs (FBS) have been termed ‘design processes’ which are defined as “transformations from one design to another” (Gero & Kannengiesser, 2014). The transformations (see Figure 5-2) are:

1. Formulation : $F \rightarrow Be$
2. Synthesis: $Be \rightarrow S$ via Bs
3. Analysis: $S \rightarrow Bs$
4. Evaluation: $Bs \rightarrow Be$
5. Documentation: $S \rightarrow D$
6. Reformulation-1: $S \rightarrow S'$
7. Reformulation-2: $S \rightarrow Be'$
8. Reformulation-3: $S \rightarrow F'$ via Be

Although these transformations are conducted through a series of cognitive processes employed by the designer, Gero recognised the neglect of the context beyond these processes. This resulted in the development of a more cognitively oriented version of FBS called the ‘situated FBS framework’ (sFBS) (Gero & Kannengiesser, 2000).

5.2.2 The Situated FBS Framework

In developing the FBS framework to account for the wider context of design, Gero and Kannengiesser (2000) included the idea that designers experience designing as a process of reflection between themselves (including their experiences), and their environment (including the contextual information). This concept, termed ‘situatedness’, can be exemplified in how designers, through visually perceiving their concept sketches, induce the unintended discovery of further attributes and properties for solutions (Goldschmidt, 1991). Situatedness emphasises how the designer’s perception of their situation changes as they perform actions (both physical and cognitive) (Dorst & Dijkhuis, 1995; Gero & Kannengiesser, 2004). It has been succinctly outlined in that the when, where, and what of the designer’s actions directly influence the design process (Gero & Kannengiesser, 2004).

The resulting sFBS framework is centred around the designer’s evolving representations of their physical, perceived, and anticipated situation. These three separate, but interacting, environments are termed the external world, the interpreted world, and the expected world. For design, the external world is physical and independent of the designer, the interpreted world is the mind’s perception and experience of the world, and the expected world is the imagined environment dependent on anticipated actions and predictions (Gero & Kannengiesser, 2000).

An important concept within the sFBS framework is constructive memory. Constructive memory considers that memories are representations of past experiences built on what happened as well as influences from the person’s knowledge, beliefs, and experiences (Goldstein, 2019). This can be seen in how people often report distorted accounts of past experiences, a cause of some of these inaccuracies in memory has been theorised to come from how memories are constructed in cognition.

In relation to designing, an aspect of the designer's knowledge that can influence this memory retrieval is the contextual knowledge i.e. the information within their environment. That is, the situatedness of the designer influences their memory. (Gero & Kannengiesser, 2014)

Alongside constructive memory, there are three processes linking the external, interpreted, and expected world. These are interpretation (i.e. the process of creating meaning from the perceived world), focussing (i.e. using this information from the interpreted world to create goals for the expected world), and action (i.e. the process of achieving these goals through altering the external world) (Gero & Kannengiesser, 2014) (see Figure 5-3).

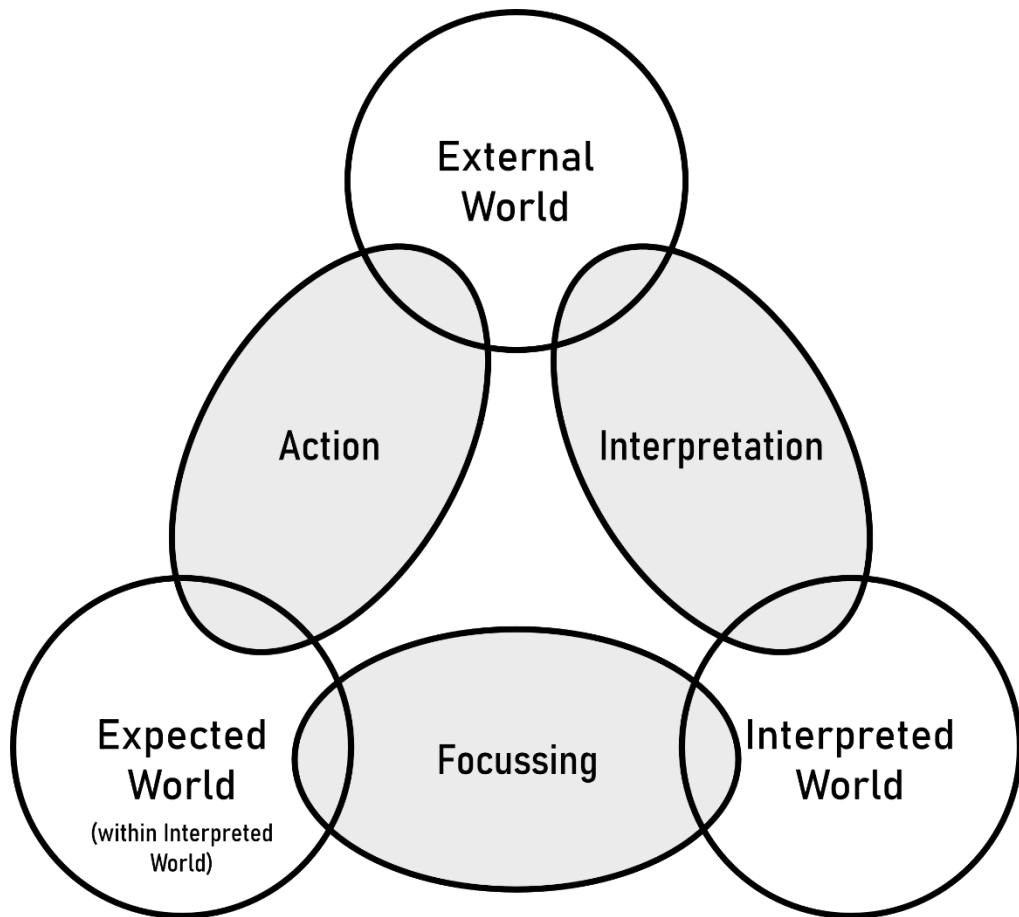


Figure 5-3 - The situated FBS framework interactions of the three worlds (redrawn from Gero and Kannengiesser (2014))

5.2.3 A proposal of conflict within the FBS framework

Bringing this back to dual-process theory, cognitive conflict occurs when two conflicting responses are generated for a given stimulus. This is the central construct behind the FBS theory of conflict that is being proposed. Connecting this to the sFBS model, potential for such cognitive conflict can be seen at different levels:

Function: When considering the purpose of a design, conflicting interpretations of the primary function of the design solution may arise.

Behaviour: When considering how an artefact performs, conflicting interpretations of behaviour may occur. For example, Type 1 processing may suggest an intuitive interpretation of behaviour while Type 2 engagement may reveal an alternative interpreted behaviour.

Structure: When considering the composition of a design, cognitive processing may generate conflicting interpretations or actions for the structure or arrangement of components.

Alternatively, conflict could also arise between FBS constructs. For example:

Function - Behaviour: When the interpreted behaviour does not align with the purpose of the artefact. That is, it is perceived to do something that was not intended.

Behaviour - Structure: The design may be perceived to behave in a certain way but upon further inspection of the structure (e.g. Type 2 engagement) a discrepancy between the two may be detected.

When breaking this down further within the sFBS framework more detail must be considered. Figure 5-4 shows how the three sFBS worlds interact (whereby X can be replaced by any of the FBS constructs e.g. Fe^i). This interaction is described through

a process of ‘push-pull’ where an internal representation is formed through perceived information (push), and the pull is when this representation is interpreted through current interpretations and expectations (Gero & Kannengiesser, 2004). This push-pull takes place both in the interaction of the designer and their external world (through interpretation) as well as the designer with their internal world (through constructive memory) (conveyed in Figure 5-4) (Gero & Kannengiesser, 2004).

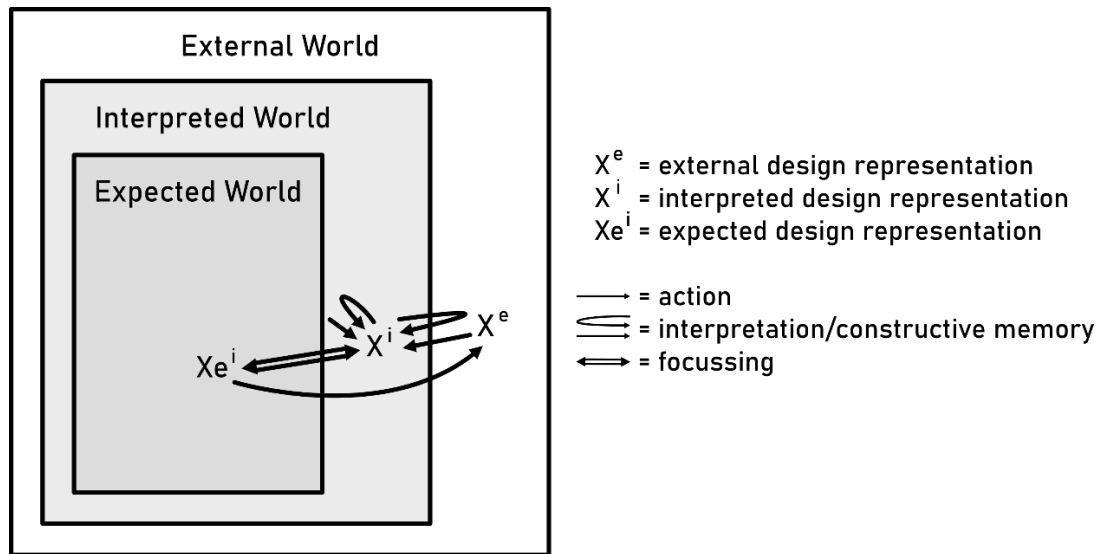


Figure 5-4 - The situated FBS framework for design representations (adapted from Gero and Kannengiesser (2014))

In traditional DPT reasoning tasks from cognitive psychology, the participant must interpret the premises of a task. Through the lens of the FBS framework, a designer must interpret the function, behaviour, and structure of a design. To illustrate this parallel, we can examine the example of a designer being given the conceptual design brief:

“Homeowners are often busy and may not always be around to water house plants. Generate concepts for products that may automate the watering of plants in the home.”

An expected function of this could be:

Feⁱ: “Provide water to houseplants”

This in turn could generate the expected behaviour of the solution:

Beⁱ: “Pour water”

A potential expected structure derived from the expected behaviour could be:

Seⁱ: “Watering can”

However, this example produces no FBS conflict. Continuing the example, the designer could sketch a watering can (S^e), interpret this structure (Sⁱ), transform this into interpreted behaviour involving the user manually pouring the watering can (Bⁱ), and through push pull processes interpret another function from the brief:

Fⁱ: Be automatic

In the expected world this could lead to the expected behaviour:

Beⁱ: Operate without simultaneous user input

Here, a clear $Be^i \rightarrow B^i$ conflict exists, where the watering can’s interpreted behaviour does not match the expected behaviour following from another function. This is an example of the proposed FBS conflict. To consider how such FBS conflict is resolved, we must determine an appropriate model of dual-process theory.

5.3 The Intervention Model

A model that accounts for the debates of dual-process theorists well is the default-interventionist view of Evans (2019) espoused in the ‘Intervention Model’ developed by Evans in 2011 and revised and extended in 2019 (see Figure 5-5) (Evans, 2011, 2019). The model was intended to be used as a framework for dual-process theory research (Evans, 2011) and provides a concrete list of factors affecting dual-processing which can be framed for design research.

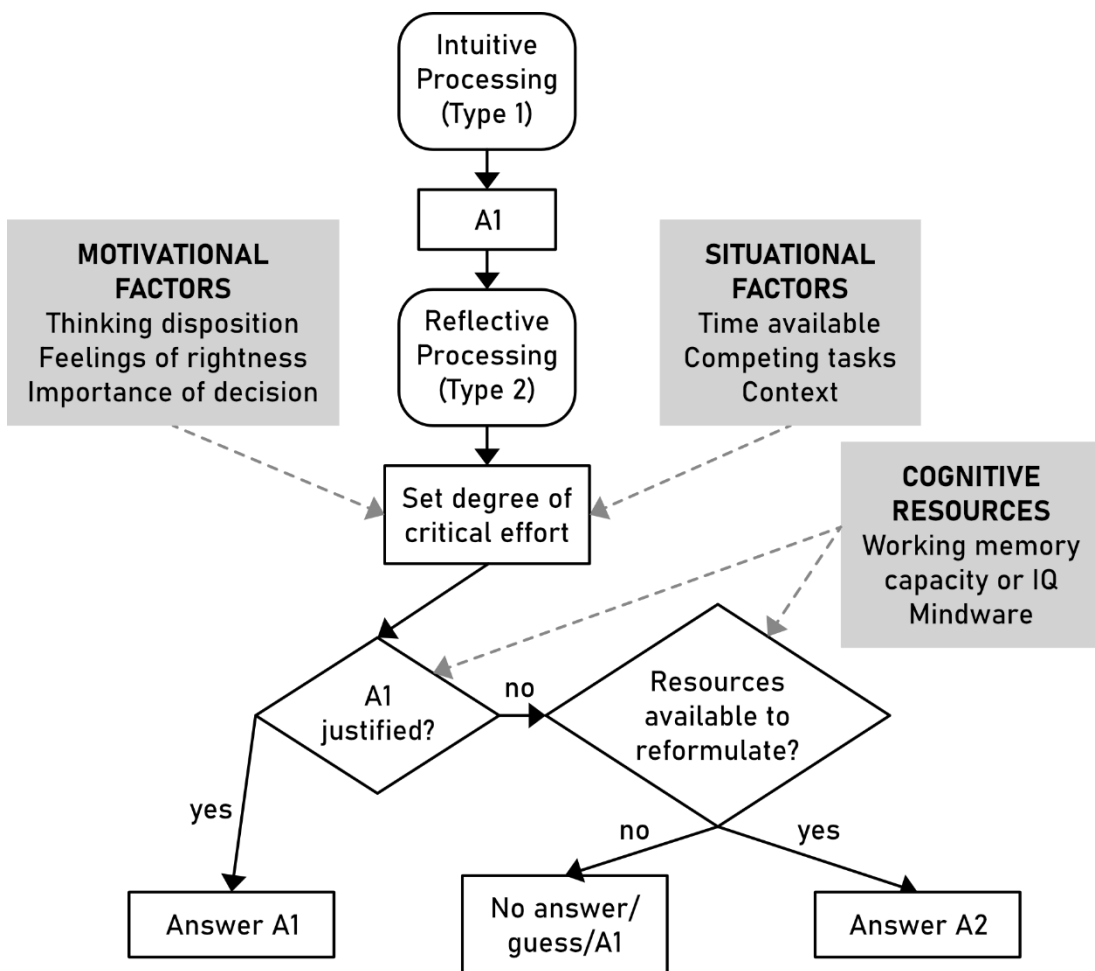


Figure 5-5 - The Intervention Model, redrawn from Evans (2019)

This model aims to give an account of intervention on the default intuitive response in tasks requiring reasoning, judgement and decision making (Evans, 2019). Here, it is assumed that the default intuition will produce the answer A1, which may, or may

not, be intervened upon to produce the alternative answer A2 (see Figure 5-5). At the top of Figure 5-5 it is assumed that, when presented with a task, a person will first use Type 1 processing to generate the intuitive response (A1) (Evans, 2019). The model then assumes that Type 2 processing is always engaged but at varying levels. The minimum level of this engagement would involve Type 2 formulating an answer based on an intuitive feeling in alignment with the given instructions (Evans, 2011). The first role of this Type 2 processing is determining whether the intuitive response (A1) is acceptable for the given task (Evans, 2019). This ‘correct until proven wrong’ approach innately biases towards the intuitive response (Evans, 2019). Determining the response suitability is affected by the degree of critical effort set. That is, how much cognitive effort will be used, which is dependent on both motivational and situational factors. These factors encompass the following:

- Motivational factors:
 - Rational thinking disposition: the inherent tendency of each individual to have different reliance on Type 1 or Type 2 processing (Stanovich et al., 2016; Trippas et al., 2015), which is greatly linked to an individual’s fluid intelligence (or IQ) (Evans, 2011). (see Section 4.3.2.2)
 - Feelings of rightness: a sense of the correctness of a generated response (Evans, 2019; Thompson et al., 2011). (see Section 4.3.1.1)
 - Importance of decision: how important a decision is to the intended goal.
- Situational factors:
 - Time available: the available time to give a response.
 - Competing tasks: other activities that would limit available cognitive resources.
 - Context: previously referred to as ‘instructional set’ (Evans, 2011), this can be considered as the instructional context of the task requiring a response.

Regarding motivational factors, more effort will be used for reasoning if the thinking disposition of the person is more inclined to test intuition with Type 2 processing, if the intuition is accompanied by a high feeling of rightness, or if the decision is important (Evans, 2019). Furthermore, situational factors can decrease

reasoning effort if task time is limited, if competing tasks are being performed, or if the participant has been instructed to respond based on beliefs rather than to reason logically (Evans, 2019).

The next stage of the model determines if the intuitive response (A1) is justified and will be intervened upon by Type 2 processing. This captures the previously discussed primary role of Type 2 processing in justifying and rationalising the intuitive response (see Section 4.3.1.2). This stage is affected by both the previously determined degree of critical effort, and cognitive resources (Evans, 2011, 2019). These are broken down into:

- Cognitive resources:
 - Working memory or IQ: an individual's capacity to temporarily store and manipulate information to support ongoing cognitive activities (Baddeley et al., 2011; Logie et al., 2021).
 - Mindware: the knowledge of explicit rules from reasoning gained through education.

Mindware can affect if an intuitive response is justified due to relevant education reducing the susceptibility to bias on tasks (Evans, 2019). Working memory capacity also affects this justification process (Evans, 2019). If A1 is determined to be unjustified and the cognitive resources are available for reformulating an answer through Type 2 processing then this results in one of two other responses (Evans, 2011). First, this can generate A2 - the reflective response gained through Type 2 processing. It should be noted that A2 is not necessarily a different response to A1. If they are the same, they either arrive at the same conclusion coincidentally, or Type 2 processing is used to retrospectively justify the intuitive response (Evans, 2011). If the required cognitive resources for reformulating an answer through Type 2 processing are not available, then a guessed response, reverting to the intuitive A1 response, or no response altogether will be given (see Figure 5-5)(Evans, 2011).

5.4 FBS Conflict in the intervention model

Taking the Intervention Model as a basis, how FBS conflict would be resolved within this model can be considered. As discussed, the Intervention Model provides an understanding of how various factors influence dual-process reasoning. This work proposes that FBS conflict would occur within the Intervention model at the stage of determining if A1 is justified (visualised in Figure 5-6).

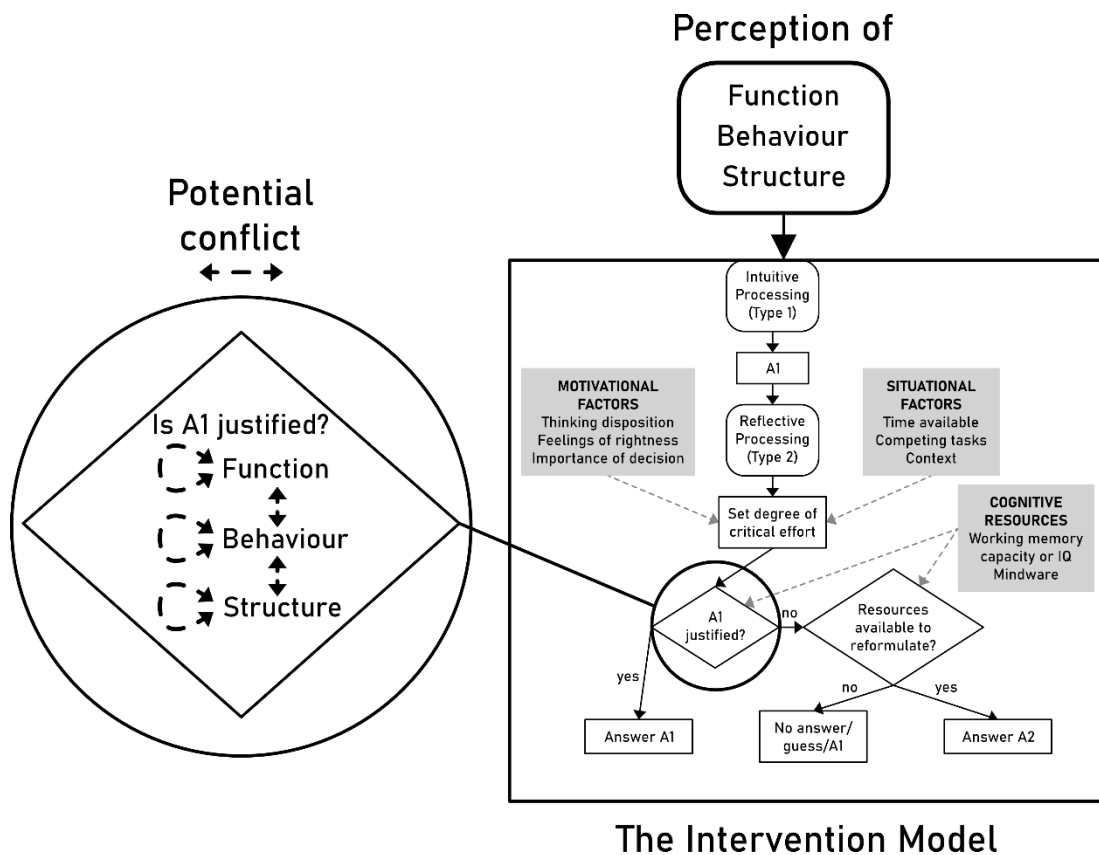


Figure 5-6 - The positioning of FBS conflict in the Intervention Model of dual-process theory

By examining these factors within a design context, we can better understand how designers might navigate FBS conflict:

- Motivational factors:
 - Rational thinking disposition: A designer's reliance on Type 1 or Type 2 processing, in addition to an individual's fluid intelligence (or IQ), likely influences FBS conflict resolution. Designers with a greater inclination towards analytic thinking may prioritise greater Type 2 engagement in conflict resolution.
 - Feelings of rightness: A designer's subjective sense of the correctness of a design concept will likely influence how FBS conflict resolution is approached with a strong feeling of rightness leading to less likelihood of rejecting the A1 response (and vice versa).
 - Importance of decision: The significance of a design decision relative to project goals. Critical decisions may prompt a higher engagement of Type 2 processing in FBS conflict resolution.

- Situational factors:
 - Time available: Constraints on time may decrease the level of critical effort set for FBS conflict resolution. For example, tight deadlines or time constrained methods (e.g. brainstorming) may prompt a designer to rely more on intuitive processing.
 - Competing tasks: The presence of other demands on a designer's cognitive resources may influence their capacity to engage in effortful conflict resolution.
 - Context: The instructional context of the design task may shape a designer's approach to conflict resolution. For example, the stage of the design process may affect the level of critical effort set for FBS processing with early stages, such as concept generation, triggering less Type 2 engagement than later stages, such as detailed design.

- Cognitive resources:
 - Working memory or IQ: A designer's cognitive capacity to temporarily store and manipulate information to support ongoing cognitive activities may influence their ability to resolve complex FBS conflicts.
 - Mindware: The designer's knowledge of how to design - dictated by education and expertise. Their knowledge of design principles and methods will guide their conflict resolution approach. For example, a designer in early concept generation performing a brainstorming task may consciously avoid effortful conflict resolution and instead let the intuitive thoughts be expressed freely.

As with generic discussions of cognitive conflict in dual-process theory literature, the occurrence of FBS conflict opens the potential to initiate varying levels of Type 2 engagement. However, FBS conflict does not itself necessitate increased Type 2 effort. Indeed, this is where these motivational factors, situational factors, and cognitive resources dictate the level of critical effort set.

5.4.1 Other triggers of Type 2 engagement in design

The proposed FBS conflict theory does not encompass all triggers of cognitive conflict and Type 2 engagement in design. To contextualise its position within the wider context of design cognition other triggers of Type 2 engagement are discussed. For example, metacognitive feelings about the progression of the design process could trigger Type 2 engagement regarding deciding the next course of action e.g. 'I have enough ideas to move on to evaluation', 'I have run out of ideas and should explicitly apply a new design method'. Through this it can also be seen that 'Mindware' plays a crucial role in cognitive conflict in design. For example, an expert will have more awareness of how to explicitly progress the design process, while a novice will experience greater uncertainty.

Contrasting experts and novices is a dominant research paradigm used to investigate design cognition and is a trend that is likely to translate to future DPT design research. While limited research exists in other fields investigating expertise from a DPT perspective, insights from diagnostic reasoning indicate that experts rely

more on Type 1 thinking than novices in visual processing tasks (Warren et al., 2018). These findings may point towards the greater knowledge base of experts leading to a greater ease in associative processing (correlated with Type 1 thinking). Greater automation of processing may also enable experts to free up cognitive resources (e.g. working memory) for use in other design activities.

Experts and novices are also likely to use Type 1 and Type 2 processing differently. Novices may employ Type 2 processing in a slow and careful manner during the design process. Alternatively, experts, with a broader knowledge base, may work in a quick and casual manner using heuristics that have been learned to automaticity but still need to be applied explicitly (i.e. using Type 2 processing)(Evans, 2011). Mathematical expertise research supports this idea with Purcell et al. (2020) finding that individuals with low experience engage in Type 1 thinking or ineffective Type 2 processing, those with intermediate experience engage in effective Type 2 processing, and high experience is associated with Type 1 processing. Consequently, both inexperienced and experienced designers may rely more on Type 1 processing and the correlation between expertise and type of processing is not perfect. However, the differences in how Type 1 and Type 2 processing are used as expertise grows could be an interesting avenue for DPT design research.

Regarding expertise, the Intervention Model prompts some interesting connections in how: (1) an intuitive response is justified and (2) an unjustified response is recalculated. Following this, design expertise is likely to play a crucial role in evaluating the justification of ideas, which aligns with research indicating that experts assess decisions before implementation (Ahmed et al., 2003). Novice designers, with limited knowledge, may struggle to recognise an unjustified intuitive response, reflecting the common novice 'trial and error' pattern (Ahmed et al., 2003; Lohmeyer et al., 2013). Design expertise may also aid in the reformulation of unjustified responses, as experts have better knowledge of methods and design heuristics, while novices may face challenges in this aspect. Ultimately, how Type 1 and Type 2 processing evolves with expertise is a crucial factor to consider in both research on FBS conflict and beyond for future DPT design research.

5.5 Quality reflection on theory development

The theory development presented in this chapter followed a deductive and theory-driven approach grounded in established principles of rigorous theory construction discussed in Chapter 2. Rather than generating theory inductively from isolated empirical observations, the proposed FBS conflict theory was developed through conceptual integration between established dual-process theory constructs and existing design ontology, particularly the FBS framework. This approach was intended to strengthen conceptual clarity, theoretical coherence, and alignment with broader cognitive psychology literature.

Several quality concerns associated with theory development were considered throughout this process. There is a risk that concepts adapted from adjacent disciplines may be transferred superficially or without sufficient consideration of contextual differences (Blessing & Chakrabarti, 2009). To address this, the development of the FBS conflict theory explicitly examined where assumptions from dual-process reasoning paradigms aligned with, and diverged from, the epistemic and representational characteristics of conceptual design. Therefore, the theory was bounded specifically to conceptual design reasoning contexts involving representations with explicit acknowledgement of the necessary existence of other triggers of Type 2 engagement in design cognition, rather than positioned as a universal account of all design cognition conflict.

Further, quality concerns regarding conceptual ambiguity and internal consistency were addressed through grounding proposed constructs within established accounts from both cognitive psychology and design research. The use of the Intervention Model provided a clear explanatory structure for how conflict may trigger varying levels of Type 2 engagement, while the FBS framework provided a design-specific ontology through which conflict could be operationalised. This enabled explicit propositions regarding where conflict may arise and how motivational, situational, and cognitive resource factors may influence conflict resolution in design.

The theory was also developed with empirical testability as a central consideration. The proposed account directly informed the development of experimental work and

the hypotheses examined in Descriptive Studies I and II. In this sense, the quality of the theory was not treated as dependent on immediate confirmation of predictions, but on its capacity to generate meaningful, and theoretically informative empirical investigation capable of supporting iterative refinement.

5.6 Summary

This chapter establishes and justifies the research focus of the thesis by synthesising two literature reviews into a structured reference model, following the Design Research Methodology (DRM). Chapters 3 and 4 identify three persistent barriers to progress in design cognition research i) the lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research. In response, it is argued that adopting theory and methods from cognitive psychology, particularly dual process theory (DPT), provides a route to address these issues. The reference model (Figure 5-1) maps key influencing factors and their directional relationships, defining improved understanding of design cognition as the overarching success criterion and highlighting the lack of suitable tests and metrics as the measurable success criterion guiding the contribution of this work.

Building on this, this chapter narrows the empirical focus to cognitive conflict and bias as central DPT constructs with established methodological precedent, and proposes a novel design specific mechanism of conflict grounded in the Function Behaviour Structure framework. By aligning FBS based conflict with the default interventionist Intervention Model, this chapter specifies how motivational, situational, and cognitive resource factors may shape whether intuitive responses are accepted, justified, or overridden during design reasoning. Overall, this chapter provides a concrete theoretical foundation on which methodological advancement will be built.

PART 2:
THEORY EVALUATION

Part 1 of this thesis answered RQ1 and RQ2 and laid a groundwork of understanding regarding the methods and constructs used in design cognition research, and how these align with dual-process theory methods and constructs. With this foundational understanding built, Part 2 answers how individual differences in dual-processing tendencies can be measured in design cognition (RQ3), and what differences in designing these individual differences in dual-processing tendencies cause (RQ4). This is done through evaluating the theoretical contribution developed in Part 1: a dual-process theory informed account of conflict in design cognition. This contribution was built from two key reviews: a foundational review of design cognition research constructs and methods, and a second review contextualising DPT literature within design cognition constructs and methods.

As outlined by the Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009), this section will evaluate the theory's descriptive and explanatory power with respect to design practice and cognition. The evaluation is performed through methodological development based on the theoretical contributions of Part 1. This methodological development is grounded in the concept of thinking dispositions. Specifically, the tendency of designers to rely more on intuitive (Type 1) or analytic (Type 2) processing in design contexts. If designers can be - a) placed on a spectrum of relying more on Type 1 or Type 2 processing in a design context, then - b) the subsequent differences in their design process can be analysed. To assess this empirically, two descriptive studies were conducted focusing on these two aspects a) and b), respectively.

As discussed in Chapter 5 in relation to the Reference Model (Figure 5-1), this work addresses three challenges in design cognition i) the lack of alignment of design cognition with established ontological and methodological standards, ii) the absence of suitable tests and metrics for studying design cognition, and iii) the lack of combining quantitative and qualitative methods in design cognition research.

Part 1 addressed the first challenge within the scope of this thesis, through aligning design cognition constructs with more established theory from cognitive psychology. To address the second challenge, Chapter 6 presents a novel psychometric instrument - the Design Conflict Test (DCT) which was based on the FBS theory of conflict

proposed in Chapter 5. The purpose of the DCT was to position designers along a dual processing spectrum, identifying thinking disposition tendencies toward Type 1 or Type 2 processing in design.

The subsequent analysis of the DCT focused on its validity. In research, establishing validity involves determining the extent to which a construct faithfully represents the phenomena it aims to explain. Validity does not have a single test with which it is demonstrated. Rather, validity can be evidenced through the construct it aims to measure fitting within broader theory. In this case, that construct is the designer's disposition toward intuitive or analytic processing. Here, validity is examined through multiple forms of evidence: convergent and divergent validity (Descriptive Study I), and predictive validity (Descriptive Study II). If the DCT is valid, it should correlate appropriately with established cognitive measures and predict differences in actual design behaviour. (Frank et al., 2025)

To address the third key challenge, the studies use a combination of behavioural, physiological, and self-report methods. In Descriptive Study I (DS I), the validity of the DCT is determined through quantitative methods, namely - eye-tracking (physiological measure) and established psychometric tools (behavioural measures). Furthermore, the DCT itself represents an advancement in behavioural measures for design cognition research. In Descriptive Study II (DS II), qualitative methods and quantitative analysis are used to deepen the insights from DS I and explore how thinking dispositions manifest in design activity, namely - a structured design task using think-aloud protocols (self-report measure) analysed through linkography. This mixed methods approach is intended to harness the respective strengths of qualitative and quantitative research.

6 DESCRIPTIVE STUDY I

This chapter presents the first of two descriptive studies - DS I. As discussed DS I and II were designed to build sequentially upon one another following their respective aims. Explicitly, they can be outlined as follows:

Descriptive Study I (Chapter 6):

RQ3: How can individual differences in dual-processing tendencies be measured in design cognition?

Aim: To place designers on a spectrum of more likely to rely on intuitive (Type 1) or analytic (Type 2) processing in a design context.

Method: Through developing, applying, and validating the DCT, assessing convergent and divergent validity with related constructs.

Descriptive Study II (Chapter 7):

RQ4: What differences in conceptual design do individual differences in dual-processing tendencies cause?

Aim: To examine how intuitive (Type 1) and analytic (Type 2) processing tendencies identified in DS I are expressed in conceptual design behaviour.

Method: Observing key participants from DS I performing a structured design task using a think-aloud protocol and linkographic analysis.

To provide an initial overview of the intended research design for both studies, the aims, hypotheses, sample selections, and methods are shown in Figure 6-1. As highlighted in the Figure 6-1, this was adapted following the analysis of DS I with the updated research design discussed in DS II presented in Chapter 7 (see Figure 7-1).

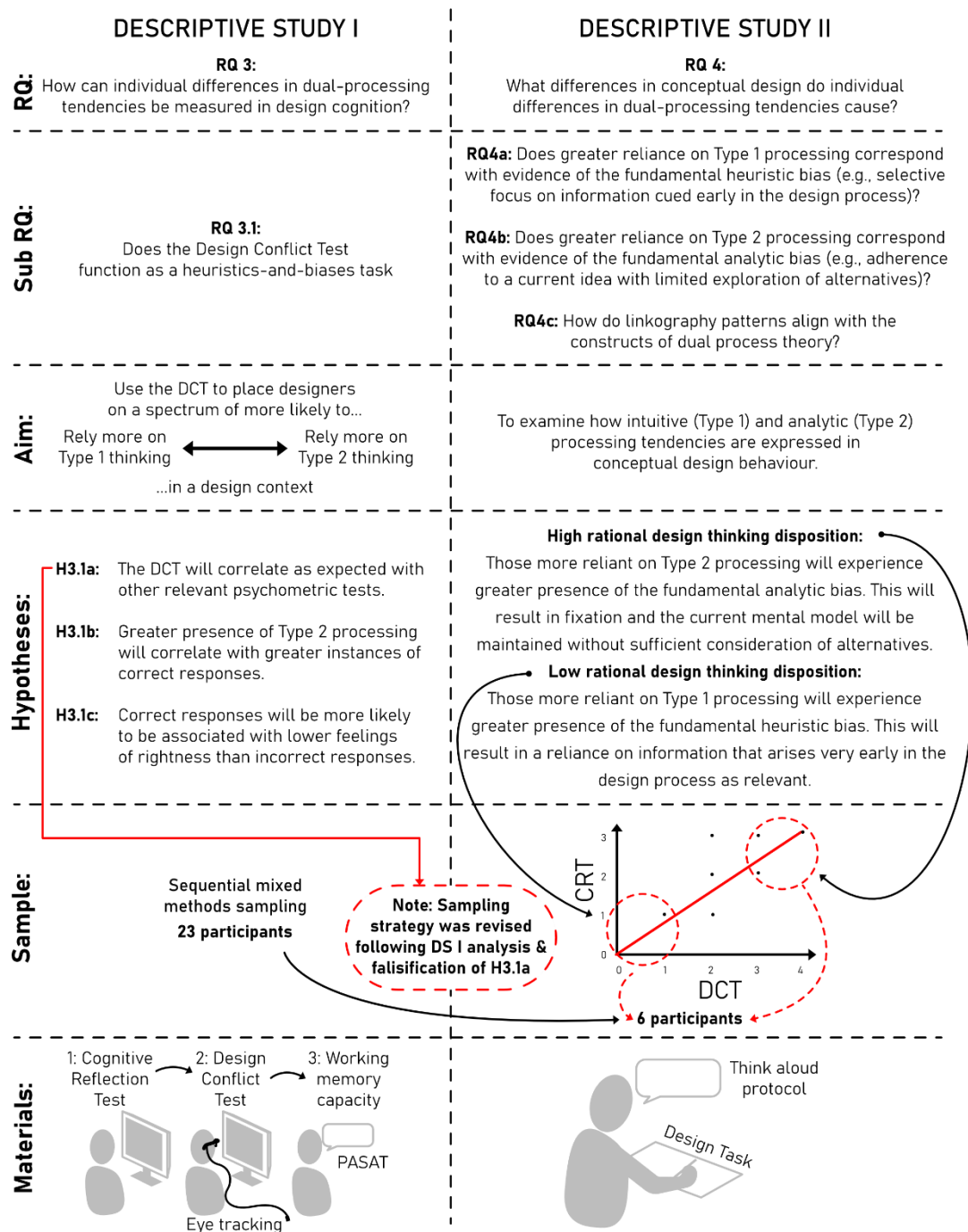


Figure 6-1 – Overview of intended evaluation approach (DS I & DS II)

The novel psychometric test developed and tested in this chapter draws on the insights from cognitive psychology literature regarding how DPT is studied. As previously discussed, the heuristics and bias program from which DPT emerged resulted in a significant body of research on the systematic errors made when people select actions and assess probabilities (bias) and the reasons behind why these errors are often made through applying mental shortcuts (heuristics) (Stanovich et al., 2016). Almost all DPT research in cognitive psychology involves giving participants written tasks that either do, or do not, require the engagement of Type 2 processing to provide the correct response. Specifically, many of these tasks induce biased responses that can be used to decipher Type 1 and 2 interactions. Task performance is then analysed and contrasted with a variety of measures.

Considering design practice and its differences with traditional reasoning tasks, measuring dual-process conflict in this context needs a more tailored framing. This was explored in the proposed FBS theory of conflict in design (see Chapter 5). Within this, the involvement of visual processing and engineering principles present in product design engineering must be considered. In light of this, the new psychometric test - the Design Conflict Test (DCT) was developed based on the FBS conflict theory and aimed to provide a design-specific heuristics-and-biases test.

The aim of this study is to use the DCT to place designers on a spectrum of more likely to rely on intuitive or analytic thought in a design context. To do this, there are several factors to be considered relating to the theoretical foundation of this work. Namely, the Intervention Model of Evans (2019) (see section 5.3). Given the model's three sets of factors (motivational factors, situational factors, and cognitive resources) the influence of these on the experimental design of DS I are central to its research questions and hypotheses. Much of the experimental design and considerations were also influenced by the work of Purcell et al. (2021) which will be referenced throughout.

This chapter will present DS I starting with the research questions and hypotheses, greater discussion on the Intervention Model, and DCT item design. With the foundation of the experimental work discussed, the tasks and apparatus, pilot study, sampling decisions, study results and discussion of these results will be presented.

6.1 Research questions and hypotheses

DS I aims to use the developed Design Conflict Test (DCT) to place designers on a spectrum of more likely to rely on intuitive (Type 1) or analytic (Type 2) thought in design conflict. This was driven by the overarching research question (see Section 1.4):

RQ 3: How can individual differences in dual-processing tendencies be measured in design cognition?

This research question is met with the proposal that a new psychometric test would be suited to such measurement - the DCT. Within this, and considering the discussion thus far regarding the Intervention Model (Evans, 2019)(Section 5.3), sub-research questions are proposed for determining if the DCT could be an answer for RQ3. For assessing individual differences in dual-processing in design contexts, the DCT must be shown to function as would be expected for a heuristics-and-biases task (RQ 3.1). Three hypotheses are made to determine an answer to this question: predicted correlations with relevant psychometric tests (H 3.1a), greater levels of Type 2 processing for correct responses (H 3.1b), and greater instances of correct responses with lower feelings-of-rightness (H 3.1c). This sub research question and the corresponding hypotheses are discussed in greater detail in the following:

RQ 3.1: Does the Design Conflict Test function as a heuristics-and-biases task?

H 3.1a. The DCT will correlate as expected with other relevant psychometric tests.

Performance on heuristics-and-biases tasks have been shown to strongly correlate with the Cognitive Reflection Test (CRT)(see Section 4.3.2.2 & Section 6.3.2.1). Despite the CRT also having a substantial correlation with measures of cognitive ability (e.g. working memory capacity (WMC)), it has been found that the CRT is a “unique predictor” of performance on heuristics-and-biases tasks (Toplak et al., 2011). Here, the DCT is proposed as a design-specific heuristics-and-biases task (see section 6.2). While higher WMC has been found to have a small correlation with better logical reasoning ability (Toplak et al., 2011), a higher WMC does not influence susceptibility

to belief bias (Robison & Unsworth, 2017).

Given this, the DCT would be partially validated through finding a positive correlation between score in the DCT and the CRT, and between working memory capacity and the CRT, while a weak correlation should be seen between the DCT and working memory capacity.

H3.1b. Greater presence of Type 2 processing will correlate with greater instances of correct responses.

The empirical evaluation of the DCT conducted here expands on the work of Purcell et al. (2021), who used eye-tracking to study the cognitive pathways (i.e. the sequence and order of cognitive processes during reasoning) and uncertainty that is experienced when performing the CRT. In their study, the eye-tracking data provided fixation (the maintenance of gaze on one location) and dwell (the duration of fixations in one area) data for participants looking at various test answers. This was tracked through areas-of-interest (AOIs) which are manually defined areas on the stimulus within which eye tracking data can be gathered (e.g. areas on a digital screen). Additionally, confidence-based uncertainty (i.e. feeling of rightness) was measured through asking people to rate their confidence in their answer (Purcell et al., 2021). They aimed to assess these factors to decipher which of two DPT models, the default-interventionist or the hybrid model, best explains their results. The adaptation of this approach taken by Purcell et al. (2021) is further discussed in section 6.2. Here, DPT models are further discussed to contextualise use of the default-interventionist approach in this thesis relative to Purcell et al. (2021).

As discussed in Chapter 4, the key difference between DPT models is the order in which Type 1 and Type 2 processing occurs. In the default-interventionist Intervention Model (see Section 5.3), intuitive responses generated by Type 1 processes are thought to arise automatically, with Type 2 processing potentially being engaged to assess their validity (Evans, 2018). This model assumes Type 2 processing is always engaged to some extent, firstly to judge whether the intuitive response should be accepted (Evans, 2018).

Further debate has been fueled from studies showing that logical reasoning and belief-based reasoning can be performed simultaneously (De Neys, 2012; Handley et al., 2011; Trippas et al., 2017). However, these studies involved simple reasoning tasks that may allow Type 1 processing to automatically process the simple logic (i.e. Type 1 processing could produce both the logical and belief-based responses) (Evans, 2019). Indeed, the findings of Purcell et al. (2021), were in accordance with this view which was taken to be in support of the hybrid model. However, considering that Evan's (2019) view of the default-interventionist model accounts for such findings, there is no conflict with the basis of this work being founded in the Intervention Model. On this basis, the models mostly differ in what is emphasised in their framing of dual-processing.

Considering these nuances in belief-based and logical responding, there are two paths presented to achieve the correct answer in a lure problem: participants engage Type 2 processing to override the initial incorrect intuitive response (a corrective cognitive pathway (Purcell et al., 2021)), or they reach the answer through a logical Type 1 response (an intuitive cognitive pathway (Purcell et al., 2021)). Considering that the DCT aims to measure tendencies in how dual-processing conflict is resolved in design, the questions should be at a level of difficulty requiring greater Type 2 engagement to reach the correct answer.

H3.1c. Correct responses will be more likely to be associated with lower feelings of rightness than incorrect responses.

The inclusion of feelings of rightness (FOR) as a dependent measure in this study is directly informed by the work of Purcell et al. (2021), who combined eye-tracking with confidence-based uncertainty measures (FORs) to examine how cognitive reflection unfolds over time in reasoning tasks. In their study, FOR was not treated as a proxy for correctness, but as an indicator of subjective confidence associated with the different cognitive pathways discussed above. Their results showed that low FOR was associated with increased rechecking behaviour, longer dwell times, and greater engagement with alternative response options, reflecting extended processing consistent with Type 2 engagement.

In designing the Design Conflict Test (DCT), by explicitly constructing items to minimise the likelihood of intuitive correctness, the necessary engagement of Type 2 processing to reach the correct answer is more likely. DCT items were designed to elicit a strong intuitive lure response grounded in design-specific heuristics, such that reaching the normatively correct response likely requires detecting conflict and engaging in additional effortful processing. Following the logic articulated by Purcell et al. (2021), this increases the probability that correct responses will predominantly emerge via the corrective cognitive pathway rather than an intuitive one.

In analysing the FORs corresponding to DCT responses, they can be taken as a cue for analytical evaluation of a response (Evans, 2019; Thompson et al., 2011). FORs have also featured in design research (Ball & Christensen, 2019; Moore et al., 2014). While FOR research does not show any evidence tying a high FOR to a correct judgement, a low FOR is a cue for Type 2 evaluation of a response (Evans, 2019; Thompson et al., 2011). Within this task context, lower FORs are expected to function as markers of low confidence in the given response, increased sensitivity to conflict, and a greater likelihood of sustained engagement with alternative interpretations. While Evans (2020) cautions against treating FOR as a causal trigger of Type 2 processing, its consistent association with rethinking behaviour supports its use as a theoretically meaningful correlational indicator when interpreted alongside behavioural and eye-tracking measures.

Accordingly, H3.1c proposes that, in the DCT, correct responses will be more likely to be associated with lower feelings of rightness than incorrect responses. It does not imply that low FOR guarantees accuracy, nor that high FOR implies error. Rather, it reflects the expectation that correct responses in the DCT are more likely to arise in trials where intuitive confidence is weakened and additional evaluative processing is undertaken, consistent with the corrective pathway identified by Purcell et al. (2021).

6.2 The Design Conflict Test

The aim of DS I - placing designers on a spectrum of greater reliance on Type 1 or Type 2 thinking - rests on the assumption that individual differences in design behaviour are partly driven by how designers detect and resolve cognitive conflict. Within the Intervention Model (Evans, 2019), this is captured by thinking disposition, one of the motivational factors influencing the degree of critical effort set during reasoning. Thinking disposition measures typically target stable tendencies to engage reflective, effortful processing, such as the tendency to gather information before taking a stance, the tendency to think comprehensively before responding, and the tendency to consider future consequences before actions (Stanovich et al., 2014). All of these differences target the reflective mind (Type 2 processing) assessing how people manage goals, self-regulate, and consider epistemic values (Stanovich et al., 2014).

Crucially, a disposition expressed in abstract reasoning tasks may not manifest identically in applied, domain-specific contexts such as design. Design problems can involve visual processing, complex requirements, and are often characterised by ambiguity and satisficing rather than optimisation. While thinking dispositions are often measured using self-report questionnaires, such approaches face challenges in design cognition research regarding their reliance on subjective introspection, and the limited established theoretical grounding available for disposition measures in design cognition. Developing a self-report instrument tailored to design may therefore require a far more mature theoretical basis than currently exists.

To address this, the Design Conflict Test was developed as a more objective, performance-based measure intended to measure thinking dispositions as they manifest in the resolution of design-specific cognitive conflict. Rather than asking designers to report on their preferences or styles, the DCT facilitates intuitive responses that conflict with logically correct interpretations grounded in function-behaviour-structure (FBS) reasoning. In doing so, the DCT follows the tradition of heuristics-and-biases tasks in cognitive psychology, whereby susceptibility to intuitive lures, conflict detection, and analytic override are inferred from behavioural performance rather than self-report.

To provide clarity and overview, Figure 6-2 presents the discussed theoretical roots of the DCT (Chapter 5) and clarifies the constructs it is intended to measure. At the highest level, the test draws on dual-process theory and the heuristics-and-biases paradigm, particularly belief-bias syllogisms, which have historically been used to study the interaction between intuitive and analytic reasoning. These paradigms are recontextualised through the function-behaviour-structure framework, allowing cognitive conflict to be considered in a design-relevant form. The resulting FBS theory of conflict in design provides the foundation upon which the DCT is built.

The DCT aims to measure how designers resolve dual-processing conflict in design. In doing so, it targets several interrelated constructs. First, it captures susceptibility to belief-based (Type 1) reasoning, reflected in the tendency to accept intuitively plausible design interpretations even when they are functionally or structurally invalid. Second, it targets the ability to engage analytic (Type 2) reasoning, operationalised as the capacity to override intuitive responses through effortful reasoning. Third, it assesses conflict detection and resolution, namely how effectively individuals recognise discrepancies between intuitive interpretations and normatively correct design reasoning and whether they successfully intervene. Finally, by examining patterns of performance across items, the DCT provides an index of individual differences in reasoning tendencies, situating designers along a spectrum of greater reliance on intuitive versus analytic processing in design contexts.

By integrating these elements, the DCT serves as a prototype psychometric instrument for examining how designers resolve dual-process conflict within a design context. Through this, it operationalises core constructs from dual-process theory within design cognition, providing a methodological bridge between established reasoning paradigms and the situated, visually mediated nature of design cognition.

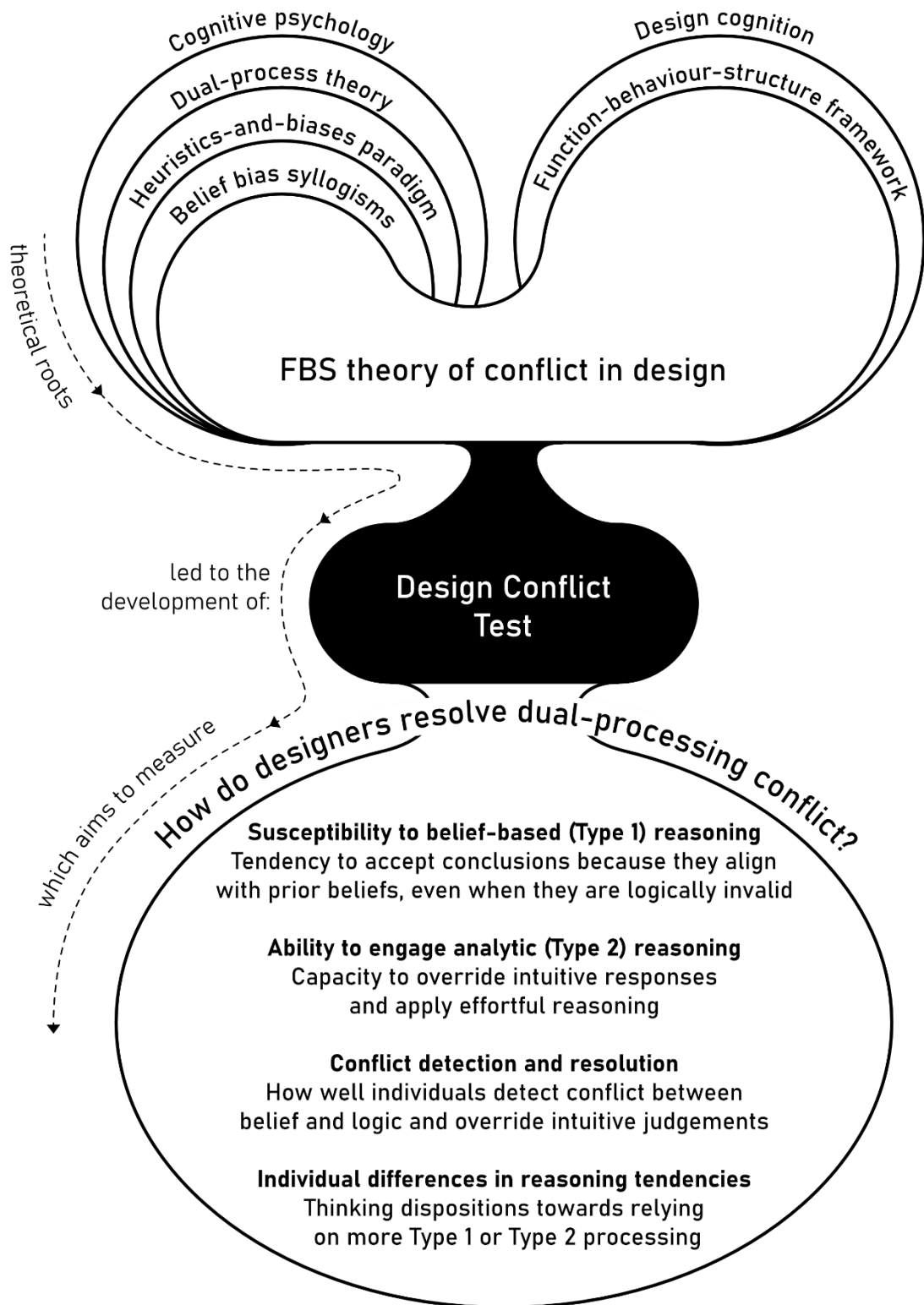


Figure 6-2 - An overview of the DCT theoretical roots and what it aims to measure

6.2.1 DCT conflict item design

As discussed, the Design Conflict Test (DCT) was developed to be a design parallel to the syllogistic reasoning tasks used in cognitive psychology - one of the most used heuristics-and-biases paradigms to study belief bias (see section 4.3.2.2). Syllogisms involve either no-conflict or conflict conclusions whereby the conclusion either follows, or does not follow, from the premises, respectively. In conflict tasks a heuristic incorrect response is triggered which is different to the logical correct response. To mirror such tasks, the developed psychometric test had to present a stimulus more similar to representations in design than the traditional written reasoning task format.

A logical syllogism is built from premises that together can be reasoned to a necessary conclusion. This structure relies on logic, where the validity of the conclusion depends on the internal consistency and truth of the premises. The major premise is a general rule or truth, like “All birds are black.” The minor premise is a specific case, like “A crow is a bird.” From this, the conclusion follows deductively: “Therefore, crows are black.”

Here, it is proposed that engineering principles could be applied. Engineering principles, once known, can be used to derive conclusions about physical structures. These could be used similarly to syllogistic premises whereby the major premise would be grounded in some physical principle. Taking the example used to describe the proposed FBS conflict theory (section 5.2.3) - this major premise could be “Containers with an opening below the water level when tilted will allow water to flow out”. The minor premise could be “A watering can is a container that holds water above its spout when tilted”. Therefore, the conclusion follows as “a watering can will allow water to flow out of its spout when tilted.”

However, such statements still rely on written stimuli. In many written stimuli used in DPT traditional reasoning tasks, the information is abstract. For example, syllogisms using the form “If square, then circle” are such that the reader has no existing knowledge about the relationship being stated (De Neys et al., 2005). This contrasts to everyday life whereby such reasoning would be more meaningful e.g. “If

you put on a jacket, then you will be warmer”. In such cases, long term memory is used (e.g. that a hat and gloves can also be used to keep warm might be considered) which has a large impact on the conclusions drawn (De Neys et al., 2005). To account for how design actually works, abstract examples would only progress the field so much. To ensure a greater fidelity to design practice and therefore a better account of design reasoning, test items for the DCT drew on existing familiar objects.

Design also relies heavily on visual stimuli. A crucial part of the design process involves visual information - both in the form of mental imagery and in the form of visually perceiving representations of ideas (e.g. sketches). For the external representations of ideas - the visual information must be processed. This can be broken down into two stages of visual processing which have clear parallels to DPT. The first pertains to visually perceiving the image as a whole to determine patterns and shapes (Baxter, 1995). This initial scanning is a fast process that occurs pre-attentively (i.e. a Type 1 process). Contrastingly, the second stage of visual processing is a consciously effortful focusing on the image details to inspect its components (i.e. a Type 2 process). There is another factor at play in determining the meaning derived from these two processes of visual perception - namely, primary global precedence. This phenomenon dictates that pre-attentive visual perception assesses information as a whole, before conscious determination of component parts, and lastly - that it possesses more influence over the overall perception than more effortful processing (Baxter, 1995). This shows an alignment with DPT as it relates to reasoning tasks where the same processing dynamics are at play in visual perception.

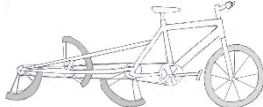

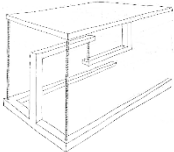

Considering this, these ideas were put forward as concept sketches of familiar products that reflected common engineering principles taught in product design. In the same way that one can interpret such functions, behaviour, and structure from written statements, one can also interpret this from visual images of products. If you know the purpose of an object, you can interpret through visual information if you think it will work. For example, the watering can shown in Figure 6-3.



Figure 6-3 - Watering can product sketch

If you can consider a visual stimulus as a parallel to a syllogism - a product that is easily interpreted as either fulfilling (e.g. Figure 6-3), or not fulfilling, its function would be a no conflict equivalent. That is, the interpreted premises align with the believable conclusion. The question then becomes, how do you create a conflict stimulus? This requires an image that looks, on first interpretation, as if it fulfils its intended function, but on further inspection - does not. Several stimuli were developed and iterated through pilots (see Section 6.4) to create a final four conflict items discussed in the following sections with a summary presented in Table 6-1. These four items reflected four fundamental concepts taught in engineering disciplines: load distribution, leverage, tension and compression, and pressure.

Table 6-1 - Design Conflict Test conflict item overview

Item name	Stimulus	Foundational principles
Bicycle		Load distribution
Scissors		Leverage
Table		Tension and compression
Wine Glass		Pressure

6.2.1.1 *The Bicycle (Item 1)*

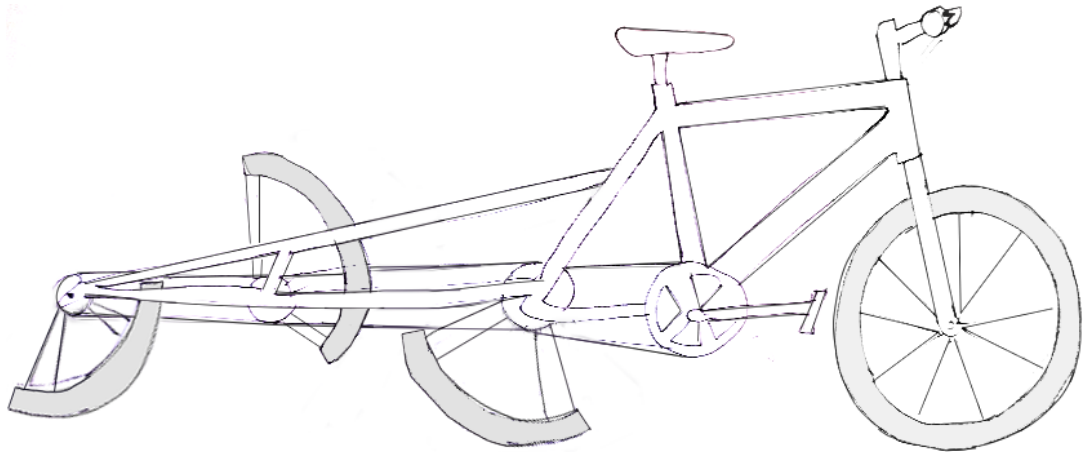


Figure 6-4 - The Bicycle DCT stimulus

The Bicycle stimulus (Figure 6-4) was developed based on the work of The Q (2022) who built a split wheel functioning bike based on load distribution. That is, if a wheel is divided into segments but each segment is aligned correctly, a part of the split wheel will always be touching the ground and therefore function as normal. Considering the popularity of the video displaying this concept, the developed stimulus image displayed offset wheels so that they did not make up one whole, but rather part of a whole wheel (see Figure 6-4). This aimed to account for people who had seen the video and were familiar with the concept in that they needed to still think about whether it would work to get the right answer, rather than the intuitive response of recognising that it works. Those who were unfamiliar with the concept would have to do the same processing to reach the correct answer. Considering this, this item acts as a conflict stimulus in that it intuitively looks like *does* work but *does not*.

6.2.1.2 *The Scissors (Item 2)*



Figure 6-5 - The Scissors DCT stimulus

The Scissors stimulus was an adaptation of traditional bent handle surgical scissors. These rely on leverage as the engineering principle with the more complex form being determined after the pilot study (see Section 6.4). This requires the consideration of the geometry of the handles, blades, and fulcrum to determine if the scissors would open and close as expected. This item acts as a conflict stimulus in that it intuitively looks like *does not* work but *does*.

6.2.1.3 *The Table (Item 3)*

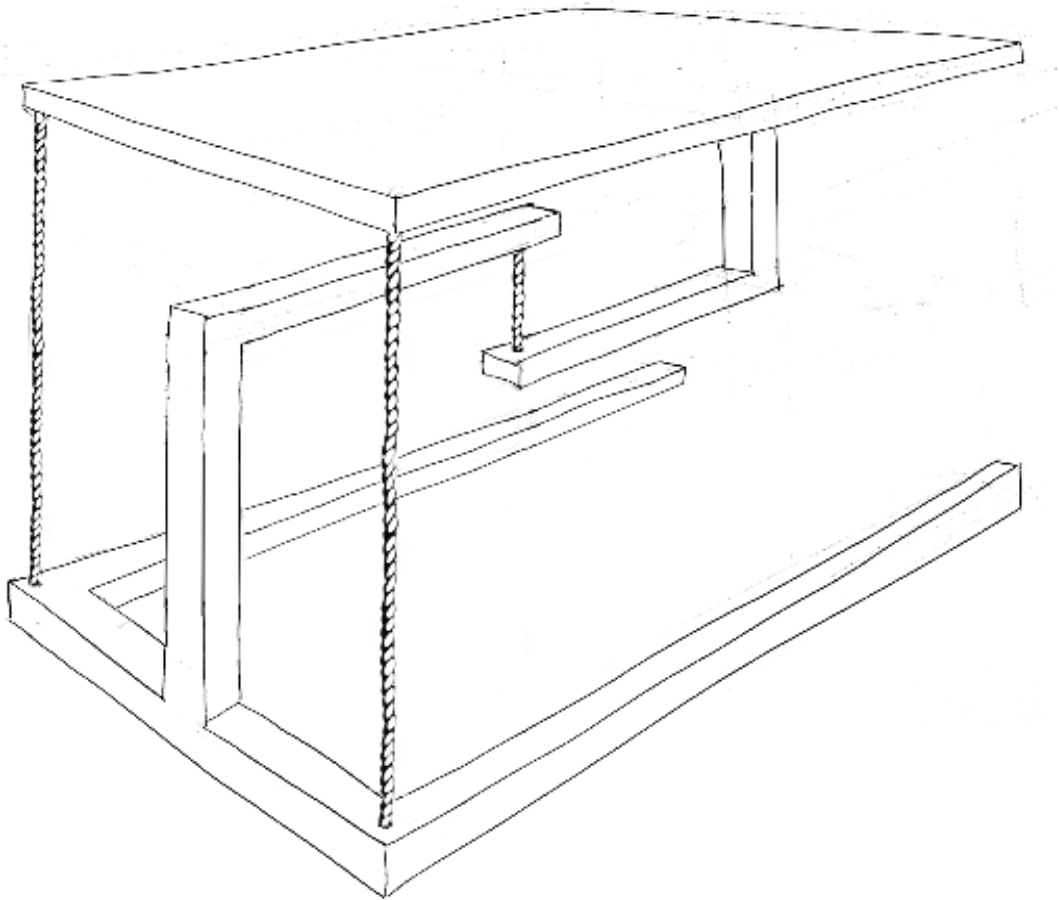


Figure 6-6 - The Table DCT stimulus

The Table stimulus was developed based on the concept of the tension and compression chair whereby the principle of tensegrity (isolated elements under compression are held in position by tension elements) holds up what appears to be a floating chair. Considering that this concept is well renowned, the design was altered from the more common structure of two rigid elements held together by five tension elements, to having the two rigid elements with only three tension elements. This functions in a similar fashion but aimed to require more engagement of logical thinking to achieve the correct conclusion. This item acts as a conflict stimulus in that it intuitively looks like *does not* work but *does*.

6.2.1.4 *The Wine Glass (Item 5)*

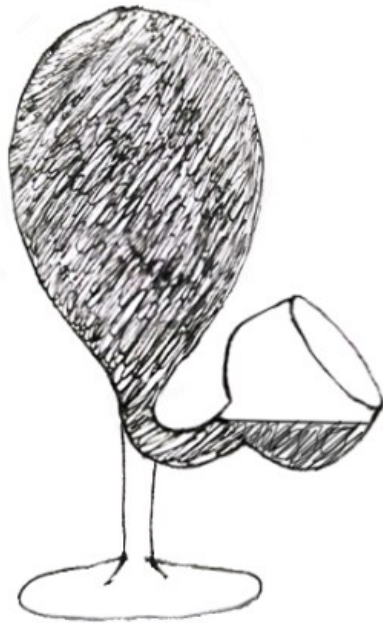


Figure 6-8 - The Wine Glass
DCT Stimulus

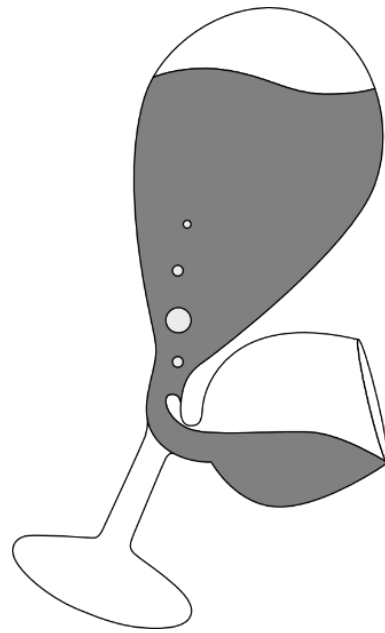


Figure 6-7 - Wine Glass
explanation (redrawn from
Kouichi Okamoto (2009))

The Wine Glass stimulus (Figure 6-7) was developed to target an understanding of pressure. Based on the art piece - “Glass Tank” by Kouichi Okamoto (2009) - the glass looks on first glance as if it would not hold the wine but rather that it would fall out immediately. However, the air and water pressure allow the wine to be contained in the vessel. As it is tilted toward the drinker’s mouth a controlled amount of liquid is moved into the glass from the vessel as air bubbles work their way around the bend in the stem (see Figure 6-8). This item acts as a conflict stimulus in that it intuitively looks like *does not* work but *does*.

The DCT, where these four items are applied, provided a domain-relevant version of a conflict reasoning task that facilitated greater ecological validity than traditional reasoning tasks. These four items built the core of the DCT. Originally, five test items were used but the fifth was discounted due to the sketch being invalid. With the material basis developed for the DCT, the foundation and materials of the subsequent empirical work can be addressed.

6.2.2 The DCT Format

In alignment with Evans's (2019) Intervention Model, the DCT format mirrored the structure of traditional syllogistic reasoning paradigms. These tasks are constructed to elicit a rapid, intuitive response (Type 1), which may either be accepted or overridden by subsequent reflective (Type 2) processing. The DCT serves here as a domain-specific equivalent, tailored to visual FBS decision-making. The 4 conflict items previously discussed were designed to cue intuitive, but incorrect, judgements, while also providing the opportunity for analytic evaluation and correct conclusions. This approach should allow for the examination of how individuals in design contexts may rely on intuitive versus analytic processing, thereby situating them along a spectrum of Type 1 to Type 2 engagement.

6.2.2.1 *Eye tracking*

Eye-tracking was identified as a means to testing Hypothesis 3.1b (see Section 6.1). Eye tracking is one of several physiological measures that have been used in DPT research (Ball et al., 2006; Gegenfurtner et al., 2011; Lawrie et al., 2024; Purcell et al., 2021; Warren et al., 2018). Eye-tracking can provide insight through: fixations - which indicate what information a person is considering (Ball et al., 2006), and through dwell - which indicates the depth at which this information is being processed (Rayner, 1998; Velichkovsky et al., 2002). Through this, greater fixations and dwell can be considered as a proxy for Type 2 engagement.

Research has shown that participants spend more time looking at the given problem in conflict reasoning tasks than in no-conflict tasks (Purcell et al., 2021). According to the concept of cognitive pathways, whereby participants reach a correct answer on a conflict task through either a corrective or intuitive pathway, it follows that measuring fixations and dwell would be indicative of the type of pathway used. That is, when presented with a heuristic answer and a logical correct answer, there would be a greater proportion of fixation and dwell on the heuristic answer following a corrective pathway, considering that the heuristic answer would be considered first and then overridden to provide the correct answer. Alternatively, following an intuitive pathway should reveal less proportion of fixations and dwell on the heuristic answer considering that the logical answer was provided through Type 1 processing and

required less effortful processing of other options (Purcell et al., 2021). Eye-tracking was, therefore, taken as an indicator of Type 2 engagement levels for this study.

6.2.2.2 *Item presentation*

To enable effective use of the eye-tracking in DS I, the participants have to be presented with stimuli - in this case, possible responses. Following design considerations from Purcell et al. (2021), each DCT item was presented alongside four potential responses (correct, heuristic lure, and two others). All items were presented in the format shown in Fig. 6-9, whereby a product sketch and title were displayed in the centre of the screen surrounded by four possible written responses (one in each corner of the screen). The product title was included to remove any doubt about intended function. Participants were asked to select one of four answers regarding the function of the product displayed. The position of the answers was randomised for each item and participant.

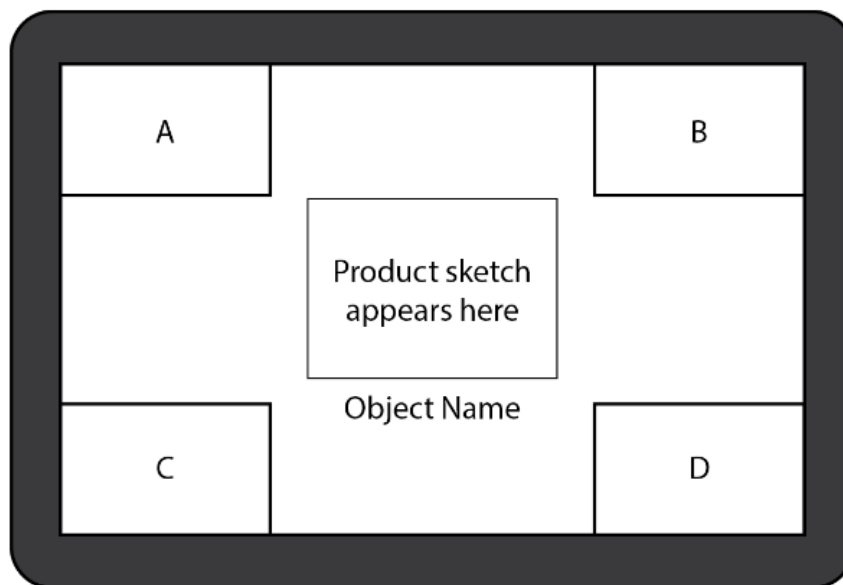


Figure 6-9 - Layout used for all items based on Purcell et al. (2021)

The DCT responses for each item were designed to be a similar number of words/length (± 1 word) (e.g. Figure 6-10 whereby responses are 8 ± 1 words long). This was to ensure a minimal effect of reading time on the resulting fixations and dwell measurements. Additionally, each response included two of each function criteria -

Work or Fail. Participants, therefore, had to determine if they thought the product would function and why. The example displayed in Fig. 6-10 has a heuristic lure answer of “Fails: Wine would fall out due to gravity”; however, the correct answer is that it “Works: pressure would contain wine and allow glass to fill” (see section 6.2.1.4). The answers Other 1 and Other 2 for each question were generated to be unlikely answers that still worked within the context of each question. The full DCT with each item, control item, and the multiple-choice responses can be seen in Appendix 2.

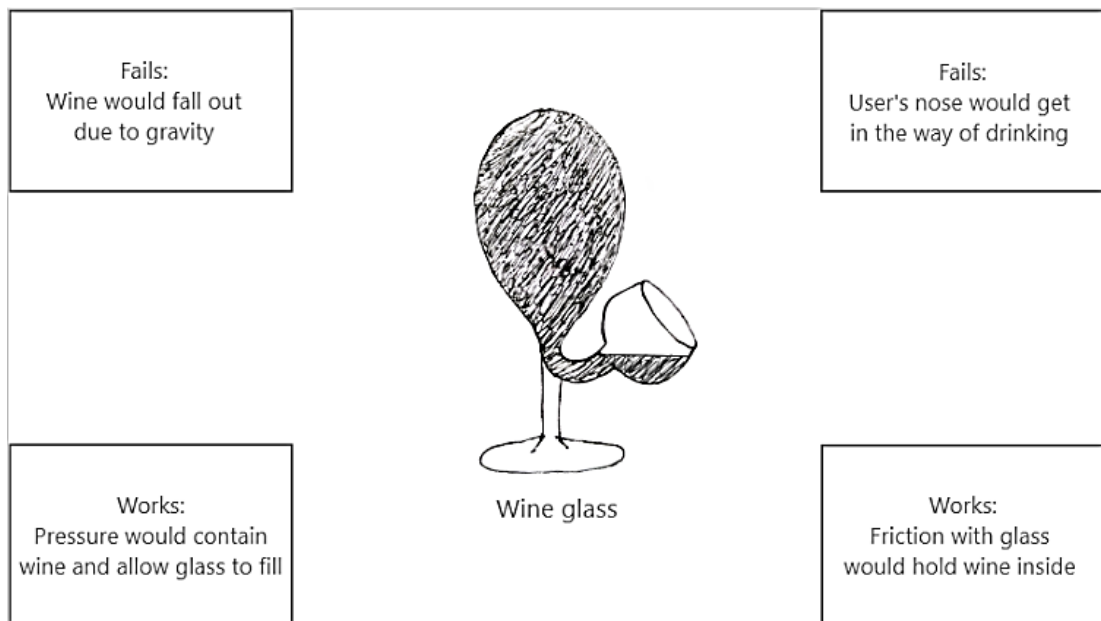


Figure 6-10 - DCT Response options example
(see full test in Appendix 2)

6.3 Tasks and apparatus

The Intervention Model (Evans, 2019) was used as a framework for designing the experimental setup. This involved accounting for the three sets of factors: Motivational Factors, Situational Factors, and Cognitive Resources (see Section 5.3), as shown in Table 6-2 and expanded on in the following sections.

Table 6-2 - Intervention Model factors and experimental design consideration in DS I

Intervention Model Factor	Experimental design consideration	
Motivational Factors	Thinking disposition	Targeted in both the DCT and the CRT
	Feelings of rightness	Assessed after each DCT Item
	Importance of decision	Participants given the same instructions
Situational Factors	Time available	Unlimited time given for the DCT
	Competing tasks	No competing tasks alongside the DCT
	Context	Participants were examined in the same room under the same conditions and instructions.
Cognitive Resources	Working memory capacity	Working memory capacity was measured using the Paced Auditory Serial Addition Test (PASAT) (Gronwall, 1977).
	Mindware	Participants were taken from a student population in similar course disciplines and stages of study.

6.3.1 The Design Conflict Test

As previously discussed, the DCT, aimed to be a design parallel to syllogistic reasoning tasks used in cognitive psychology. Four conflict items (see Section 6.2.1) and four no-conflict items (see Appendix 1) were created for this. The conflict items were created to have a heuristic incorrect response as in the CRT (Frederick, 2005). The no-conflict items were developed within the same format but without a heuristic incorrect response. That is, no-conflict items either intuitively looked like they would work and would work, or intuitively looked like they would not work and would not work - the premises match the believable conclusion (see Appendix 1). The use of both no-conflict items and conflict items was intended to create a balanced mix of question types and reduce participant awareness of the experimental manipulation. While prior studies (e.g., (De Neys, 2012)) have used no-conflict items for baseline analysis, in this case, no-conflict items served purely to maintain the ecological validity of the task environment and were not subsequently analysed.

Participants were presented with a practice item to familiarise themselves with the task and eye tracking equipment. The practice item was represented by a simple no-conflict concept shown in Figure 6-11.

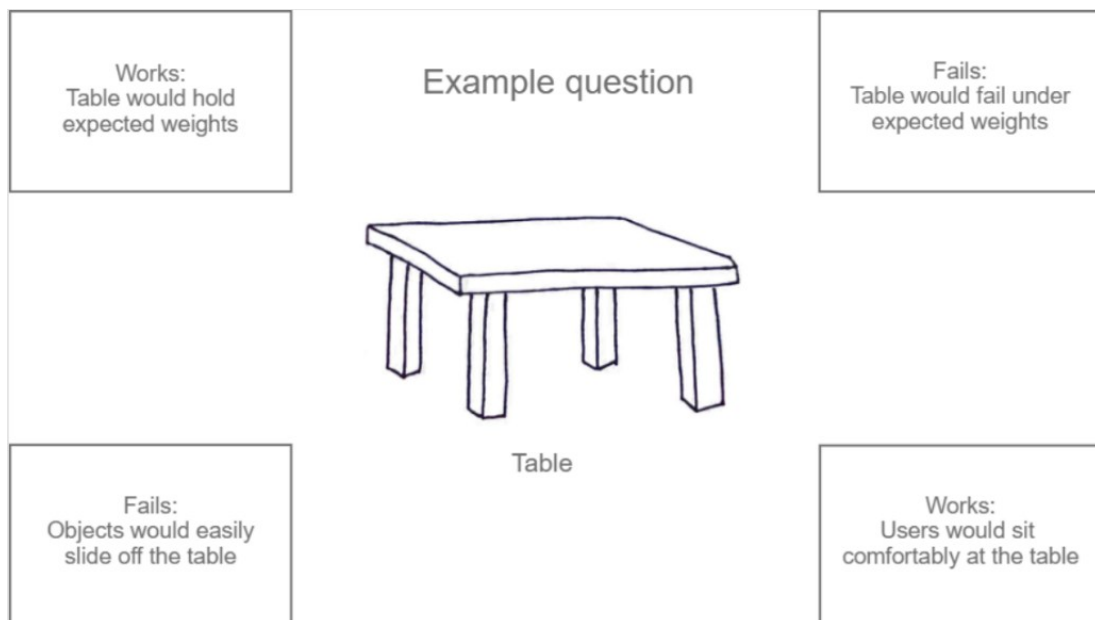


Figure 6-11 - DCT practice item

6.3.2 Correlational Testing

Relating to Hypothesis 3.1a:

- H3.1a.** The DCT will correlate as expected with other relevant psychometric tests.

To assess the DCT, it was compared to correlations of other psychometric and heuristics-and-biases tasks in cognitive psychology (Toplak et al., 2011). Considering that the DCT was proposed as a design-focused alternative to a syllogistic reasoning task, this should result in it aligning with findings for such tasks. Here the correlation of the DCT was analysed with the CRT and a working memory capacity test and assessed according to the correlation findings of Toplak et al. (2011).

6.3.2.1 *Cognitive Reflection Test*

Participants were presented the standard three item version of the CRT:

- (1) A bat and a ball cost £1.10 in total. The bat costs £1.00 more than the ball. How much does the ball cost? _____ cents
- (2) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? _____ minutes
- (3) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? _____ days

(Frederick, 2005)

This was presented on the same monitor, interface, and mouse control used for the DCT (see section 6.3.3). Participants were given instructions on the reasoning task they were about to perform and told they had as much time as they needed to answer. Participants were required to give their answers verbally before continuing to the next question.

6.3.2.2 *Working memory capacity measurement*

The working memory test that was used was the Paced Auditory Serial Addition Test (PASAT)(Gronwall, 1977). The PASAT has been shown to be a reliable and valid test of working memory (Nikraves et al., 2017) and is the measure used in the reference data for validating the developed DCT (Toplak et al., 2011). The PASAT is a serial addition task that measures working memory, information processing speed, and divided attention. A computer auditorily presented one digit per 3 seconds (Trial 1) and per 2 seconds (Trial 2) to a participant. The participant must add each subsequent digit to the preceding one and voice the result aloud. The produced measure consists of the number of correct additions from a total of 60 sums per trial. The participants were given a short practice test for both the 3 second and 2 second trials prior to each real test. This ensured that participants were prepared for the speed of the test. Scores were averaged across both tests for analysis.

6.3.3 **Cognitive pathway measurement**

Relating to Hypothesis 3.1b:

H3.1b. Greater presence of Type 2 processing will correlate with greater instances of correct responses.

The experimental setup is visualised in Figure 6-12. The DCT was presented on a 24” LCD monitor (ViewSonic - VA2445-LED, refresh rate 75 Hz, natural resolution 1,920 × 1,080). The user interface for the test was Adobe XD and was entirely mouse controlled to reduce eye movements off-screen (e.g. towards a keyboard). Eye movements were recorded binocularly (both eyes) with wearable eye-tracking glasses at a rate of 200 Hz (Pupil Core; Pupil Labs, Berlin, Germany). Data were collected using Pupil Capture (Pupil Labs), extracted using Pupil Player (Pupil Labs), and analysed with SPSS Version 29.0.

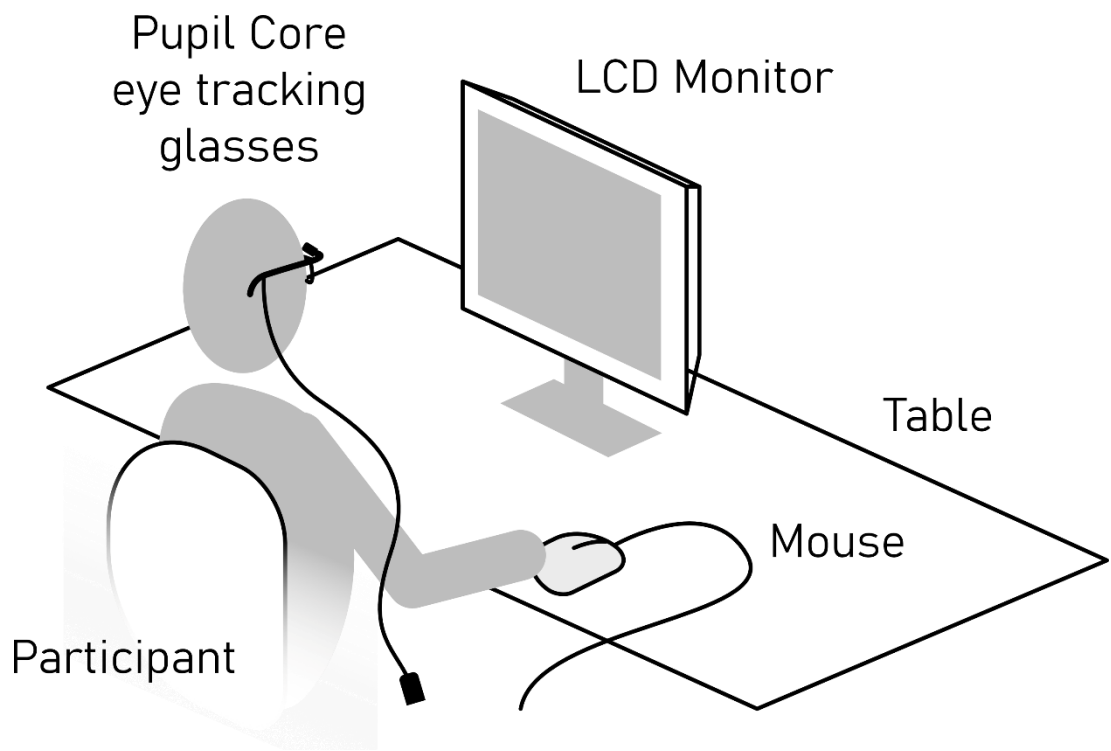


Figure 6-12 - DS I Experimental setup

For the analysis, areas of interest (AOIs) were created for each of the four multiple choice answers in conflict items. These were coded according to the response of each participant for each item (Purcell et al., 2021). The coding comprised of ‘Selected’, ‘Other Relevant’, ‘Other 1’, ‘Other 2’. That is, that for participants who selected the heuristic answer as their response, this answer was coded as ‘Selected’ and the AOI of the correct answer was coded as ‘Other Relevant’, and vice versa for trials where the correct response was selected. The analysis considered each separate AOI to gather data on the fixations and dwell of each of the four multiple choice answers. Each multiple-choice answer was given a randomly allocated corner of the screen for each new participant. The number of fixations and the duration of these (dwell) were each summed for the four AOIs per trial.

To assess the cognitive pathways of participants during the DCT, these fixation and dwell measurements were assessed. For all trials it was expected that the selected response would have the greatest proportion of fixations and dwell. To determine if the DCT was functioning similarly to a traditional heuristics and biases task, the

cognitive pathways were assessed. Corrective pathway use was predicted to present greater consideration of the other-relevant option than the other two options. An intuitive pathway would be expected to present with greater fixation and dwell on the selected option than all three other options. Rather than attempting to reconstruct the precise order in which options were evaluated, the aim was to determine whether attention patterns reflected engagement with competing ideas. This would indicate an alignment with the functioning of heuristics and biases tasks.

6.3.4 Uncertainty measurement

Relating to Hypothesis 3.1c:

H3.1c. Correct responses will be more likely to be associated with lower feelings of rightness than incorrect responses.

To assess the uncertainty of participants in relation to each DCT item, they were asked to rate their confidence in their answer on a scale of 1-100 (see Figure 6-13). These ratings were then reverse coded to reflect uncertainty (Purcell et al., 2021). Considering the correlation of tendency to engage rational thinking and feeling of rightness - this was a key variable in assessing how participants reached their answer. If the intuitive incorrect answer was selected with a high feeling of rightness, this likely indicates that no conflict was detected between it and the correct response and the participant relied on Type 1 thinking. However, if the intuitive incorrect response was selected with a low feeling of rightness, this likely indicates that the participant perceived some conflict but either chose not to, or did not manage to, determine the correct response. This would work similarly for the correct answer being selected. That is, a high feeling of rightness would indicate more reliance on intuitive logical pathways, while a low would indicate conflict that has, in selecting the correct answer, been resolved correctly.

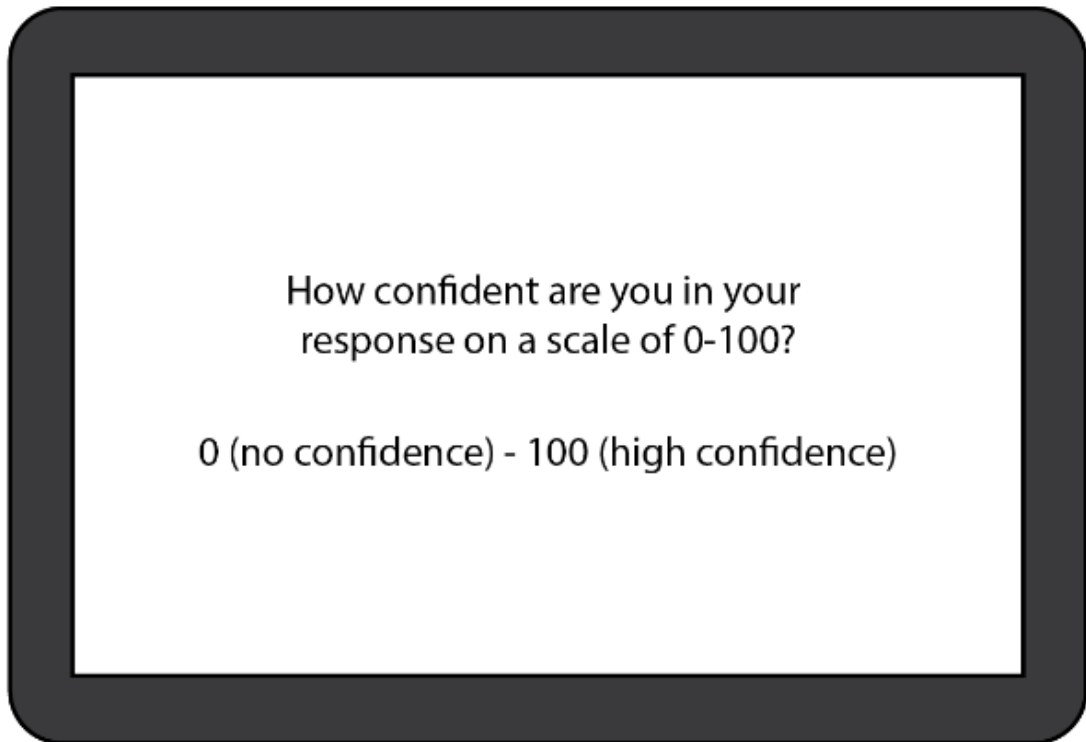


Figure 6-13 - Layout for participant to assess their confidence in their answer

6.4 Pilot study

The pilot study for both DS I and DS II were completed simultaneously, with participants completing the battery of psychometric tests in DS I (DCT, CRT, and PASAT) followed by a 10-minute break and completion of the design task described in DS II (Section 7.4.3). The findings of the pilot study for DS I and DS II are discussed here together.

The pilot study aimed to test the methodology of the experiment. Considering this, analysis was not performed on the data collected. Rather, insights on the methodological considerations were gathered and corresponding changes were made to the study design.

Five engineering design researchers were selected for the pilot study. This prior engineering and design knowledge was a requirement for being able to reason to the correct answer in the DCT questions. Five participants were used for the psychometric

stage of the experiment and four of these subsequently completed the design task too. The participant who only performed the psychometric stage of the experiment was used first to determine if this stage was methodologically valid to perform the design task afterwards. The pilot participant profiles are presented in Table 6-4 with each being assigned a code number for anonymity.

Table 6-3 - Pilot participant profiles

Pilot Participant ID	Field	Years of experience
P01P	Systems Engineering	8
P02P	Automotive design	8
P03P	Product design	5
P04P	Product design	6
P05P	Product design	9

The procedure that was followed was similar to the procedure outlined in section 6.3. The only difference was that participants were asked to also think aloud during the DCT. This was to gain insight into hidden factors that might arise with interpretation and understanding of the items and task. Changes to the study design were made following pilot study insights to both DS I and DS II. The methodological changes made to DS I are documented in Table 6-5.

Table 6-4 - Pilot study resulting methodological changes

Study section	Issues encountered	Solutions
DCT	Confusion over wording of some multiple-choice answers	Change the wording, and instructions for test. These were subsequently tested on later pilot participants.
DCT	Confusion in thinking that two answers could be correct.	The instructions were changed to say that more than one answer could be correct. This aimed to make the test flow more smoothly as these issues appeared in the pilot during control items, not conflict items. This was due to it being difficult to generate wrong but reasonable multiple-choice options for no conflict items.
DCT	One participant indicated that they thought the Wine Glass item would not work due to the nose hitting the glass.	This response option was intended to be one of the 'Other' options, not the lure or correct response. Considering this, it should seem like a statement that could make sense but does not with the given item sketch. To account for this, the sketch was changed to allow more space between the rim and the vessel.
DCT	Calibration of eye-tracking was not perfect every time	Changed from the use of the digital calibration to the physical calibration marker which proved to be more effective. Add calibration screen set up similarly to the test questions to see if when they look at an answer it calibrates to the area of the screen the answers will appear in during the test (see Appendix ###).
PASAT	People counting on their fingers during the working memory test.	This minimised the use of working memory. Therefore, the instructions of the test were changed to instruct participants that they should not count on their fingers.

6.5 Sampling

6.5.1 Sample demographic

The Cognitive Resource factors proposed in the Intervention Model (Evans, 2019)(Evans, 2019) include mindware (see Section 5.3). This was accounted for by selecting undergraduate or integrated master's students studying a product design course with a focus on engineering at the University of Strathclyde (Glasgow, United Kingdom)(see Table 6.2). This ensured all participants had a similar education - a proxy for similar mindware.

6.5.2 Sample size

This work outlines an experimental study conducted for small-scale theory building (Cash et al., 2022; Onwuegbuzie & Collins, 2007). As such, following the recommendations of Onwuegbuzie (2007) based on a statistical power analysis of the most common research designs, a minimum sample size of 21 participants were to be used, the resulting sample of 25 was therefore adequate and the final sample of 23 used in the analysis (due to errors in data collection) remained appropriate.

6.6 Procedure

Participants gave consent prior to the study beginning. Before the first task, participants were given written and verbal instructions about the general procedure (see Appendix 3). The aim of the experiment was not revealed to maintain the integrity of the study. The participant was given a computer mouse and told to start the study when they were ready. Prior to the CRT and DCT, the participant was presented with an instruction page on the monitor screen (see Appendix 4). The instructions for the PASAT were given verbally. The CRT was the first task given, followed by the set-up of the eye-tracking equipment. Calibration was conducted (see Appendix 5) and the practice item for the DCT was performed. They were offered the chance to ask any questions, and if needed, the calibration was completed again until accurate. The 8-item DCT was then performed (containing 4 conflict and 4 no-conflict questions). To prevent order effects, items were randomised for each participant. Immediately after

they selected a response for each item, the participants were asked to state their confidence in this response (see Figure 6-13). Following the DCT, the eye-tracking recording was stopped, and the equipment was removed from the participant. Subsequently, the PASAT was explained and performed. The tests took approximately 10 minutes in total.

6.7 Results

Results are structured according to the three hypotheses proposed (see Section 6.1):

- Correlational analyses (Section 6.7.1):
 - H3.1a.** The DCT will correlate as expected with other relevant psychometric tests.

- Cognitive pathways analysis (Section 6.7.2):
 - H3.1b** Greater presence of Type 2 processing will correlate with greater instances of correct responses.

- Uncertainty (Section 6.7.3):
 - H3.1c.** Correct responses will be more likely to be associated with lower feelings of rightness than incorrect responses.

These analyses were followed by some additional analysis to provide further insight into unexpected findings (section 6.7.4). All statistical tests were performed using SPSS under the guidance of Laerd Statistics (2025) statistical test guides for SPSS. All statistical tests and relevant assumption testing can be seen in Appendix 6. Raw eye-tracking data can be seen in Appendix 7, and participant scores across the psychometric tests can be seen in Appendix 8. For item level analyses, Items 1, 2, 3,

and 5 are discussed. As mentioned in Section 6.2.1, this was due to there being an original five test items but the fourth being discounted in analysis due to the sketch being invalid.

6.7.1 Correlational analyses

H 3.1a. The DCT will correlate as expected with other relevant psychometric tests.

6.7.1.1 *CRT and PASAT analysis:*

When assessing the scores of the CRT, PASAT, and DCT, not all variables were normally distributed, as assessed by Shapiro-Wilk's test ($p < .05$). Therefore, a Spearman's rank order correlation was run as it is more robust to the violation of normality and linearity. On initial exploration of the data, a scatterplot of the PASAT and CRT scores was monotonic.

In alignment with our hypothesis, there was a statistically significant, moderate positive correlation between number of CRT correct responses and the number of PASAT correct responses, $r_s(21) = .499, p=.015$. The correlation coefficient found in Toplak et al. (2011) for the CRT and PASAT was .33, suggesting a stronger correlation found from the current analysis. This may reflect the use of a nonparametric method, which better captures monotonic but non-linear associations, or differences in sample characteristics and task administration.

6.7.1.2 *CRT and DCT analysis*

The CRT scores against DCT scores, and the PASAT against the DCT scores suggested a non-monotonic relationship. Specifically, the data did not exhibit a clear, consistent increase or decrease in CRT scores as DCT scores increased. Therefore, the Spearman's rank order correlation was not appropriate. Instead, linear regression analyses were used to model the relationship between the variables.

Firstly, a linear regression analysis was conducted to examine if a linear relationship existed between participants' scores on the Cognitive Reflection Test (CRT) and their scores on the Design Conflict Test (DCT). The results of the linear

regression model revealed that the overall model was not significant, $F(1,21) = 0.15$, $p = 0.705$, accounting for less than 1% of the variance in CRT scores, $R^2 = 0.007$, $R = 0.084$. This suggests that the DCT questions answered correctly does not significantly predict the variance in CRT scores. Furthermore, the correlation coefficient found in Toplak et al. (2011) for the CRT and Belief Bias Syllogistic Reasoning, was .36, this contrasts to the value found for the correlation with the DCT of .08. This shows deviation from the predicted function of the DCT as a parallel of syllogistic reasoning tasks in terms of correlation with the CRT.

6.7.1.3 *PASAT and DCT analysis*

A linear regression analysis was also conducted to explore the relationship between participants' scores on the PASAT and DCT. The analysis revealed that the linear model was not statistically significant, $F(1,21) = 0.25$, $p = .624$, explaining only 1.2% of the variance in PASAT scores, $R^2 = 0.012$, $R = 0.11$. These results suggest a very weak and non-linear relationship between PASAT and DCT scores, with the model not explaining a significant proportion of variance in PASAT scores. This is in alignment with our hypothesis, that there would be a weak correlation between PASAT and DCT scores. Furthermore, the correlation coefficient found in Toplak et al. (2011) for the PASAT and Belief Bias Syllogistic Reasoning, was .22, the value found for the correlation coefficient with the DCT was .11. While this suggests deviation from the proposed parallel of the DCT to syllogistic reasoning tasks in terms of correlation with working memory capacity, it remains in alignment with the hypothesis of a weak linear relationship.

6.7.2 **Cognitive pathways analysis**

H 3.1b Greater presence of Type 2 processing will correlate with greater instances of correct responses.

To assess the use of Type 2 processing, the gaze-patterns for the conflict items with correct responses (correct conflict trials) were compared to conflict items with heuristics responses (heuristics conflict trials). The number of fixations and dwell for each AOI was assessed for these two trial types. As discussed (Section 6.3.3),

selection-contingent coding was applied whereby the labels ‘Selected’, ‘Other Relevant’, ‘Other 1’, ‘Other 2’ were applied to the AOIs according to the chosen answer for each participant and each item. Trials where neither the heuristic nor the correct answer were selected were removed from this analysis.

It was expected that there would be a difference in the pattern of fixations and dwell on the four AOIs for the correct versus heuristic trials. In our analysis this was captured with a two-way ANOVA which examined the effects of trial type and AOI on proportion of fixation and dwell.

6.7.2.1 *Fixation*

A two-way ANOVA was conducted to examine the effects of trial type and AOI on proportion of fixations in the DCT. Data are mean \pm standard error, unless otherwise stated. Residual analysis was performed to test for the assumptions of the two-way ANOVA. Outliers were assessed by inspection of a boxplot, normality was assessed using Shapiro-Wilk's normality test for each cell of the design, and homogeneity of variances was assessed by Levene's test. There were 4 outliers, as assessed by being greater than 1.5 box-lengths from the edge of the box in a boxplot. There were no extreme outliers, as assessed by being greater than 3 box-lengths from the edge of the box in a boxplot. To control for these outliers, they were modified to slightly larger/smaller than the next most extreme answer in their group. Following this, residuals were normally distributed ($p > .05$) and the assumption of homogeneity of variances was violated ($p = .005$). Considering that the group sizes were approximately equal and the ratio of largest to smallest group variances was below 3, the ANOVA is considered robust under these conditions and was continued (Jaccard, 1998).

The interaction effect between trial type and AOI on proportion of fixations was not statistically significant, $F(3,288) = 1.931$, $p = .125$, partial $\eta^2 = .020$. Therefore, an analysis of the main effect for AOI was performed, which indicated that the main effect was statistically significant, $F(3,288) = 38.742$, $p < .001$, partial $\eta^2 = .288$. All pairwise comparisons were run where reported 95% confidence intervals and p-values are Bonferroni-adjusted. The unweighted marginal means of "Proportion of Fixations" for Selected, Other Relevant, Other 1, and Other 2 - AOIs for heuristic and correct trial

types were 33.98 ± 1.02 , 24.41 ± 1.02 , 20.82 ± 1.02 , and 20.35 ± 1.02 , respectively.

The Selected AOI had a significantly higher proportion of fixations than the Other Relevant AOI (mean difference = 9.57%, 95% CI (5.75, 13.39), $p < .001$), Other 1 (13.63%, 95% CI (9.81, 17.45), $p < .001$), and Other 2 (13.16%, 95% CI (9.35, 16.98), $p < .001$). In addition, the Other Relevant AOI had a significantly higher proportion of fixations than Other 1 (4.06%, 95% CI (0.24, 7.88), $p = .031$), though this difference is marginal given the Bonferroni-adjusted alpha ($.05/6 = .0083$). No other pairwise comparisons were statistically significant. Figure 6-14 illustrates the distribution of fixation proportions across areas of interest for correct and heuristic conflict trials, highlighting the strong main effect of AOI reported above.

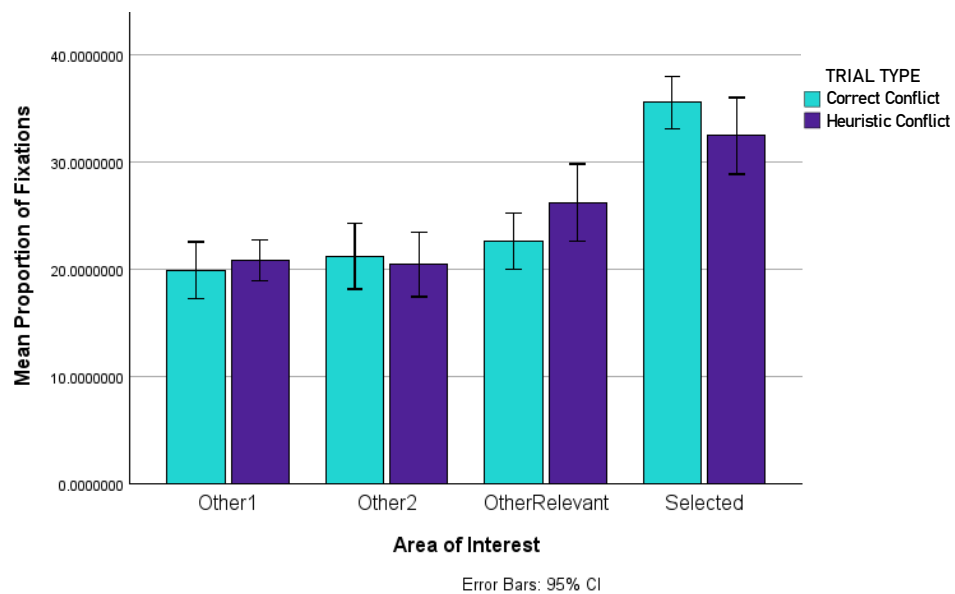


Figure 6-14 - Proportion of Fixations by Area of Interest by Trial Type

6.7.2.2 *Dwell*

Dwell was also analysed through a two-way ANOVA to examine the effects of trial type and AOI on proportion of dwell in the DCT. Data are mean \pm standard error, unless otherwise stated. Residual analysis was performed to test for the assumptions of the two-way ANOVA. Outliers were handled as in the analysis of proportion of fixations. Again, there were 4 outliers, and no extreme outliers, which were modified to slightly larger/smaller than the next most extreme answer in their group. Following this, residuals were normally distributed ($p > .05$) and the assumption of homogeneity of variances was violated ($p = .004$). Considering that the group sizes were approximately equal and the ratio of largest to smallest group variances was below 3, the ANOVA is considered robust under these conditions and was continued (Jaccard, 1998).

The interaction between trial type and AOI on dwell time was not statistically significant, $F(3, 288) = 2.471$, $p = .062$, partial $\eta^2 = .025$, although it approached conventional significance ($p < .05$). In light of this trend and theoretical expectations, simple main effects of trial type were examined within each AOI without applying a correction for multiple comparisons, due to the limited number of planned contrasts.

A statistically significant difference in dwell time between trial types was found in the Other Relevant AOI, where heuristic conflict trials had a higher mean proportion of dwell (26.96 ± 11.54) than correct conflict trials (22.61 ± 8.19), $F(1, 288) = 4.23$, $p = .041$, partial $\eta^2 = .014$. No statistically significant differences were observed between trial types in the Selected, Other 1, or Other 2 AOIs (all $p > .001$).

Within each trial type, a main effect of AOI was observed. For correct conflict trials, the effect of AOI was statistically significant, $F(3, 288) = 22.97$, $p < .001$, partial $\eta^2 = .193$. Dwell time in the Selected AOI was significantly higher than in the Other Relevant (mean difference = 12.85%, 95% CI [7.24, 18.47]), Other 1 (15.35%, 95% CI [9.74, 20.97]), and Other 2 AOIs (14.33%, 95% CI [8.72, 19.95]), all $p < .001$.

For heuristic conflict trials, the main effect of AOI was also statistically significant, $F(3, 288) = 13.94$, $p < .001$, partial $\eta^2 = .127$. The Selected AOI had higher dwell than Other 1 (11.18%, 95% CI [5.57, 16.80]) and Other 2 (11.76%, 95% CI [6.14, 17.37]),

both $p < .001$. However, the difference between Selected and Other Relevant AOIs was not statistically significant (4.92%, 95% CI [-0.70, 10.53], $p = .124$). The Other Relevant AOI was associated with significantly more dwell than Other 1 (6.26%, 95% CI [0.65, 11.88], $p = .020$) and Other 2 (6.84%, 95% CI [1.23, 12.46], $p = .008$).

A contrast was performed to compare the difference between trial types in dwell time for the Selected and Other Relevant AOIs. In correct conflict trials, the Selected AOI had 3.59% more dwell than in heuristic trials, while the Other Relevant AOI had 4.35% less dwell. The difference between these differences was statistically significant, 7.94% (95% CI [2.05, 13.82]), $p = .008$. Figure 6-15 visualises this interaction pattern, showing greater concentration of dwell on the Selected AOI in correct conflict trials, and relatively increased dwell on Other Relevant AOIs in heuristic conflict trials.

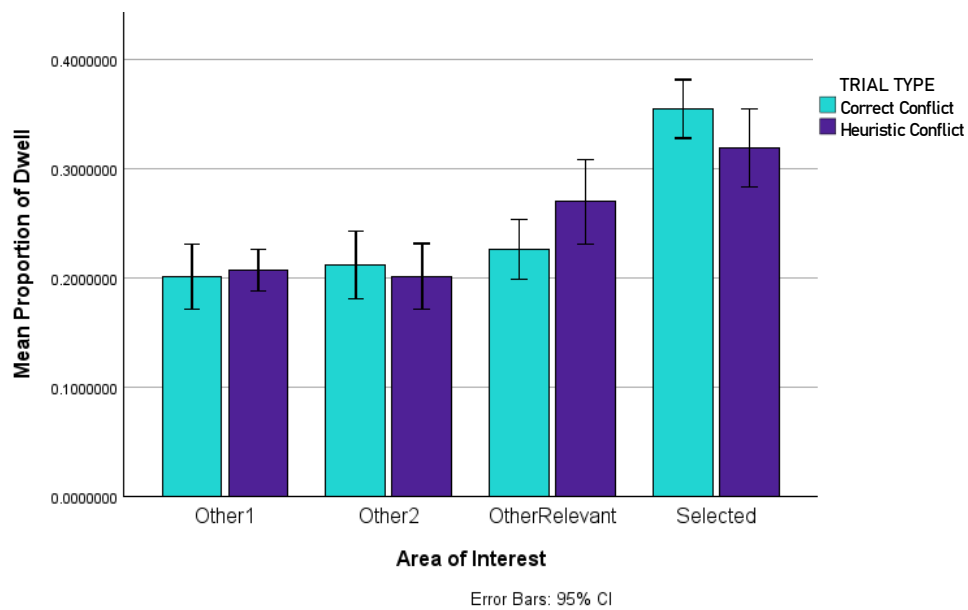


Figure 6-15 - Proportion of Dwell by Area of Interest by Trial Type

6.7.3 Uncertainty

H 3.1c. Correct responses will be more likely to be associated with lower feelings of rightness than incorrect responses.

For correct conflict and heuristic conflict trials, mean uncertainty was 31.35 ± 3.08 for correct conflict trials and 26.46 ± 3.272 for heuristic conflict trials, a statistically insignificant mean difference of 4.89 (95% CI, -13.85 to 4.06), $F(1, 72) = 1.186$, $p = .280$, partial $\eta^2 = .016$. While this shows that there was likely more use of Type 2 processing in the correct conflict trials - as expected (due to greater uncertainty levels), this result was not significant (see Figure 6-16).

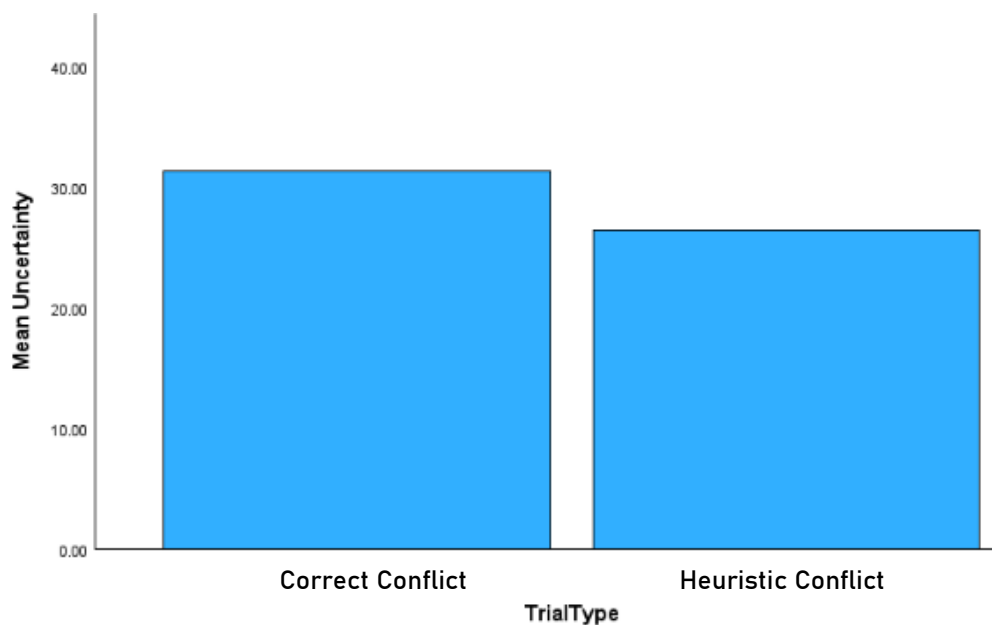


Figure 6-16 - Uncertainty by trial type

To explore this further, uncertainty was analysed across individual items, between trial types, through performing a two-way-ANOVA. Data are mean \pm standard error, unless otherwise stated. Residual analysis was performed to test for the assumptions of the two-way ANOVA. Outliers were assessed by inspection of a boxplot, normality was assessed using Shapiro-Wilk's normality test for each cell of the design and homogeneity of variances was assessed by Levene's test. There was 1 outlier, as

assessed by being greater than 1.5 box-lengths from the edge of the box in a boxplot. There were no extreme outliers, as assessed by being greater than 3 box-lengths from the edge of the box in a boxplot. To control for the outlier, it was modified to slightly larger/smaller than the next most extreme answer in its group. Following this, residuals were normally distributed ($p > .05$) and there was homogeneity of variances ($p = .292$).

The interaction effect between trial type and item was statistically significant, $F(3, 66) = 3.546$, $p = .019$, partial $\eta^2 = .139$, indicating that the effect of trial type on uncertainty differed by item. No significant main effects were found for trial type, $F(1, 66) = 2.041$, $p = .158$, partial $\eta^2 = .030$, or item, $F(3, 66) = 1.704$, $p = .175$, partial $\eta^2 = .072$.

To follow up the interaction, simple main effects of item were examined separately for each trial type. For correct conflict trials, the effect of item on uncertainty was statistically significant, $F(3, 66) = 3.402$, $p = .023$, partial $\eta^2 = .134$. For heuristic conflict trials, the effect of item was not significant, $F(3, 66) = 1.401$, $p = .250$, partial $\eta^2 = .060$. This suggests that uncertainty varied by item in correct conflict trials, but was more consistent in heuristic conflict trials.

Simple effects of trial type were then examined within each item. For Items 1, 2, and 3, there were no significant differences in uncertainty between correct conflict and heuristic conflict trials (all $p > .05$, partial η^2 's $\leq .008$). However, for Item 5, uncertainty was significantly higher for correct conflict trials compared to heuristic conflict trials, $F(1, 66) = 10.093$, $p = .002$, partial $\eta^2 = .133$. Specifically, mean uncertainty was 36.54% (95% CI, 13.577 to 59.507) higher in correct conflict trials than in heuristic conflict trials for Item 5. (see Figure 6-17)

This result suggests that Item 5 may have elicited more deliberative, Type 2 reasoning in participants who answered it correctly, relative to those who provided the heuristic response, as reflected in their reported uncertainty. In contrast, the smaller or absent uncertainty differences in the other items suggest they may not have elicited the same degree of conflict or metacognitive evaluation.

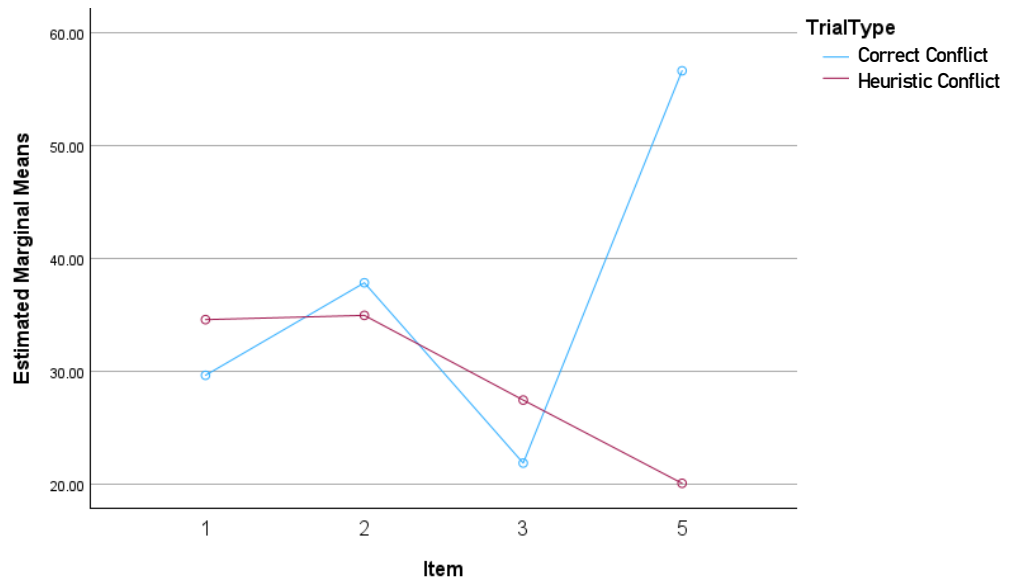


Figure 6-17 - Estimated marginal means of uncertainty for items between correct conflict and heuristic conflict trials

6.7.4 Exploratory follow-up: Analysis of Uncertainty and CRT as Predictors of DCT Performance

The two-way ANOVA on uncertainty revealed differences between items 1-3 and item 5. These differences suggest that items 1-3 may be a less effective measure of conflict, or be measuring something different to item 5. This may have affected the earlier correlational analyses with the CRT and DCT that did not match predictions. To explore this further, Binomial Logistic Regression analyses were conducted to assess whether uncertainty (feeling of rightness) at the item level and CRT score at the participant level predicted the likelihood of providing a correct response on each DCT item.

6.7.4.1 Logistic regression on all items

The binomial logistic regression was performed initially on all items. Linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell (1962) procedure. A Bonferroni correction was applied using both continuous predictors in the model, resulting in statistical significance being accepted when $p < .025$ (Tabachnick & Fidell, 2014). Based on this assessment, both continuous independent variables were found to be linearly related to the logit of

the dependent variable.

The logistic regression model was not statistically significant, $\chi^2(2) = 1.253$, $p = .534$. The model explained 2.2% (Nagelkerke R^2) of the variance in DCT accuracy and correctly classified 51.4% of cases, which is near chance level. Sensitivity was 56.8%, specificity was 45.9%, positive predictive value was 37.9% and negative predictive value was 38.1%. Of the two predictor variables, neither was statistically significant: CRT score and uncertainty did not significantly predict whether a participant would provide a correct DCT response (as shown in Table 6-5). While higher uncertainty was weakly associated with an increased likelihood of a correct response (OR = 1.013), this effect was not statistically meaningful. These findings suggest that neither cognitive reflection ability (CRT) nor feeling of rightness significantly influenced accuracy on the DCT.

Table 6-5 - Logistic Regression Predicting Likelihood of Correct DCT Responses on all Items based on Uncertainty, and CRT

	<i>B</i>	SE	Wald	<i>df</i>	<i>p</i>	Odds ratio	95% CI for Odds Ratio	
							Lower	Upper
CRT Score	-.042	.196	.047	1	.829	.959	.653	1.407
Uncertainty	.013	.012	1.148	1	.284	1.013	.989	1.038

6.7.4.2 *Logistic regression on items 1-3:*

The analysis was run again - this time only using the data from Items 1 - 3. Again, both continuous independent variables were found to be linearly related to the logit of the dependent variable.

The logistic regression model was not statistically significant, $\chi^2(2) = .233$, $p = .890$. The model explained 0.6% (Nagelkerke R^2) of the variance in DCT accuracy and correctly classified 61.8% of cases. Sensitivity was 100%, specificity was 0%, positive predictive value was 34% and negative predictive value was 0%. This classification pattern indicates that the model predicted all responses as correct, correctly identifying all actual correct responses while misclassifying all heuristic responses. Such skewed

classification suggests that the model lacked discriminatory power and defaulted to the dominant outcome, likely due to the negligible contribution of the predictors. Of the two predictor variables, neither was statistically significant: CRT score and uncertainty did not significantly predict whether a participant would provide a correct DCT response (as shown in Table 6-6). These findings suggest that neither cognitive reflection ability (CRT) nor subjective uncertainty significantly influenced accuracy on the DCT for items 1-3.

Table 6-6 - Logistic Regression Predicting Likelihood of Correct DCT Responses on Items 1-3 based on Uncertainty, and CRT

	<i>B</i>	SE	Wald	<i>df</i>	<i>p</i>	Odds ratio	95% CI for Odds Ratio	
							Lower	Upper
CRT Score	-.049	.232	0.44	1	.833	.952	.605	1.499
Uncertainty	-.007	.016	.210	1	.647	.993	.963	1.024

6.7.4.3 *Logistic regression on Item 5:*

Running the analysis for a final time on only the data from Item 5 revealed some different insights. Again, both continuous independent variables were found to be linearly related to the logit of the dependent variable.

The logistic regression model was statistically significant, $\chi^2(2) = 8.227$, $p = .016$. The model explained 60.4% (Nagelkerke R^2) of the variance in DCT accuracy and correctly classified 84.2% of cases, suggesting a substantially better fit than previous models. Sensitivity was 33.3%, specificity was 93.8%, positive predictive value was 9.5% and negative predictive value was 88.2%. Of the two predictor variables, uncertainty approached significance ($p = .071$), with higher uncertainty associated with increased odds of a correct response. Specifically, for each one-unit increase in uncertainty, participants were estimated to be 1.13 times more likely to respond correctly (OR = 1.132, 95% CI [0.989, 1.296]). In contrast, CRT score did not significantly predict response accuracy (see Table 6-7).

Table 6-7 - Logistic Regression Predicting Likelihood of Correct DCT Responses on Item 5 based on Uncertainty, and CRT

	<i>B</i>	SE	Wald	<i>df</i>	<i>p</i>	Odds ratio	95% CI for Odds Ratio	
							Lower	Upper
CRT Score	-.574	.876	.429	1	.512	.563	.101	3.137
Uncertainty	.124	.069	3.254	1	.071	1.132	.989	1.296

These results suggest that for Item 5, unlike the other DCT items, participants' feeling of rightness may have played a more meaningful role in response accuracy. This could indicate that Item 5 is more likely to trigger conflict, and therefore more likely to require greater Type 2 reasoning or cognitive capacity to override this conflict and answer correctly. However, given the marginal *p*-value and small sample size for this item-level analysis, these findings should be interpreted with caution.

6.8 Discussion

This study aimed to answer the overarching research question of:

RQ 3: How can individual differences in dual-processing tendencies be measured in design cognition?

A proposed answer to this question was the developed Design Conflict Test. However, to determine if this was a suitable answer, the DCT was analysed according to the sub-research question:

RQ 3.1: Does the Design Conflict Test function as a heuristics-and-biases task?

Here, a shorter discussion is presented to answer this sub-research question focusing on DCT validity, design, experimental considerations, and specific metric analysis. Broader conclusions on the DCT and its validity as it relates to implications for design research, practice, and future work are presented in Chapter 8 and 9, following the conclusion of both DS I and DS II as the experimental components of this work.

6.8.1 Validity

DS I aimed to test the theory of cognitive conflict in design based on dual-process theory and the FBS framework. The developed Design Conflict Test built on this theoretical basis and studied in this chapter did present with results that are in accordance with the behaviour of heuristics and biases tasks in several aspects. It was predicted that the DCT would not correlate strongly with working memory capacity - which was the case. This suggests that the DCT does indeed act independently from working memory as a variable. This is a necessary behaviour of such a test to ensure that it does measure a design tendency to detect and override FBS conflict and not act as a proxy measure for another variable. Furthermore, the cognitive pathways displayed through eye-tracking analysis showed promise for inducing conflict between Type 1 and Type 2 processing in participants. Feelings of rightness, measured through uncertainty associated with responses also suggested that intuitive responses were being often being rethought - increasing the likelihood of Type 2 engagement.

However, some aspects reflect the exploratory nature of this work as the first attempt at generating such a test for design cognition. That is, several aspects of the analysis revealed a discrepancy from predicted behaviour as a parallel to existing heuristics and biases tasks. It did not correlate as expected with other psychometric tests. Heuristics and biases tasks have been shown to correlate with the Cognitive Reflection Test, thought to be a measure of fluid intelligence and rational thinking disposition. Following this, it was expected that the DCT would correlate positively with the CRT. However, no such relationship was found. Furthermore, the test items did not perform similarly to one another. Namely, Item 5 appeared to be significantly more effective at differentiating between participants who would reach the correct answer through more effortful processing, reflected in the increased levels of uncertainty. Developing iterations of the DCT and trying to adapt questions to be more effective in this way could reveal different insights about cognitive conflict in design.

This mix of predicted and unpredicted behaviour poses many questions for how to interpret the results. These discrepancies could be the result of the DCT design (e.g. item design), or DS I experimental design (e.g. sample size). However, it could also suggest that reasoning in design contexts may operate differently from more abstract, syllogistic problems. This would call into question the assumption that dual-process indicators observed in common DPT tasks would transfer to applied domains like design. The observed divergence may reflect the influence of domain knowledge, visual processing, or task ambiguity - factors more prevalent in design than in traditional logic-based reasoning tasks.

6.8.2 Item design

One of the main insights from this study is an understanding of the key considerations for developing design cognition research methodology in alignment with cognitive psychology and more objective measures suitable to larger scale research. This work was an exploration into these goals of the field. Indeed, the variation in the results from the hypotheses set out for DS I reflect this. Particularly with regards to item design. One of the central behaviours necessary for the psychometric test that the DCT was aiming to emulate is item consistency. Particularly for dual-processing and assessing Type 1/Type 2 conflict, items must consistently be

complex enough to instill conflict and require the override of the intuitive response. Item 5 - the Wine Glass, appeared to do this most effectively - suggesting a complexity to the stimulus that instilled a high level of Type 2 engagement needed to devise the correct response.

Item 3 - the Table, resulted in the lowest uncertainty for correct respondents. This could indicate that the item was easily answered through a Type 1 logical response (rather than a Type 1 heuristic response) (see Section 6.1, H3.1b.). Alternatively, it could suggest correct responses were more easily verified through a low level of Type 2 engagement. Additionally, the item design may not have been different enough from the standard tensegrity chair (see Section 6.2.1.3) to cause any conflict. Participants familiar with the working concepts of the chair could have had greater ease than intended in determining the correct behaviour of the table through assessing the structure of tension and compression components.

An additional factor was the design of the multiple-choice responses. Particularly, Item 2 - the Scissors, resulted in 11 participants selecting Other 1 as their response - an issue that did not arise in the pilot study. Only trials involving the selection of the heuristic or correct answer were included in the analysis which limits the effect of this design flaw on the analysis. However, this also resulted in the sample size of participants analysed for Item 2 being limited and potentially obscuring participants with tendencies of interest towards Type 1 or Type 2 processing. Item 1 and 3 performed far better in this respect with only 2 and 1 participants, respectively, selecting answers other than the heuristic or correct answers. Item 5 resulted in 4 participants selecting Other 1, and none selecting Other 2. While these are limited discrepancies, these Other options could be adapted to be less likely to be selected.

A further development of the DCT in the future would be to study it in the method that the CRT is usually administered. That is, issuing the task but not providing predetermined answers. This would enable a deeper insight into how participants visually process and interpret the function, behaviour, and structure of each item. Such insights could be used to refine the test items further to be more accurate in inducing a strong intuitively wrong response and a correct response that requires a high level of Type 2 engagement to reach.

This study used control items to reduce participant awareness of the experimental manipulation and maintain the ecological validity of the task environment. However, future work could leverage no-conflict items for baseline analysis, as in De Neys (2012). This would provide insight into the differences between participants in how those who score well on the DCT compared to those who score poorly in terms of how they respond to no conflict items and their susceptibility to design conflict biases.

6.8.3 Cognitive Pathways

The cognitive pathways revealed by the eye-tracking analysis of the DCT also provided many insights. The difference between the Other-Relevant and Selected AOIs in correct conflict trials may suggest that participants responding with the correct answer were more likely to be using intuitive pathways. That is, the fixation and dwell times in correct conflict trials across the Other 1, Other 2, and Other Relevant responses was similar, while the correct selected answer was higher. In contrast, those who provided the heuristic response seem to be more likely to sense the conflict and consider the Other Relevant option for longer compared to Other 1 and Other 2. This suggests that while conflict may have been better detected, ultimately there was a failure to intervene and calculate the correct answer. Either through tendencies resulting in setting a lower level of Type 2 engagement, or through a limit in cognitive capacity.

These patterns revealed in the analysis on fixation and dwell align with considerations relating to expertise. Specifically, it has been found that those with low expertise rely on Type 1 or ineffective Type 2 processing (Purcell et al., 2020). This is precisely what is seen in the analysis of fixations and dwell. However, it would be expected that the sample group of this study could be considered to have intermediate experience - considering their advanced stage in their determined education program of product design. Intermediate experience has been found to present with effective Type 2 processing (Purcell et al., 2020). This would align with the idea that intermediate experience results in possessing the necessary knowledge but not having learnt this to automacity. Further research involving expertise as a variable would provide necessary and deeper insights into both the development of a more effective DCT iteration and insights into the function of expertise in design through a DPT lens.

Alternatively, the difference in the fixations versus the dwell when considering AOIs between trial types may indicate that while there is less difference in what information is being considered between heuristic lure and correct lure trials (i.e. the proportion of fixations) for the 'Selected' AOI, that there is greater depth of processing of the 'Selected' answer in correct lure trials than in heuristic trails. This is shown in the greater fixation and dwell on the selected answer for correct trials; however, this difference was not statistically significant so this aspect of the discussion is proposed cautiously. These insights may point to expertise in design, or potentially some design ability that enables effective use of Type 1 processing. The statistical analysis of the fixations and dwell on the DCT AOIs was occasionally on the cusp of significance. Using the insights discussed here, iterating the DCT design, items, multiple-choice answers, and increasing the sample size would provide a stronger basis on which to draw conclusions. This would also open the door for analysing expertise in design through psychometric testing and comparing design expertise insights to those found in other domains (e.g. Purcell et al., 2020; Evans, 2011).

6.9 Summary

The initial experimental design intended that the DCT be used to place designers on a spectrum of more likely to rely on intuitive or analytic thought by measuring how they resolved design-based conflict. This was to be done through cross referencing scores on the CRT - based on the assumption that cognitive reflection tendencies would translate to design. However, the analysis of DS I showed that such a spectrum was not as straight forward as selecting those who scored low on the CRT and DCT, and those who scored high on the CRT and DCT. While the validity of the DCT has not been confirmed by proving all hypotheses presented in Section 6.1, the results do provide some interesting insights worthy of further exploration. Indeed, if design conflict tendencies are more independent from the CRT than first thought, investigating this relationship further would be important. Having the metrics of working memory, and CRT performance available, means that interesting areas of DCT score distribution could be investigated further in DS II. How individual designers perform on psychometric measures has been analysed, what must then be asked is how this influences the design process. To further explore what the DCT has measured and relates to, the second study DS II will examine key participants across the spectrum of DCT and CRT scores, controlling for working memory capacity, to explore potential correlations with design behaviour and how these align with concepts from the dual-process theory literature.

7 DESCRIPTIVE STUDY II

Building on the findings of DS I (Chapter 6), DS II (this chapter) was designed to examine more deeply the relationship between individual cognitive tendencies and observable design behaviour. DS I primarily examined whether the Design Conflict Test (DCT) could be used to classify designers along a spectrum of intuitive versus analytic thought. The original research design for DS II, therefore, assumed a linear association between DCT and Cognitive Reflection Test (CRT) scores, and was intended to contrast participants at either end of this spectrum (see Figure 6-1).

However, the results of DS I highlighted a more complex picture. The predicted linear relationship between DCT and CRT scores was not found, suggesting either that design conflict tendencies may reflect aspects of cognition not directly captured by the CRT, or that the design of the DCT would require changes to reveal a greater crossover of observable phenomenon between the two tests. This finding indicated that the original extreme-groups sampling plan would not have targeted regions of the distribution that were most informative about the observed pattern.

Although the DCT requires refinement at the item level, DS I provided process evidence that it engages the intended mechanisms. Therefore, DS II used DCT scores as a provisional individual-difference index. Through this, DS II was reframed to adopt a maximum-variation (contrastive case) sampling strategy designed to target different regions of the CRT \times DCT space (see Figure 7-1) rather than test the original linear hypotheses. Participants were selected from three profiles discussed in Section 7.4.1.

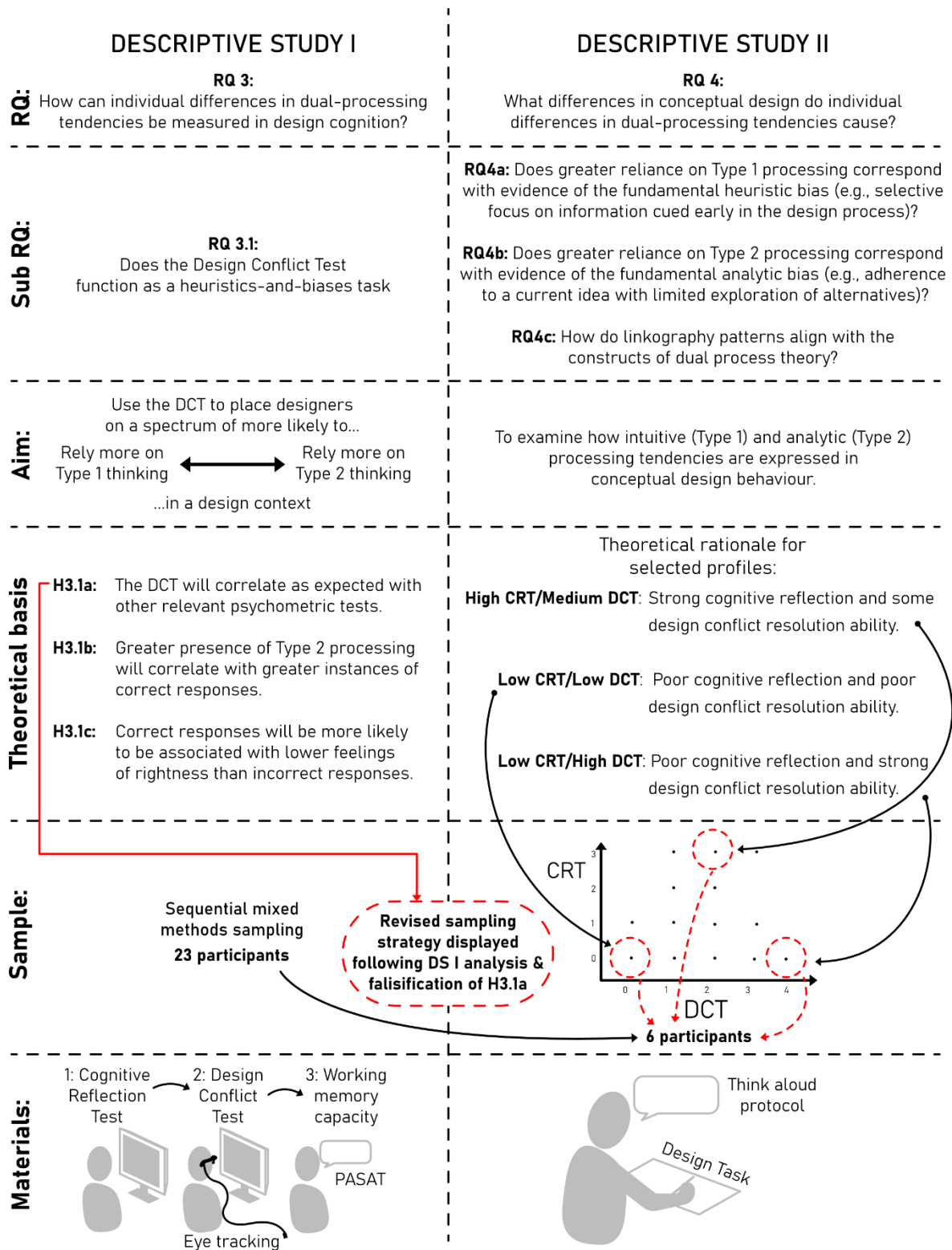


Figure 7-1 - Overview of updated evaluation approach (DS I & DS II)

DS II aims to examine how intuitive (Type 1) and analytic (Type 2) processing tendencies are expressed in conceptual design behaviour. Importantly, the focus here is not on re-testing the falsified linear hypothesis from DS I, but on examining how dual-process theory can help explain the distinct patterns of design behaviour that emerged across contrasting cognitive profiles. DS II, therefore, is structured around the following:

RQ4: What differences in conceptual design do individual differences in dual-processing tendencies cause?

Aim: To examine how intuitive (Type 1) and analytic (Type 2) processing tendencies identified in DS I are expressed in conceptual design behaviour.

Method: Observing key participants from DS I performing a structured design task using think-aloud protocols and linkographic analysis.

This chapter presents the design, methodology, and analysis of DS II. It investigates not only how designers' cognitive profiles relate to their design process, but also what this reveals about the interplay between intuitive and analytic modes of thought in a design context.

The concept of rational thinking disposition, on which much of this research is built, posits that individuals have an inherent inclination towards relying on more or less Type 1 or Type 2 processing (Trippas et al., 2015; Stanovich et al., 2016). Since Type 2 processing is dependent on working memory (De Neys, 2021; Evans, 2012, 2018), individual differences in cognitive capacity affect performance in dual-process reasoning tasks. However, this is not the only factor. Indeed, Stanovich and West (Stanovich & West, 2000) found that residual variance in normative responding across heuristic and biases tasks could be predicted through thinking disposition measures when cognitive ability is factored out. Therefore, it is crucial to understand both a person's cognitive ability and rational thinking disposition to get a comprehensive picture of their capacity for rational decision-making. Indeed, it then follows that to get a comprehensive picture of one's capacity for rational decision making in design

that both cognitive ability and thinking dispositions relevant to design would need to be examined.

The psychometric tests applied and developed in DS I, and the controlled environment and parameters they necessitate, are far removed from the context of real-life situations. Despite this, there is a body of research connecting rational thinking dispositions to making real-life decisions e.g. (Bruine de Bruin & Parker, 2007; Hilton, 2003; Milkman et al., 2008; Parker et al., 2015). To examine the consequences of such thinking dispositions in more naturalistic situations, a lens through which to analyse them is necessary.

Fundamental biases (first discussed in Section 4.3.2.2), were identified as a potential aspect of dual-process theory that could be used to explore the design process. With the aim of examining how Type 1 and Type 2 processing tendencies are expressed in conceptual design behaviour - these biases could be the useful lens needed to examine emerging patterns. While hypotheses are not proposed for this study, research questions are used to guide the examination of fundamental biases and how they can be linked to design behaviour through linkography.

7.1 Research Questions

Although DS I showed that the relationship between CRT and DCT was not linear, this did not undermine the role of dual-process theory as a framework for DS II. Rather, it highlighted the importance of examining how different combinations of general analytic reasoning (CRT) and design-specific tendencies (DCT) are expressed during design activity. Fundamental biases provide a useful lens for this purpose. Instead of treating CRT and DCT as points along a linear spectrum, DS II investigated how profiles across the distribution may be associated with DPT constructs - particularly evidence of the fundamental heuristic bias (arising from Type 1 processing), the fundamental analytic bias (arising from Type 2 processing), and how patterns in linkography arise across the profiles. These biases inform the sub-research questions guiding the analysis that fit under the main research question for DS II:

RQ4: What differences in conceptual design do individual differences in dual-processing cause?

RQ4a: Does greater reliance on Type 1 processing correspond with evidence of the *fundamental heuristic bias* (e.g., selective focus on information cued early in the design process)?

RQ4b: Does greater reliance on Type 2 processing correspond with evidence of the *fundamental analytic bias* (e.g., adherence to a current idea with limited exploration of alternatives)?

RQ4c: How do linkography patterns align with the constructs of dual process theory?

To provide greater context for these questions, the fundamental biases of Type 1 and Type 2 processing and how these may present in the design process are discussed. Additionally in addressing these questions, a method was needed that could capture fine-grained patterns of reasoning as they unfolded during design activity. Linkography was identified as a method which offers such a lens, making it possible to detect whether design moves align more closely with the manifestations of heuristic (Type 1) or analytic (Type 2) biases.

7.2 Fundamental DPT biases in design

The workings of Type 2 processing have been elaborated by Evans (2007a) in relation to hypothetical thinking which is considered the foundation of rational thought (Stanovich, 2004, 2009). The ‘Hypothetical Thinking Theory’ rests on three premises, with the first stating that a single hypothetical scenario is examined at a time (the singularity principle) (Evans, 2011). The second states that the most relevant hypothetical, prompted by context and probability, will be considered first (the relevance principle). The last states that the current hypothetical will be kept unless a reason to abandon it is found (the satisfying principle). These three premises play a significant role in the apparent biases found on many cognitive tasks. Evans (2011) divided these biases into two fundamental types that arise from each of the processing types (see Table 7-1). The bias arising from Type 1 processing was termed the fundamental heuristic bias - whereby only information preconsciously signalled as relevant is considered; arising from Type 2 is the fundamental analytic bias - the maintenance of only the current hypothesis in cognition without sufficiently considering alternatives. While interpretations of DPT often consider bias a phenomenon dominated by Type 1 processing (Evans, 2012), Evans (2011) places equal responsibility of both Type 1 and Type 2 processing as sources of cognitive bias.

Table 7-1 - Fundamental biases of Type 1 and Type 2 processing (Evans, 2007)

Fundamental heuristic bias (arising from Type 1 processing)	Selectively focusing on information that is preconsciously cued as relevant
Fundamental analytic bias (arising from Type 2 processing)	Maintaining the current mental model with insufficient consideration of alternatives/evaluation

This work aims to investigate if these fundamental biases can be detected in conceptual design. To do this, we must consider how these biases might manifest in the design process. The fundamental heuristic bias, whereby there is a selective focus on preconsciously cued relevant information, could result in associative exploration of the problem and solution space with a reliance on information that arises very early in

the design process as relevant. A greater reliance on Type 1 processing (i.e. tending towards an intuitive rational thinking disposition), could result in more of this pattern of thought than someone with a more analytic design thinking disposition (tendency towards Type 2 processing). A design process that has more of this broad exploration of a minimal number of initial problem-foci could be indicative of someone with this more intuitive design thinking disposition. This could lead designers to make rapid initial progress by focusing on what feels immediately relevant. However, failing to push the understanding of the design brief beyond initial framings may limit the solution space.

Alternatively, the fundamental analytic bias could result in the often-studied phenomenon of fixation in design - whereby there is an illogical adherence to a perceived set of limitations or ideas while designing (Jansson & Smith, 1991). That is, the current mental model being maintained without sufficient consideration of alternatives. If this is the case, designers with greater Type 2 reliance would display more fixation in their work, while those with less reliance on Type 2 processing would display greater evidence of narrow associative exploration.

7.3 Linkography

Developed by Gabriela Goldschmidt in 1990, linkography is a method for analysing cognitive aspects of the design process (Goldschmidt, 1995, 2014). The method expands on protocol analysis (see section 3.3.1) through mapping and visualising the relationships between actions taken in the design process which are denoted by small chunks of verbalisations known as “design moves” (Goldschmidt, 2014). Design moves are “a step, an act, an operation, that transforms the design situation” (Goldschmidt, 2014, p. 42). Developing an understanding of how the design process evolves through these moves, necessitates links to be established by assessing the content of the moves (Goldschmidt, 2014). Links are formed through analysing each pair of moves for possible links which are then depicted by a network of nodes (Goldschmidt, 2014). Through this, a representation of the pattern, origin, and development of ideas is presented which may well reveal manifestations of the fundamental biases targeted in RQ4a and RQ4b.

7.3.1 Types of design moves in linkography

Analysis of linkographs is done through considering the patterns and components of a linkograph (depicted in Figure 7-2). Links create “backlinks”, a backward link (e.g. where we can see that move 2 connects to move 1), or, once backlinks are established, we can also refer to “forelinks”, a forward link (e.g. from move 1 to move 2). There are also three types of moves that can be considered - unidirectional, bidirectional, and orphan moves. In the example shown in Figure 7-2, moves 6, 8, 10, 15, 22, 25, 31, 35, and 44 (the last move which cannot have forelinks) are all moves that only have backlinks. Move 1 is the only move that only has forelinks. These two sets of moves are unidirectional - only having links in one direction, while the remaining moves are all bidirectional - having links in both directions. The only exception is move 23 which has no back- or forelinks - referred to as an orphan move. (Goldschmidt, 2014)

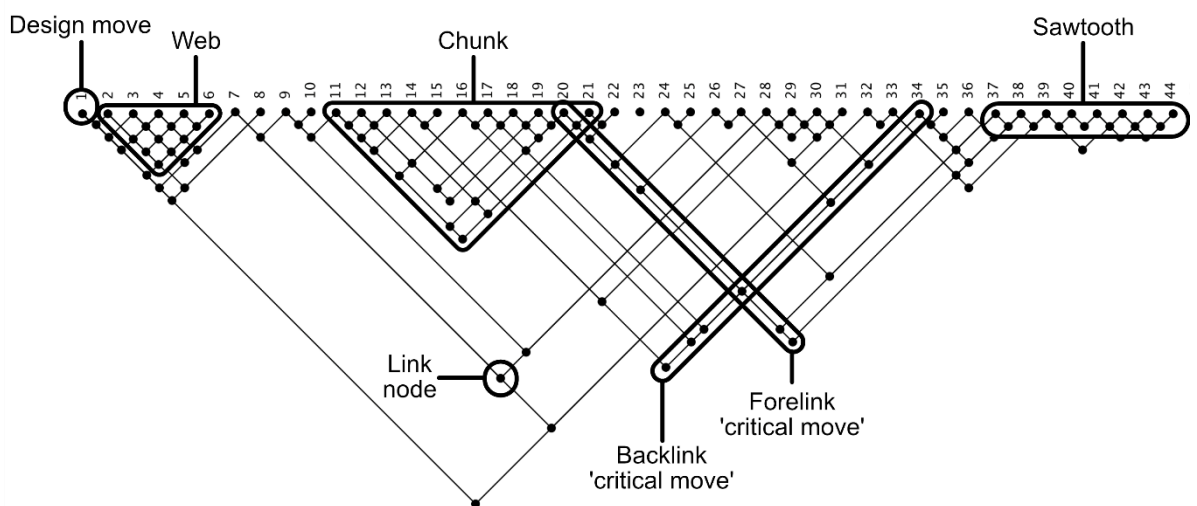


Figure 7-2 - An example linkograph and its components

An imbalance between unidirectional and bidirectional moves can indicate weak and strong aspects of a design segment. Goldschmidt (2014) gives an example where the first half of a design sequence has many unidirectional moves - suggesting little progress, while the second half is dominated by bidirectional moves - suggesting more creativity. The example given in Figure 7-2 shows a reasonably consistent distribution of link directions throughout the design segment with no clear stronger or weaker parts of the process.

A particularly important type of move, which also indicates quality in the design session, is a 'critical move' - a move which generates a large number of links. Critical moves generate roughly twice the average number of link contributions of all moves. Either a large number of forelinks or backlinks can contribute to being a critical move. A high number of forelinks indicates that the move was very influential in the design process and contributed to many future moves while moves with a high number of backlinks indicates synthesis of ideas, evaluation, or that the move was influenced by many previous moves (Goldschmidt, 2014; Hatcher et al., 2018). In the context of this study, such distinctions are useful because they can indicate whether a designer is expanding on early cues (potential fundamental heuristic bias) or repeatedly reinforcing an existing idea (potential fundamental analytic bias), directly aligning with the research questions. (Goldschmidt, 2014)

The balance of forelink critical moves and backlink critical moves also has a significance. A dominance of forelink critical moves suggests advancement of new ideas without bringing them to fruition. That is, that ideas are proposed but not developed, evaluated, or synthesised. A balance of fore- and back-link critical moves indicates a balance of idea generation and evaluation, where each idea is considered and conclusions are drawn before advancing. (Goldschmidt, 2014)

7.3.2 Link patterns in linkography

Linkograph patterns can also be used to analyse a design session. Namely, chunks, webs, and sawtooth tracks. Chunks are graphically distinct triangles within the linkograph that denote a set of successive links that are loosely connected or completely unconnected with other moves. An example chunk is shown in Figure 7-2 between moves 11-21, moves 1-8 could also be considered to be a chunk. Chunks indicate that a designer thinks about problems in a systematic manner while a lack of chunks indicates thinking about a single issue or switching between several issues. Webs are created when a relatively small number of design moves generates a large number of links. These dense groups of links are also graphically depicted by a triangle - shown in moves 2-6 in Figure 7-2. A sawtooth track is another distinguishable pattern whereby each subsequent move links to the preceding one in a sequence - shown between moves 37 and 44 in Figure 7-2. Sawtooth tracks show very linear and narrow

thinking lacking a holistic view of the process. (Goldschmidt, 2014)

Fixation, already identified here as a potential phenomenon of the Type 2 fundamental bias, has been studied through linkography (Kan et al., 2007; Kan & Gero, 2008). In a linkograph, fixation is identified through near saturation of forelinks for a given move, or dense sections where all moves are interconnected such as a web (Kan et al., 2007; Kan & Gero, 2008).

The link index, or the ratio of the number of links generated to the number of moves in a design sequence, is another analysis tool used in linkography. It can be taken as an indicator of the amount of linking activity in a sequence and therefore the designer's effort towards synthesising ideas. However, a high link index is not necessarily indicative of good or creative design. Indeed, a high link index can be due to repetitive exploration of alternative ideas with no continuity between them. While the link index can indicate the productivity of a design session, critical moves can provide more insight. (Goldschmidt, 2014)

Entropy in linkography, founded in Shannon's Information Theory, is a measure of the productivity of design processes by examining the distribution of links (Kan et al., 2007; Kan & Gero, 2008). Forelink entropy captures the concept generation opportunities, with low forelink entropy often indicating limited ideation or potential fixation (Kan et al., 2007; Kan & Gero, 2008). Backlink entropy reflects the enhancements to a move by assessing how it builds on prior ideas, with low backlink entropy occurring in very novel ideas with no backlinks or non-novel ideas with high backlink density (Kan et al., 2007; Kan & Gero, 2008). Horizon link (links along rows parallel to the design moves) entropy accounts for the temporal distance between linked moves, assessing opportunities regarding cohesiveness and incubation of ideas, low horizon link entropy shows very cohesive ideas. Together, these entropy measures provide a picture of the exploration and integration in design sessions. For the purposes of this research, these measures are not only indicators of productivity or creativity but also proxies for the expression of rational thinking dispositions in design. Thus, the linkographic analyses serve as the means of answering RQ4a, RQ4b, and RQ4c.

7.4 Method

7.4.1 Sampling

This study builds on DS I which employed a sample of 23 participants who were undergraduate or integrated master's students studying a product design course with a focus on engineering. This work follows sequential mixed methods sampling whereby the first study informs the sampling used in the second (Cash et al., 2022). A non-probability sample was selected whereby individuals were purposively selected based on characteristics of the population.

The main hypothesis of this first study predicted a linear association between CRT and DCT test scores. The sample for this study would then have been taken from the two extremes: low scores on both tests and high scores on both tests. However, no association was found in the first study. To explore the sample across variables, this study instead selected participants from three points on the distribution: low CRT/low DCT scores (Dyad 1), high CRT/medium DCT scores (Dyad 2), and low CRT/high DCT scores (Dyad 3) (shown in Figure 7-3).

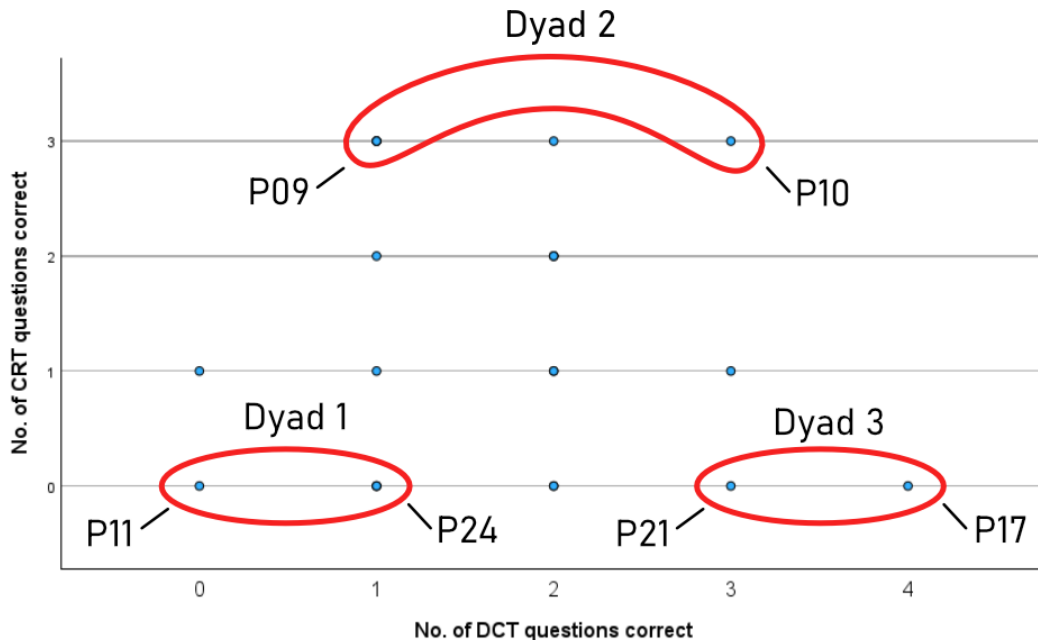


Figure 7-3 - Scatter plot of Cognitive Reflection Test scores by Design Conflict Test scores of 23 participants from DS I and selected participants for DS II

The three dyads together resulted in a total sample size of six. Where there were multiple participants with the same scoring profile in each dyad, participants were selected who had the closest working memory capacity - thus minimising the effects of this variable. The resultant PASAT scores (averaged from the 3 second and 2 second trials) from each dyad were 42, 43.5 (Dyad 1); 52.5, 55 (Dyad 2); and 28.5, 38.5 (Dyad 3). Dyad 2 represents the pairing with the biggest disparity on one of the variables due to the participant closer in DCT score having a PASAT score of 38.5, determined to be too distant from the adjacent participants with 52.5 and 55. Considering the resource intensive nature of protocol analysis and linkography, the median sample size of design protocol analysis studies - six participants (Hay et al., 2017a) - was used.

7.4.2 Procedure

Participants were instructed that they would have 30-minutes to come to a final concept from a given design brief. The think aloud methodology was explained, and participants were instructed to voice all their thoughts while they were designing and try to say as much as possible on their thoughts, actions, and feelings (see Appendix 3). To prepare them for the task, participants were given a warmup task and informed that this was to give them space to familiarise themselves with the think aloud process. The warmup task consisted of a 5-minute creative ideation task where participants were instructed to: *Imagine a planet somewhere in the universe that is very different to Earth. First think about the environment on this planet then generate and draw an animal with attributes that would suit this environment.* Following the warmup, participants were asked if they had any questions before being presented with the 30-minute design task (Section 7.4.3). Participants were informed when they had 15-minutes left, then 5-minutes left. A simple verbal prompt of “keep speaking” was given if participant were silent for more than 30 seconds to remind them of the think aloud instructions with minimal interruption to their process. The 30-minute design task was video and audio recorded, then transcribed using Otter.ai and corrected manually.

7.4.3 Design task

The growth of dual-process theory use in design research has been accompanied by proposals that Type 1 and Type 2 processing are likely used in different ratios at different stages of the design process (Flus & Olechowski, 2023; Gonçalves & Cash, 2021). To gather a more comprehensive view of the design process, the given design task dictated that participants should both: generate multiple ideas (to allow for breadth in concept generation) and select a final concept (to allow for concept evaluation). An open-ended design task was used to allow participants freedom in their process. The design task consisted of a brief adapted from Hay et al. (2019) which was as follows: *Camping is a popular activity but can have negative environmental impacts through disruption to wildlife, litter, and pollution of water sources. Through your own design process, generate multiple ideas and come to a final concept that reduces some, or all, of these negative impacts of camping.*

7.4.4 Creating the linkographs

From the transcriptions, sketches (see Appendix 9), video, and audio recordings of the design tasks, linkographs were created for all 6 participants (see Appendix 10), the process of which is visualised in Figure 7-4. Linkographs are created based on assessing the content of each move by researchers well-acquainted with the discipline and the given design segment (Goldschmidt, 2014). Therefore, two coders were used to improve the validity, both of whom were design researchers familiar with the design episode. Researcher 1 (see Figure 7-4) was the author of this thesis and Researcher 2 was a design researcher of similar research experience who was familiar with the work as a pilot study participant (see Section 6.4). The software used to generate the linkographs was LINKODER (www.linkoder.com) (Pourmohamadi & Gero, 2011).

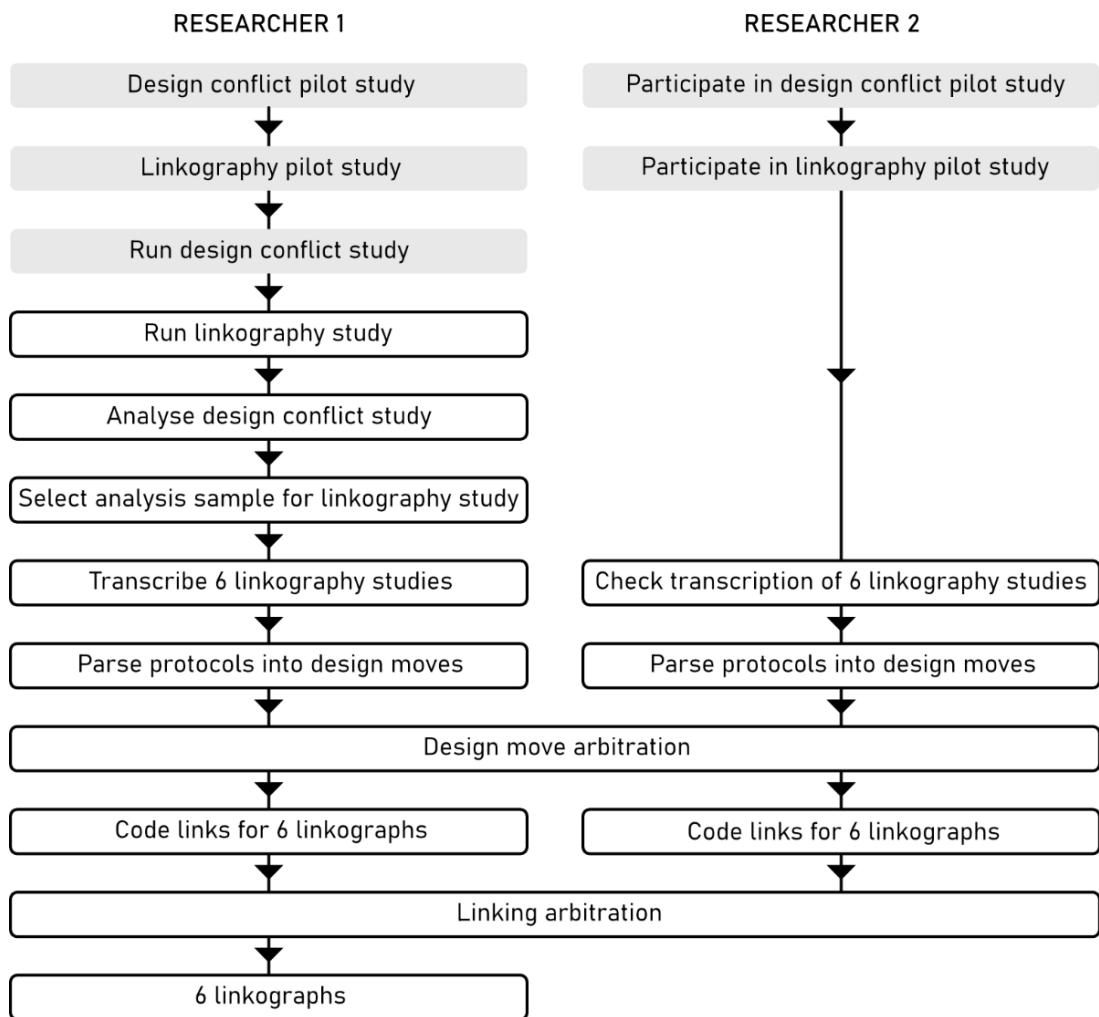


Figure 7-4 - Linkography creation process

To determine the design moves, linkography requires the protocol to be parsed. This parsing was done separately by both researchers. These were compared and instances of disagreement were resolved by each researcher stating their reasons and then coming to a mutual agreement. Links were then determined by both researchers separately on the following criteria taken from Hatcher et al. (2018): participants directly referenced previous ideas; a previous idea was applied in a different context; visible indicators showed the connection of ideas (e.g. gestures); there were similarities in function, behaviour, or structure; and sequential design moves occurred in the same line of thought to develop one idea (van der Lugt, 2000). Following independent coding of links, the researchers addressed areas of disagreement as with the parsing of design moves.

While coding of design moves or segments could be a key direction for developing the use of linkography for dual-process theory design research, this work focused on identifying patterns of links based on rational-thinking disposition and therefore the linkography creation did not include coding categories.

7.5 Results

Six linkographs were created - two for each dyad. Several metrics of the linkographs were analysed and compared (see Section 7.3): critical moves, fixation, link indexes, sawtooth tracks, and entropy. Chunks were not clearly found in many of the linkographs suggesting quite unstructured design processes, this may reflect the limited level of design expertise in the sample. These metrics and results are displayed in Table 7-2 and broken down in the following.

7.5.1 Critical moves

Critical moves (CMs) were set at a threshold yielding roughly 10-12% of the total number of moves in the sequence, as recommended by Goldschmidt (2014). When this threshold could not be reached exactly, a minimum of 8.77% and a maximum of 12.24% were used.

It was thought that participants towards more intuitive rational thinking dispositions could display a greater focus on information pre-consciously cued as relevant - the fundamental heuristic bias. It was supposed that this focus could manifest as a greater focus on thoughts and ideas brought up in the initial stages of the design session (see Section 7.2).

Examining the patterns of CMs across dyads revealed that Dyad 1 (low CRT, low DCT), displayed a difference in critical move distribution. Dyad 1 produced 80-83.3% of CMs in the first half of the design session (see Figure 7-5).

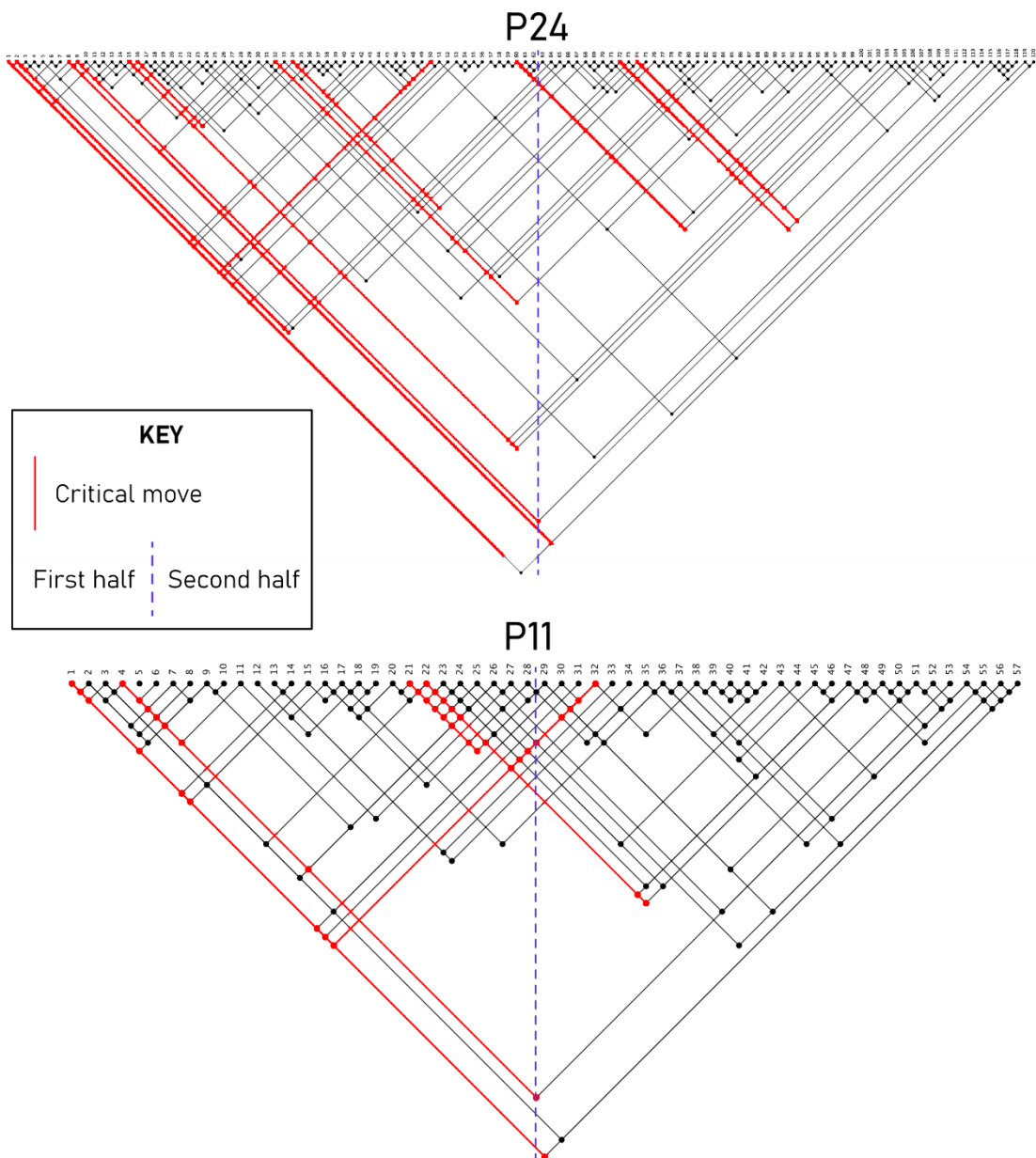


Figure 7-5 - Dyad 1: Critical moves by chronological half of design session

The percentage of CMs in the first half of the design session dropped when looking at Dyad 2 - 60-61.54% of CMs, and Dyad 3 - 40-60% of CMs (see Figure 7-6 and Figure 7-7). This showed potential evidence of this reliance on early thoughts and ideas in the design process. While Dyad 3 scored equally to Dyad 1 on the CRT - their pattern of CMs was different. This could reflect that the Design Conflict Test does indeed differentiate designers on a metric relevant to design performance. Dyad 3 may be displaying greater revisiting and refining of ideas throughout the process rather than prematurely converging on initial ideas.

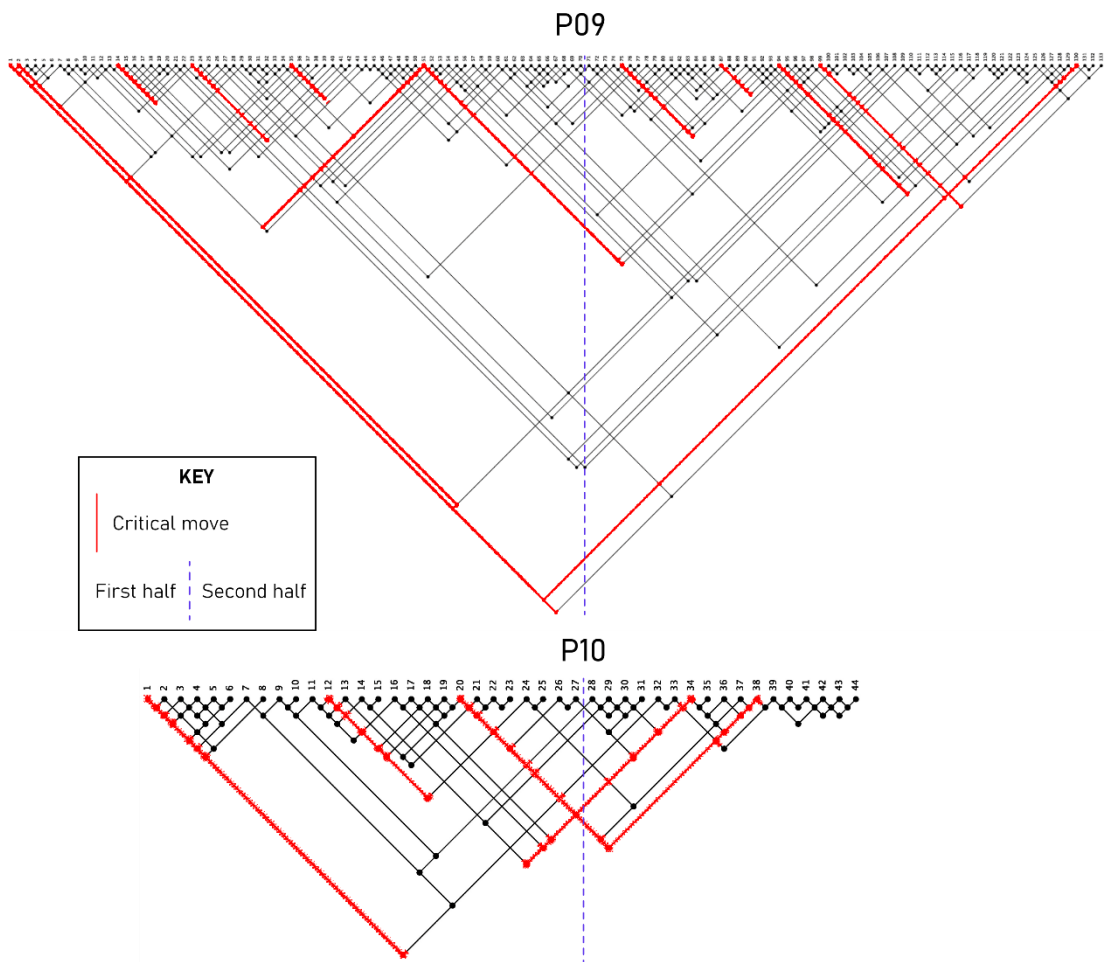


Figure 7-6 - Dyad 2: Critical moves by chronological half of design session

Dyad 3 had lower values of CMs $>$ (critical moves that are forelinks) than any other dyad - 40% compared to 60-83.33% (Dyad 2) and 80-91.67% (Dyad 1). This appears to suggest greater divergent thought as DCT scores lower, and greater convergent thought as DCT scores increase (Goldschmidt, 2014). Furthermore, having balance in the proportion of critical moves that are forelinks or backlinks is tied to expertise (Goldschmidt, 2014). That is, ideas that are generated are pursued and explored rather than wasted. This suggests another potential connection between higher DCT scores and greater design ability.

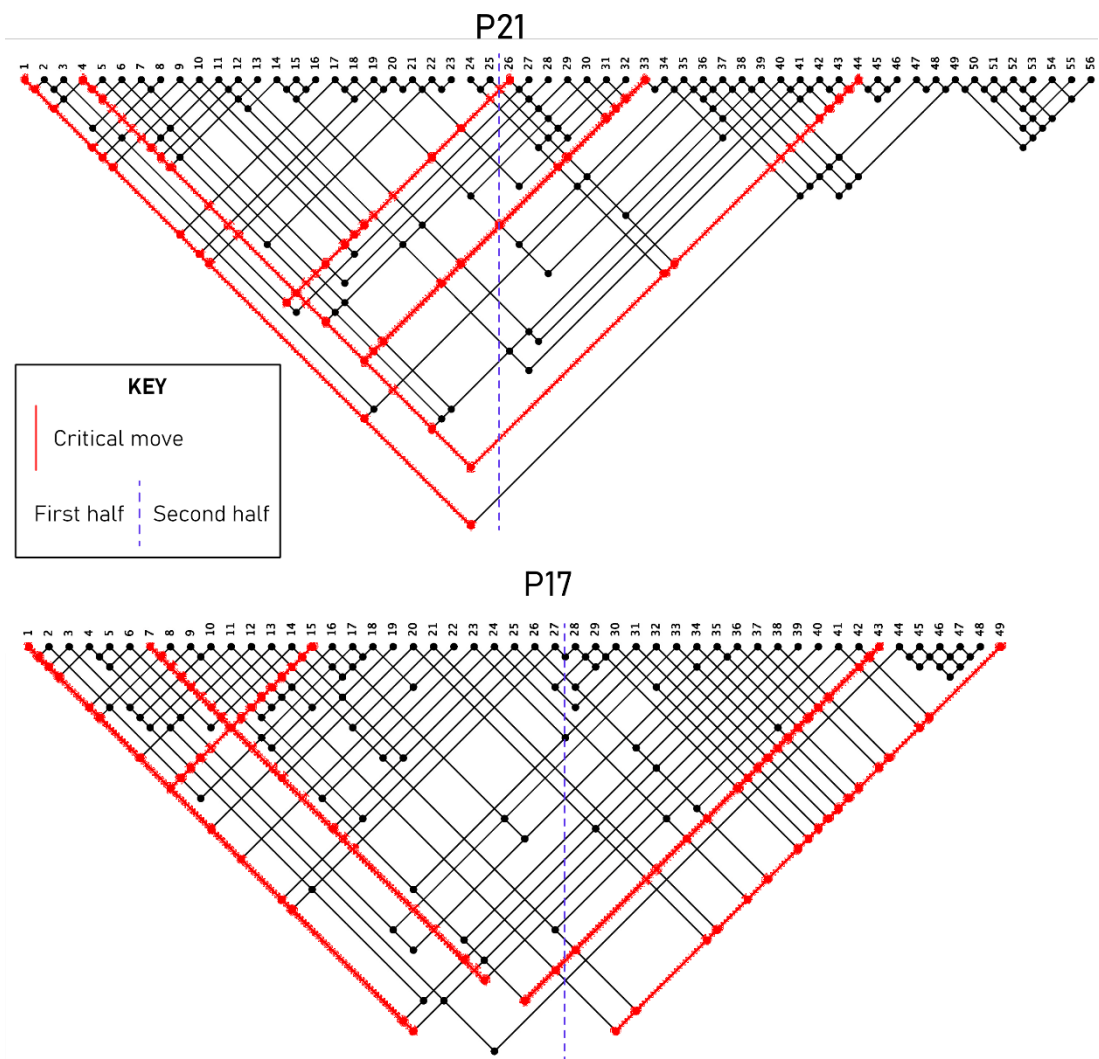


Figure 7-7 - Dyad 3: Critical moves by chronological half of design session

Another difference in CM metrics was the average number of links in CMs. Dyad 3 presented the greatest number of links in CMs taken at the determined ~10-12% of total moves with a range of 9.2-14 links. This dropped to 6-6.85 in Dyad 2, and 6.42-7.8 in Dyad 3. This suggests greater synthesis of ideas in Dyad 3, furthered by Dyad 3 also presenting the greatest percentage of moves in the higher threshold of CMs (5.36-10.20 at a threshold of 10 links).

7.5.2 Fixation

It was proposed that the fundamental analytic bias resembled characteristics of design fixation. In that, the maintenance of the current mental model without considering alternatives could manifest as the illogical adherence specific ideas or restrictions i.e. design fixation. Fixation can be detected in a linkograph by a move with near saturation of forelinks (Kan et al., 2007). In this study, a move that displayed fixation was determined by a threshold of five or more forelinks with a maximum of one gap in the chain of links. This resulted in 0.83-3.51% for Dyad 1, 2.72-3.76% for Dyad 2, and 1.79-2.04% for Dyad 3. Here there are not clear distinctions between the dyads. While Dyad 1 has the lowest amount of fixation, it also has the second highest. Dyad 2 participants both displayed relatively high fixation which could align with the high scores on the CRT but distinctions are not clear.

7.5.3 Productivity

When observing the Link Index (LI) across the three dyads it can be seen that Dyad 3 presents a slightly larger link index, 2.41 - 2.75, than the other two dyads: Dyad 1 with 1.80-2.12 and Dyad 2 with 1.86-2.18 (see Figure 7-8). This greater productivity with the high DCT scores bears an interesting resemblance to the greater density of links in linkographs of expert design sessions compared to novices. This could suggest that the DCT has some capacity in measuring qualities relevant to aptitude in design.

Further insights can be drawn from assessing the differences in LI between the first half and second half of the design session. Greater differences in LI from the first half to the second half can be seen for Dyad 3 (see Figure 7-8). This suggests a greater iterative and evaluative approach to the design session with Dyad 3. Indeed, as the scores in the DCT increase, there is a greater productivity in the second half of the design session. This greater revisiting of ideas in Dyad 3 likely indicates a more cohesive nature to the design sessions.

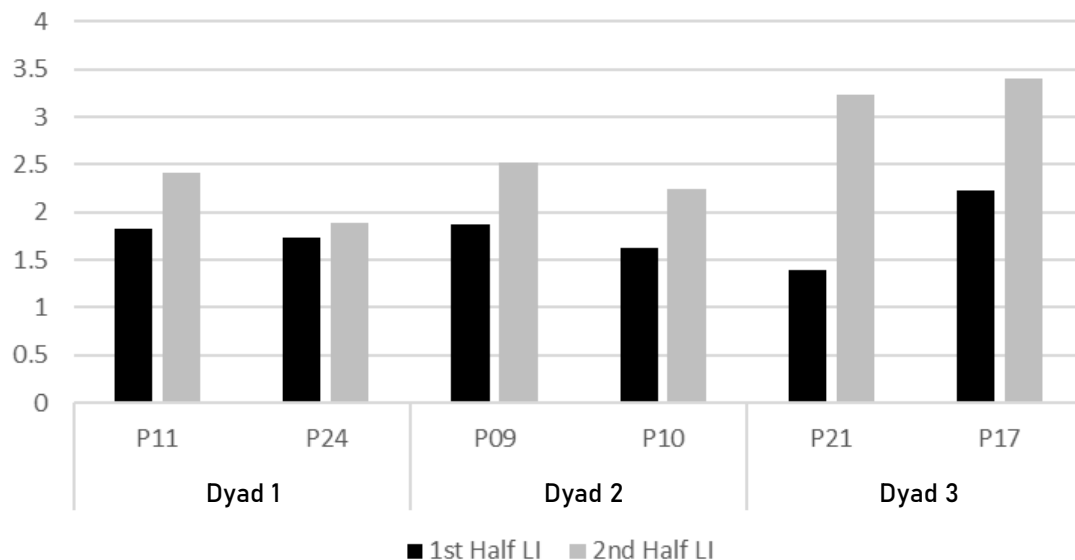


Figure 7-8 - Link Index (LI) in the 1st and 2nd half of the design session

7.5.4 Entropy

This potential greater cohesiveness would be expected to be mirrored in the horizonlink entropy of Dyad 3 - a measure of incubation and cohesiveness. Indeed, it is, with Dyad 3 displaying greater horizonlink entropy - 13.63-17.83, compared to Dyad 1 - 10.61-11.72, and Dyad 2 - 7.64-11.80. In contrast, there were no clear distinctions in the forelink and backlink entropy across the dyads.

7.5.5 Orphan moves

Orphan moves only appeared twice in the sample with one orphan move in both P11 and P24. Greater presence of orphan moves has been connected to a lack of expertise, following the thinking that experts may be better equipped at anticipating the role of moves further into the future, making it easier to avoid such moves (Goldschmidt, 2014). Notably, an orphan move featured in both participants of Dyad 1, suggesting that characteristics of expertise may have some crossover with dual-processing tendencies and ability. While the evidence for this based on orphan moves is minimal, the support of other constructs pointing to Dyad 3 as possessing characteristics associated with better design abilities aid in framing this emerging picture.

7.5.6 Bidirectional moves

Bidirectionality is thought to signify quickly shifting between divergent and convergent thought, with greater proportion of bidirectionality tied to expertise (Goldschmidt, 2014). The percentage of moves in each linkograph that were bidirectional (as opposed to unidirectional or orphan moves), did not vary greatly across participants with the lowest at 70.18% (P11) and the highest at 83.67% (P17). However, following the trend of other analysed metrics there appears to be a correlation with those on the lowest end of the DCT scores (Dyad 1), presenting with the lowest proportion of bidirectional moves (70.18% and 76.67%), and the highest end (Dyad 3) presenting with some of the highest proportion of bidirectional moves (77.79% and 83.67%). This furthers the evidence that characteristics of design expertise may have an overlap with abilities tested by the DCT.

7.5.7 Sawtooth tracks

Sawtooth tracks were also analysed - taken at a threshold of involving 4 moves minimum and represented as a proportion of the total moves involved in a sawtooth track. Contrasting to several of the other metrics assessed, there was a far less distinct differentiation between the dyads. Dyad 1 and Dyad 3 presented with a wide spread of values (35.09% and 56.67% for Dyad 1, and 50% and 18.37% for Dyad 3). Dyad 2 was far closer in range and presented with the two highest values of 61.65% and 59.10% of total moves being involved in a sawtooth track. Considering that sawtooth tracks are indicative of linear thinking where a holistic view is lacking, this could potentially be connected to the logical analysis required to do well in the CRT, with participants in Dyad 2 with the greatest evidence of such linear thinking also presenting with the highest CRT scores. However, considering the diversity in the other groups - all of whom scored low in the CRT, this is a tentative suggestion.

Table 7-2 - Critical Moves, Link Index, Sawtooth tracks, & Entropy of Linkographs (CMs at threshold of ~10-12% of total moves in bold)

		Dyad	Dyad 1		Dyad 2		Dyad 3	
		Participant	P11	P24	P09	P10	P21	P17
CM Threshold	%CM5	21.05	10.00	17.29	11.36	26.79	24.49	
	%CM6	15.79	6.67	9.02	6.82	19.64	20.41	
	%CM7	8.77	4.17	4.51	4.55	8.93	12.24	
	%CM8	7.02	1.67	2.26	-	7.14	12.24	
	%CM9	1.75	0.83	0.75	-	5.36	10.20	
	%CM10	-	0.83	-	-	5.36	10.20	
Forelinks	%CM5	12.28	9.17	12.03	6.82	14.29	14.29	
	%CM6	10.53	5.83	7.52	4.55	8.93	14.29	
	%CM7	7.02	3.33	3.01	4.55	3.57	6.12	
	%CM8	5.26	1.67	1.50	-	3.57	6.12	
	%CM9	1.75	0.83	0.75	-	3.57	4.08	
	%CM10	-	0.83	-	-	3.57	4.08	
Backlinks	%CM5	8.77	0.83	6.01	4.55	12.50	10.20	
	%CM6	5.26	0.83	2.26	2.27	10.71	6.12	
	%CM7	1.75	0.83	1.50	-	5.36	6.12	
	%CM8	1.75	-	0.75	-	3.57	6.12	
	%CM9	-	-	-	-	1.79	6.12	
	%CM10	-	-	-	-	1.79	6.12	
CM% in 1st half		80.00	83.33	61.54	60.00	40.00	60.00	
% of CMs that are CMs>		80.00	91.67	83.33	60.00	40.00	40.00	
Avg. no. of links in CMs		7.8	6.42	6.85	6	9.2	14	
Link Index		2.12	1.80	2.18	1.86	2.41	2.75	
Forelink entropy		20.27	24.17	33.71	18.47	22.35	23.27	
Backlink entropy		22.86	31.63	35.53	18.53	24.99	23.60	
Horizonlink entropy		11.72	10.61	11.80	7.64	13.63	17.83	
% of moves in Sawtooth tracks		35.09	56.67	61.65	59.10	50.00	18.37	
Fixation (% of moves with near forelink saturation)		3.51	0.83	3.76	2.72	1.79	2.04	
% of Bidirectional moves		70.18	76.67	82.71	77.27	77.79	83.67	
Number of orphan moves		1	1	0	0	0	0	

7.6 Discussion

This study built on the work conducted in DS I to investigate the role of intuitive (Type 1) and analytic (Type 2) processing biases in design and how these tendencies might appear within linkography. While many findings of DS I aligned with predictions, the strength DS II findings are limited by the necessity of future changes to the DCT (see Section 6.8). Despite this, clear distinctions emerged from the three Dyads that align well with theoretical implications of DPT. To structure the findings of DS II, each Dyad will be discussed in turn, with some overlap where pertinent. The general theoretical implications of each dyad are presented in the updated sampling figure below (Figure 7-9). Broader insights will be discussed in Chapters 8 and 9.

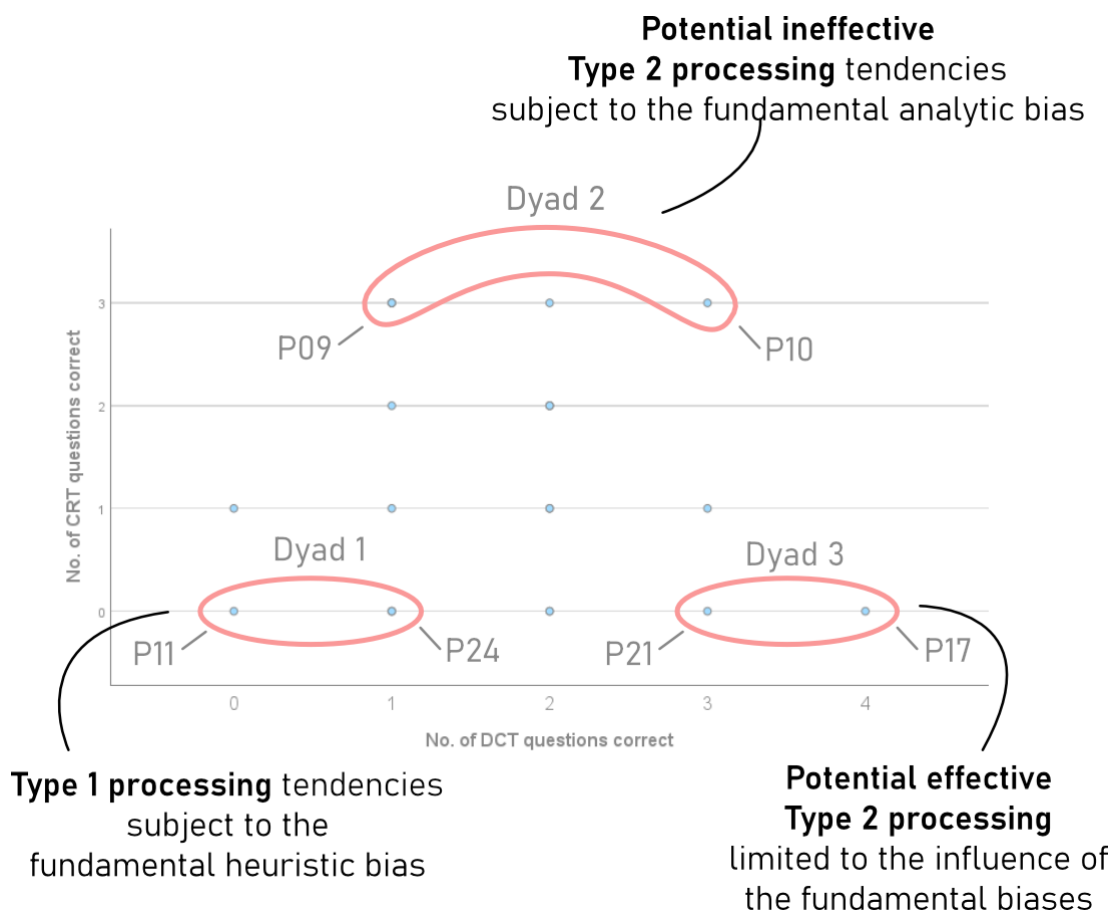


Figure 7-9 - DS II sample selection from plot of DS I CRT scores by DCT and proposed alignment with DPT processing type and biases.

7.6.1 Dyad 1: Dominance of biased Type 1 processing

Dyad 1: Greater ineffective Type 1 processing tendency

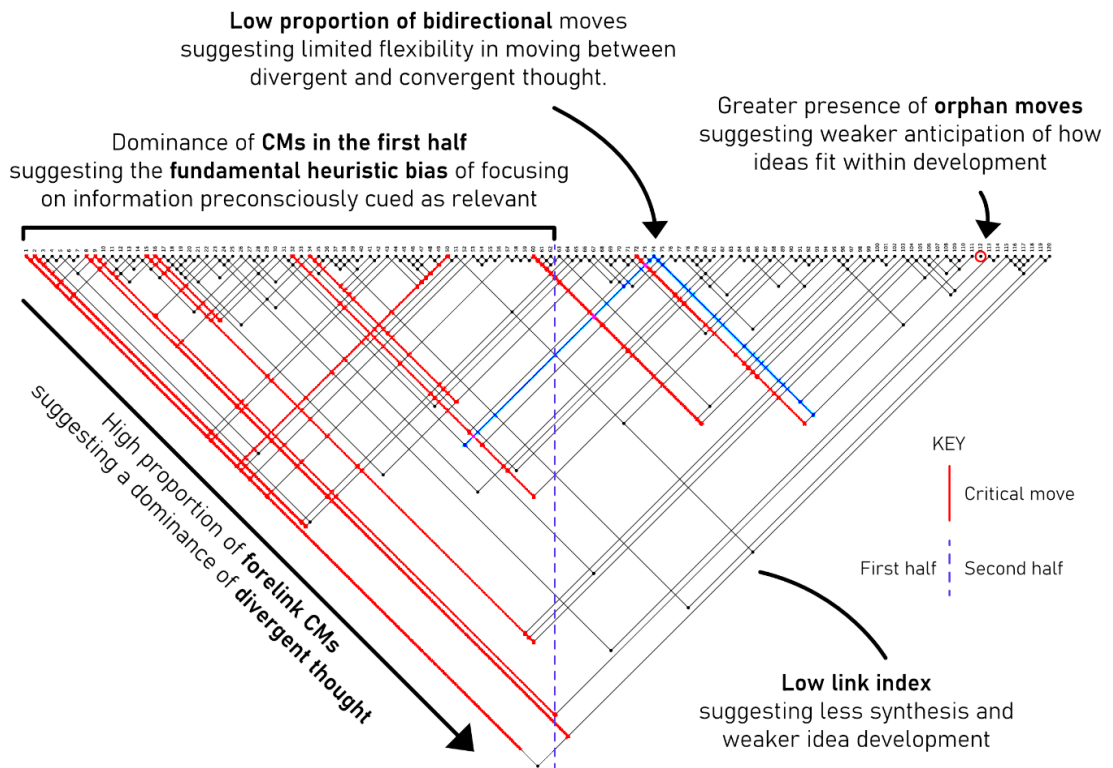


Figure 7-10 - Dyad 1 - proposed features of Type 1 processing tendencies

Dyad 1 consisted of participants with low DCT and CRT scores. This suggests a tendency towards Type 1 processing, with limited capacity in detecting conflict or having the resources to resolve it. This Type 1 processing dominance was validated through several linkography metrics. The dyad exhibited a strong reliance on early-stage ideas, with a higher concentration of critical moves (CMs) in the first half of the design session. This aligns with the fundamental heuristic bias of Type 1 processing, where preconsciously cues dominate thinking. The high proportion of forelink critical moves suggests a greater tendency towards divergent thought, which has also been proposed as overlapping with Type 1 processing. This behaviour is consistent with Type 1 biases and suggests a rapid initial idea exploration but a limited attempt at evaluating or synthesising ideas.

Interestingly, the results showed patterns in Dyad 1 that are consistent with how DPT is considered within the context of expertise (or mindware). Particularly, the findings of Purcell et al. (2020), who found that low experience is associated with greater Type 1 processing or ineffective Type 2 processing, intermediate experience with effective Type 2 processing, and high experience also with Type 1 processing. That is, Dyad 1 presented with Type 1 tendencies that were ineffective at supporting performance in either the CRT or the DCT - suggesting a lack of either ability to perceive conflict - relying instead on intuitive Type 1 responses, or a lack of cognitive resources to override it and reach correct answers (mindware or working memory) to reformulate answers.

The parallel of these findings with expertise may suggest that characteristics learned through practice overlap with the presentation of more effective Type 1 and Type 2 engagement. Indeed, this difference is unlikely to be related to working memory alone with Dyad 1 presenting with less expert-like patterns than Dyad 3 despite both Dyad 1 participants having higher working memory (PASAT scores of 42 and 43.5 in Dyad 1 compared to 28.5 and 38.5 in Dyad 3).

Despite similar expertise levels across participants (see Section 6.5.1), these findings may highlight difficulties in controlling for mindware. Indeed, those in Dyad 3 may well have possessed greater mindware - potentially through greater engagement with university education. This could account for Dyad 3 having the greatest DCT performance despite also having the lowest working memory capacity. Being better educated in knowledge relevant to the DCT may have allowed them to overcome limitations in cognitive ability to answer more effectively in the design context. However, Dyad 3's low CRT score may not have been supported by such mindware that could compensate for cognitive ability and, therefore, produced a weaker performance.

Backing this apparently biased Type 1 tendency in Dyad 1 are several metrics. Dyad 1 was the only dyad to possess orphan moves - typical of a weaker ability in anticipating how design moves fit within the process. Further, the low link index suggests that the initial overreliance on early ideas (potential fundamental heuristic bias) may have led to less synthesis of ideas and ability to apply convergent and

evaluative thinking - considered to overlap with Type 2 processing. This lack of convergent thinking is further seen in Dyad 1 having the lowest proportion of bidirectional moves.

These findings suggest that DPT constructs and theoretical implications can indeed be seen in design - particularly through an approach that connects methods typical of experimental cognitive psychology to more naturalistic design research.

7.6.2 Dyad 2: Dominance of biased Type 2 processing

Dyad 2 (medium DCT, high CRT scores) produced the weakest contrast to the other dyads. Its participants measured consistently in the middle of Dyad 1 and Dyad 3 across the metrics of: proportion of CMs in the first half, proportion of forelink CMs, link index, and proportion of bidirectional moves. While some fixation was observed across all dyads, its presentation differed. It was proposed that fixation may be a manifestation of the Type 2 fundamental analytic bias. Those scoring highly on the CRT are more likely to have a rational thinking disposition towards Type 2 processing. With working memory capacity also playing a role in how likely it would be for a Type 2 response to be given. While Dyad 2 did present with the greatest and third greatest fixation, the second greatest fixation was seen in Dyad 1. This collectively higher fixation in Dyad 2 compared to the other dyads provides some backing for the proposal that the fundamental analytic bias presents as fixation - but greater validation would be needed.

Dyad 2 also presented with the greatest proportion of moves within a sawtooth track - suggesting a stronger tendency towards linear thinking that lacks a holistic perspective on the design process. This could also be a presentation of the fundamental analytic bias. However, with a participant in each of the other dyads nearing similar, but lower, values for this metric as produced in Dyad 2, again this is a tentative proposal that would require further research.

Dyad 2: Greater Type 2 processing tendency

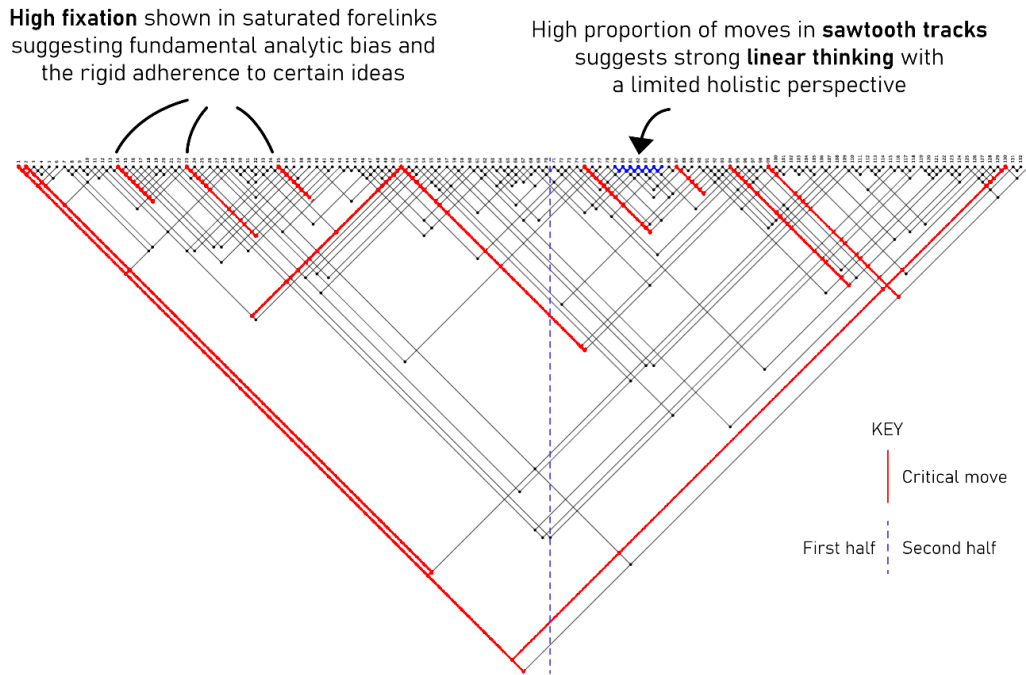


Figure 7-11 - Dyad 2 - proposed features of ineffective Type 2 processing tendencies

While Type 2 processing tendency could explain the scoring profile of Dyad 2, other factors must be considered. Dyad 2 was measured to have the highest working memory capacities across the dyads, with PASAT scores of 52.5 and 55 compared to 42, 43.5 (Dyad 1) and 28.5, 38.5 (Dyad 3). This elevated working memory capacity likely played a role in the successful performances on the CRT - considering it is a measure of both rational thinking disposition and cognitive ability.

7.6.3 Dyad 3: Dominance of effective Type 2 processing and greater metacognitive control

Dyad 3 (low CRT, high DCT) presented with the most well balanced and productive design session. This was seen in the more balanced temporal distribution of CMs (40-60% in the first half). This suggests a greater tendency for iterative refinement and synthesis, evident in the high average number of links in CMs (9.2-14) and the highest percentage of moves at the higher CM thresholds (5.36-10.20%). Furthermore, Dyad 3's higher productivity (LI of 2.41-2.75), particularly in the second half of the session - when participants would conduct much of their evaluation, reflects this more evaluative and iterative design approach. This greater synthesis and productivity of Dyad 3 despite lower working memory capacities, adds to the proposition that the Design Conflict Test (DCT) may capture aspects of a thinking disposition linked to synthesis and evaluation. This aligns with findings that cognitive capacity and thinking dispositions are often weakly correlated (Stanovich, 2011). Indeed, it also suggests that the DCT may provide a measure relevant to designing due to the difference in results between Dyad 1 and Dyad 3 despite scoring the same on the CRT.

Dyad 3: Greater effective Type 2 processing tendency and metacognitive control

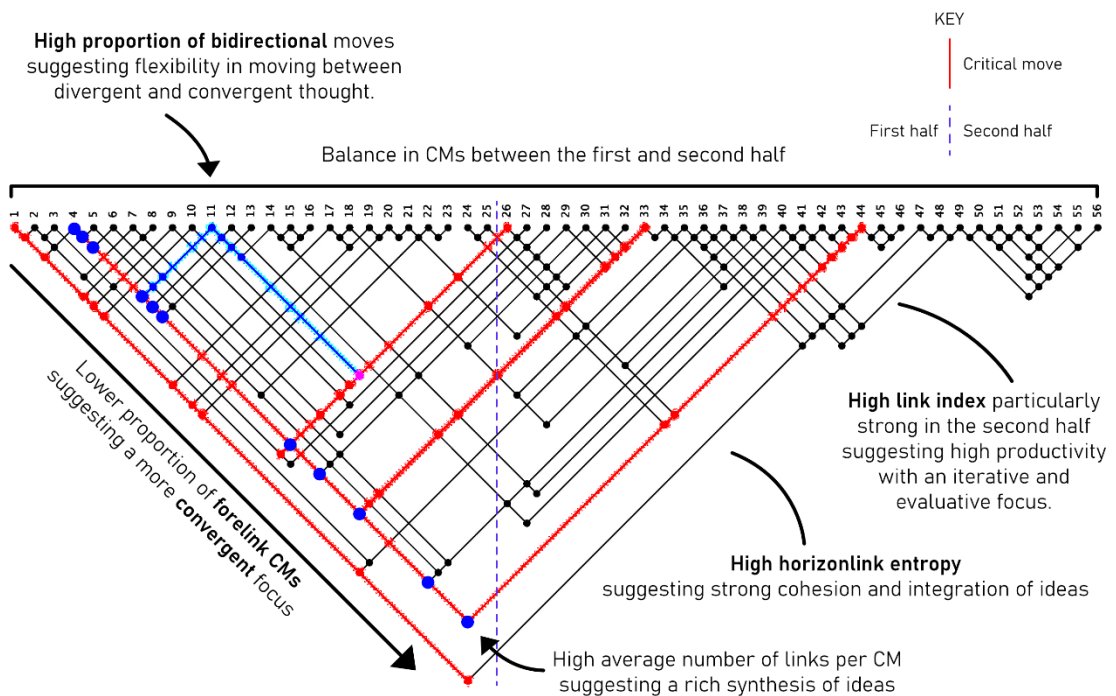


Figure 7-12 - Dyad 3 - proposed features of effective Type 2 processing tendencies

Horizonlink entropy, which reflects incubation and cohesiveness of ideas, was highest for Dyad 3 (13.63-17.83), suggesting that these participants produced more cohesive ideas and had less diversity. This could be a result of the greater synthesis and evaluation displayed in the critical moves analysis. That is, the greater evaluation and synthesis may have limited the exploration of diverse ideas.

Considering the balance, limited fixation, and productivity of the Dyad 3 session, this picture may suggest that participants in Dyad 3 were not as susceptible to the biases of Type 1 or Type 2 processing. We can consider how this profile of extremes (one low - CRT, and one high - DCT) relates to Type 1 and Type 2 processing.

The low performance on the CRT may suggest a tendency towards Type 1 processing. However, the high performance on the DCT presents an interesting case. Indeed, if success in the DCT is reliant, in part, on a higher thinking disposition relevant to design - a disposition towards Type 2 processing could well produce such a scoring profile with low CRT and high DCT. Through having less expertise in mathematical reasoning, a Type 2 processing tendency could lead to low CRT scores via a lack of cognitive resources (working memory or mindware) to reach the correct answer. As a parallel, the increased mindware available for design tasks could produce the high performance on the DCT. This follows considering the lowest capacities for working memory found in Dyad 3 paired with a greater reliance on mindware based on the domain relevance of the DCT.

Indeed, Dyad 2 with significantly higher working memory capacity likely used their higher cognitive capacity to bolster performance in the tests, while Dyad 3 could have relied on mindware to support performance. This would also support the proposal of the presentation of Type 2 analytic bias in that mindware (understanding of the design process, techniques, tendency to apply methods) could lead to less bias. While a reliance on working memory (Dyad 2) may not benefit from the explicit application of design process knowledge - leading to greater fundamental analytic bias. Thus, it could be the case that Dyad 2 presents with ineffective (or more biased) Type 2 processing tendencies, while Dyad 3 presents with effective (or less biased) Type 2 processing tendencies.

Further, Purcell et al.'s (2020) findings regarding expertise could support this. That is, that those with intermediate experience present with effective Type 2 processing. The expertise level of this sample - 4th and 5th year undergraduates - could fit within this 'intermediate' range. That is, Dyad 1 presented with Type 1 tendencies that were ineffective at supporting performance in either the CRT or the DCT - suggesting a lack of either ability to perceive conflict - relying instead on intuitive Type 1 responses, or a lack of ability to overcome it and reach correct answers - suggesting a lack of resources (e.g. mindware or working memory) to reformulate answers. This profile likely limited the engagement of Type 2 processing and the effect of expertise to generate effective Type 2 processing. In contrast, Dyad 3 may have harnessed this effective Type 2 processing through greater Type 2 processing tendency and application of mindware. However, Dyad 2 may have relied instead on cognitive capacity with a Type 2 processing tendency - also limiting the effect of expertise in generating effective Type 2 processing.

Higher levels of mindware also affects conflict detection and feelings of rightness (Stanovich, 2018). That is, that mindware learned to automaticity will be brought up early in the reasoning process leading to a greater likelihood of detecting conflict. In turn, conflict detection would lower the perceived feeling of rightness. For example, a logical Type 1 response generated from mindware learned to automaticity may accompany the intuitive Type 1 response. These two conflicting responses may well trigger a lower feeling of rightness and therefore be more likely to trigger greater Type 2 engagement. (Stanovich, 2018). Again, if Dyad 3 had a greater reliance on mindware, this could add to the explanation of the high DCT performance with the low CRT performance.

Indeed, this is somewhat reflected when considering the FORs across the dyads. Average feeling of rightness for Dyad 1 was the highest collectively across DCT items (P24: 77, P11: 66). Following these high FORs, it would be less likely that conflict was detected and, therefore, heuristic intuitives response was given. Dyad 2 presented with middle values of FOR (P10: 65, P9: 68) and Dyad 3 with the lowest collective average FORs (P21:67, P17:48)(FORs averaged across the DCT items answered correctly or heuristically). This, within the context of other metrics, shows support for

lower FOR indicating greater conflict sensitivity and rechecking, which can support correctness. This points to aspects of metacognitive reflection and control. That is, those with greater abilities in metacognitive reflection and regulation may detect conflict more regularly and set levels of critical effort (see the Intervention Model, Section 5.3) such that Type 2 processing is more engaged in resolving this conflict. While the sample size of DS II is too small to run statistical analysis on any values presented here, this again suggests a trend in alignment with DPT implications. The metacognitive implications of this work are discussed further in Chapter 8 (see Section 8.2.2).

7.7 Summary

Taken together, the dyad findings suggest that dual-process theory (DPT) has explanatory potential within design cognition research. Dyad 1's reliance on Type 1 processing aligns with divergent exploration but lacks evaluation and synthesis. Dyad 3, in contrast, displayed a more balanced approach across divergent and convergent thinking while scoring low on the CRT and high on the DCT which likely represents greater metacognitive control and a Type 2 processing tendency, potentially made effective by a better use of mindware. Dyad 2's metrics often landed in the middle of Dyad 1 and Dyad 3 which may suggest a Type 2 processing tendency that was less effective in the DCT due to a greater reliance on cognitive capacity than mindware.

The insights presented here are particularly interesting considering that most differences between the dyads were along the DCT scoring spectrum (Dyad 1 to Dyad 2 to Dyad 3), rather than the CRT scoring spectrum (Dyads 1 and 3 to Dyad 2). The significance of these findings lies less in the strength of statistical generalisation and more in demonstrating that design-specific dual-processing tendencies can be meaningfully linked to observable design behaviour.

The written reasoning tasks used in DPT psychometric tests such as the CRT contrast to the visual processing required for the DCT. The DCT as an attempt to measure thinking disposition in a representation more relevant to design may provide more insight into individual differences in design behaviour regarding dual-process theory. The sample for DS I consisted of 23 participants, and DS II of 6 participants, which limits generalisability and the strength of claims. Therefore, further refinement of the DCT alongside greater sample sizes across such experimental design will be needed to verify the findings of this work. However, this work was framed as an exploratory theory-building study - and as such, has provided some key advancements and insights for both the workings of DPT in design and methodology for investigating design through DPT.

How the findings of DS I and DS II can be expanded to wider implications for impact across design researchers, design research methods, future work, and design itself including process, methodology, and tools is discussed in the following chapter.

PART 3:
REFLECTIONS

8 DISCUSSION

This discussion brings together and develops the insights of this thesis as a whole. While much has already been discussed in the respective discussion sections of DS I and DS II, the motivation of this research is revisited to structure broader discussion. That is, the three persistent challenges in the field identified in Part 1 of the thesis:

- Lack of ontological and methodological alignment driving the need to connect design cognition more firmly to established cognitive psychology.
- Absence of suitable tests and metrics for studying design cognition driving the need for reliable, design-specific instruments for studying individual cognitive differences.
- Lack of combination of quantitative and qualitative methods in design cognition research driving the need for method development to be well-suited for the integration of methods.

This chapter discusses how the work reported here responds to those challenges and advances design cognition research. It highlights the theoretical and methodological developments of dual-process theory in design cognition research from this thesis and their implications for design research, practice and education.

8.1 Synthesis of Core Findings

Together, Descriptive Study I (DS I) and Descriptive Study II (DS II) provide a more detailed picture of how intuitive (Type 1) and analytic (Type 2) cognitive processes manifest in design cognition, adding both new insights to existing work and validating previous propositions. While DS I focused on the measurement of design-related dual-processing tendencies through the development of the Design Conflict Test (DCT), DS II examined how these tendencies are expressed in observable design behaviour through linkographic analysis. Taken together, the studies reveal the promise and complexity of applying dual-process theory (DPT) to design cognition.

While DS I results were not aligned with all hypotheses, the eye-tracking metrics, measured feelings-of-rightness, and independence from working memory all suggested that the test did result in the engagement of both intuitive and reflective processing - as targeted in heuristics and biases tasks. This offers preliminary evidence that the DCT can elicit cognitive conflict between intuitive and analytic reasoning in design contexts. The predicted correlation between DCT and the CRT did not emerge. This lack of a linear association implies that the DCT may access design-specific reasoning tendencies not captured by the CRT which could reflect how designers balance domain knowledge, visual reasoning, and problem ambiguity over the purer logical reflection targeted in the CRT.

DS II explored this possibility directly. By observing designers positioned at different points in the DCT \times CRT space, it demonstrated that dual-process tendencies are visible in conceptual design process. Indeed, several expected patterns of Type 1 or Type 2 reliance were seen. Participants with lower DCT scores displayed patterns consistent with fundamental heuristic bias. That is, early fixation on pre-cued ideas and limited synthesis. Those with high DCT scores, by contrast, exhibited more balanced and iterative behaviour, characterised by greater link density, bidirectionality, horizon-link entropy all of which are indicators of more synthesised and cohesive design reasoning. The high CRT scoring profile also showed some evidence of fundamental analytic bias, reflected in the fixation and sawtooth patterns being among the highest presented.

The fact that despite unpredicted results in DS I, expected patterns still emerged in the smaller sample of DS II is itself an exciting step towards understanding design through a DPT lens. One of the main questions arising from this is why this was the case? Answered in the DS II discussion, several options were presented that widen the discussion within the field and highlighted several opportunities for future work and developing our understanding of how dual-processing plays its role in design.

Ultimately, DS I established that cognitive conflict relevant to design can be experimentally induced and measured. While the DCT as a metric requires refinement to be most effective, it points this aspect of the field's development in an exciting and promising direction. DS I is a significant step towards addressing the question of whether a psychometric instrument can capture design-relevant individual differences in dual-processing tendencies. Building on this, DS II showed how those individual differences can be connected to behaviour through more qualitative methods - strengthening our understanding of how they shape actual design activity. Together, they show that dual-process constructs can be both operationalised and observed within design contexts, a step towards bridging the gap between laboratory-style cognitive research and more naturalistic studies of designing.

8.2 Theoretical development of DPT in design cognition research

This thesis advances theoretical understanding of design cognition by interpreting design activity through the lens of dual-process theory (DPT). This work aimed to strengthen our understanding of design cognition by building from well-established cognitive psychology knowledge. Namely, the default interventionist account presented in the Intervention Model of DPT (see section 5.3). The details regarding the development in our understanding of design and DPT from the experimental work presented in this thesis are discussed in DS II (Sections 11.1-11.3). Here, a broader summary is given and contextualised within design cognition literature before identifying three key areas of theoretical development.

Existing DPT research in design cognition has determined that Type 1 processing

is typically relied upon in generative, divergent contexts while Type 2 processing dominates evaluative, convergent phases (Cash & Maier, 2021; Gonçalves & Cash, 2021; Moore et al., 2014; Vieira et al., 2022). However, while these tendencies have been identified, there is an acknowledgement that both processing modes contribute to generative and evaluative phases of design (Cash & Maier, 2021; Gonçalves & Cash, 2021; Moore et al., 2016). This work extends this understanding by introducing a nuanced account of individual differences in dual-processing and showing how this might translate into design behaviour. Through this emphasis on individual differences, we can begin to understand in greater depth, and identify with greater certainty, the patterns, roles, and tendencies in dual-processing that present across different design activities.

Working towards this greater depth of understanding, this has shown that, given opportunities for both idea generation and evaluation, the designers analysed in DS II presented with three different profiles of how Type 1 and Type 2 processing shaped their design process. Some displayed strong reliance on early intuitive cues, some more narrowed analytic processing, and others a more even balance across the session. These results reinforce that both processing modes operate within each phase of design, as noted in previous research (Cash & Maier, 2021; Gonçalves & Cash, 2021), but further show that the way designers coordinate these modes is an individual-difference with behavioural consequences. Therefore, rather than treating design activities as dominantly intuitive or analytic, these results suggest that designers bring different dual-process tendencies to the same activity - and that these tendencies shape the resulting process.

Exploring these tendencies, the theoretical advancements presented in this thesis centre on three aspects: the mechanism that creates conflict, the processes that regulate responses to conflict, and the behavioural manifestations of biases arising from these processes. That is, FBS conflict theory as a theoretical development in design cognition, metacognitive processing in design through a DPT lens, and the fundamental biases of DPT in design.

8.2.1 FBS Conflict Theory as a theoretical development in design cognition

A key theoretical outcome of this research is the FBS Conflict Theory proposed in Part 1: Theory Development, and tested in Part 2: Theory Evaluation. This proposed mechanism builds on the FBS framework (Gero & Kannengiesser, 2014) and posits that a trigger of cognitive conflict in design occurs when perceiving the function, behaviour, and structure of a concept and an intuitive interpretation contrasts to an analytic interpretation, or when two competing intuitive interpretations arise. The Design Conflict Test (DCT) operationalised this idea, revealing that such conflict can be induced and measured in a design-specific context. The independence of DCT performance from working-memory capacity, together with eye-tracking evidence of alternating attention between intuitive lure and analytic correct options, aligned with the view that design reasoning follows the default-interventionist account: intuitive defaults are produced automatically, potential conflict is detected, and intervention is optional rather than guaranteed.

The absence of a linear correlation between DCT and CRT performance may suggest that the reasoning in design, even when broken down to tasks in the DCT, differs from that in abstract reasoning tasks. While the CRT elicits conflict between intuitive heuristics and analytic reflection over decontextualised, domain-general problems, FBS conflict requires reasoning about the causal and functional behaviour of artefacts. This reasoning is situated and representational, drawing on visual reasoning, and physical knowledge, to retrieve the propositional logic. The propositions in a visual image are behaviour, and structure, and also inferred function if interpreting a familiar form. This requires different cognitive processing than clearly written text e.g. function being given as the object name in written text in the DCT. Consequently, effective intervention of Type 2 processing depends not only on cognitive capacity (see the Intervention Model) but also on a designer's ability to move from visually processing the image as a whole, to effortfully breaking it down into components, analysing the engineering of these components (through domain knowledge), and determining if it would function satisfactorily.

Assessing the role of this visual reasoning ability regarding FBS conflict could be an important avenue for future development. Additionally, FBS conflict theory was

developed a priori - aligned with the deductive logic used in the design of traditional reasoning tasks which may not translate to a posteriori knowledge. FBS conflict, as operationalised in the DCT, did elicit some of the expected response from DPT conflict mechanisms in DS I. However, this a priori approach may need further validation in more naturalistic design observation to determine if FBS conflict, and other potential sources of cognitive conflict, can be directly observed in design behaviour.

While FBS conflict captures conflict arising from a mismatch between perceived function, behaviour, and structure, there are other potential routes through which analytic thought may be engaged in design. Other triggers could include representational conflict - when an evolving sketch or model contradicts expectations. For example, a designer sketches an idea, and the drawing materialises in an unintentional or unexpected way. This could well trigger conflict that relates to Schön's (1983) concepts of reflection-in-action and reflection-on-action. Further conflicts could even arise from other constructs in the FBS framework. For example, design requirements and design descriptions are the key input and output of the framework, respectively (Gero, 1990). As such, one can see how cognitive conflict could arise from other mismatches e.g. requirements → function, or, behaviour → design description. Conflict could additionally involve constraint violation (when proposed solutions exceed material or functional limits), or different metacognitive reflections.

In this work, feeling of rightness was featured as a key metacognitive variable in dual-processing and as an indicator of potential conflict (De Neys, 2012; Thompson & Johnson, 2014). Other metacognitive variables could also play a role in Type 2 engagement. Beyond uncertainty in a design concept - like that measured through FOR in the DCT, general uncertainty regarding gaps in understanding or ambiguous outcomes could trigger Type 2 intervention. Progress monitoring could be another metacognitive trigger, perhaps through a feeling of progress or the perception that your actions no longer serve the intended function. In this way, FBS conflict extends the default-interventionist account by identifying a design-specific form of cognitive conflict. Here, it is proposed that this could be situated within a broader understanding of perceptual and metacognitive triggers that may govern dual-processing in design.

8.2.2 Metacognition in design

While FBS conflict was proposed as a mechanism of Type 2 engagement in design, how this conflict is regulated was also considered. The differing scoring and linkographic patterns between the three dyads depend on the ability to both engage Type 2 processing and apply it effectively. Metacognition involves the ability to redirect attention, increase the effort of engagement with a task, and convene the required cognitive processes required for Type 2 engagement with a task (Thompson, 2009); otherwise termed as Type 3 processes by Evans (2019)(see section 4.3.1.1). Indeed, much of the DS II discussion centres on metacognitive reflection and control (e.g. thinking dispositions and feelings of rightness). The initiation of more effortful reasoning is itself a function of metacognitive control. That is, the ability to monitor the quality or confidence of an intuitive response and to determine when further reflection is needed.

The differences observed across dyads in DS II reflect variation in the sensitivity and calibration of metacognition. Dyad 1's reliance on early cues and limited intervention following intuitive responses may indicate weak metacognitive monitoring through either a failure to detect conflict or a low threshold for accepting intuitive solutions. Dyad 2's more linear analytic reasoning may reflect strong engagement of Type 2 processes but insufficient metacognitive oversight to redirect or modulate them. By contrast, Dyad 3's balance between exploration and evaluation appears to demonstrate better metacognitive control as it relates to the design process.

In this, it can be seen that metacognitive cues serve as internal feedback that inform whether continued intuitive processing will suffice or whether additional analytic thought is needed. This system operates largely unconsciously, managing attentional shifts and effort allocation in response to perceived conflict or doubt. From this perspective, metacognitive regulation and control become differentiating factors in design performance. That is, the ability to detect when an intuitive idea feels wrong (Thompson, 2009) and to engage analytic reasoning in response, or the ability to sense it is time to move on in the design process and redirect attention (potentially to more evaluative, analytic thought). Conversely, the inability to sense or act on such reflections can result in fixation or premature convergence. Through this, and

particularly the DPT lens, researching metacognition can be seen as a critical lane in the road to understanding design cognition. Indeed, integrating findings from existing work on metacognitive variables such as uncertainty (Ball & Christensen, 2019; Cash & Kreye, 2018), provides another foundation for future DPT design cognition research.

Design presents a particularly interesting case for investigating these metacognitive processes. The act of designing involves multiple stages - problem framing, concept generation, evaluation, development - each characterised by different levels and sources of uncertainty and ambiguity. Within these transitions, designers must judge when to trust intuition, when to reflect analytically, and when to reframe or redirect their approach. These are metacognitive processes that integrate perception, action, and domain knowledge to coordinate the engagement of different reasoning modes.

To illustrate this further, Dyad 3 can be considered in relation to other constructs of duality in design. Dyad 3 presented with a more even balance between divergent and convergent thought, greater productivity, and stronger integration and synthesis of ideas. This work provides initial evidence for greater ability in switching between Type 1 and Type 2 processing being aligned with traits of more expert-like designing. This resonates with expertise in switching between concepts of bidirectionality - the oscillation between divergent and convergent thought (Goldschmidt, 2014), the co-evolution of problem and solution (Maher & Tang, 2003), and ideas of reflection-in-action and reflection-on-action (Schön, 1983). Here, the concept of dual-processing and other dualities in design are not being equated, rather, that the capacity to switch these dualities may link to a metacognitive ability in regulation and control of Type 1 and Type 2 processing. While Dyad 3 had no more expertise than the other dyads, their design process reflected more expert like patterns - indicating that this switching ability of dual-processing may also be more honed in experts. In this light, metacognitive processes detect the need to reassess a move and initiate analytic reasoning to either redirect or deepen thought, thus integrating design theory constructs within a dual-process framework.

This discussion of metacognitive ability can be abstracted from the dyads to propose that high DCT profiles may produce more balanced, productive, and synthesised design outputs which could be explained through greater metacognitive reflection and control between Type 1 and Type 2 processing (see Figure 8-1). Particularly taken within the context of lesser cognitive ability (seen in Dyad 3), this adds to the idea that regulation can be resource-efficient. While metacognitive control has been shown to depend on working-memory resources (Coutinho et al., 2015), Dyad 3's effective regulation despite lower capacity indicates that domain-specific strategies or heuristic shortcuts that reduce cognitive load could have been used. Indeed, this links to experience, whereby designers are able to internalise patterns of when analytic checking is required, suggesting that metacognitive sensitivity - more than cognitive capacity - may be a mark of expertly design.

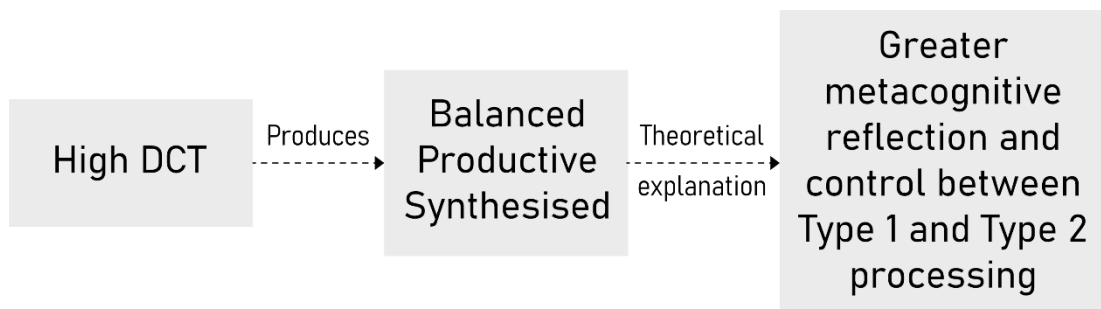


Figure 8-1 - A proposed link between the DCT performance and expert-like designing.

8.2.3 Fundamental biases in design cognition

The discussed mechanism and regulation of dual-processing conflict in design was also linked in DS II to behavioural consequences. By applying Evans's (2011) fundamental heuristic and fundamental analytic biases to design, this work has reframed fixation and early convergence as potential expressions of underlying cognitive biases that can be explained through the DPT lens. While further research is required to validate these proposals more strongly, this work provides initial evidence and a focus for future work in the field. The fundamental heuristic bias offers an explanation for rapid commitment to early ideas signalled as relevant by intuition.

Contrastingly, the fundamental analytic bias offers an explanation for adherence to a current concept through insufficient consideration of alternatives. Framing these behaviours as biases inherent to dual-processing allows dominant preconscious cues and fixation to be conceptualised not as outcomes of cognitive architecture which can be managed through sufficient metacognitive regulation and control in redirecting attention. This reconceptualisation contributes to the psychological grounding of design creativity and iteration and further informs future works.

Indeed, both biases were observed in DS II across the different dyads to some extent. The evidence for the fundamental heuristic bias presenting in this manner was, however, stronger. Despite this, the tentative evidence for the expression of the fundamental analytic bias in design offers direction for future work and advancing theory on concepts such as fixation. Indeed, the link between fixation and Type 2 processing can be deepened through existing theory. One of the frequent uses of Type 2 processing regards justification being sought for an initial intuition and that intuition, therefore, being rationalised (Wason & Evans, 1974) (see section 4.3.1.2). This rationalising function is a mechanism of the fundamental analytic bias (Evans, 2020) that has been tied here to the concept of fixation. How this rationalisation appears in design is yet to be researched; however, the idea that the maintenance of an intuitive response can be supported by Type 2 rationalisation (even if incorrect or unsatisfactory) furthers insights drawn in the DS II discussion. Fixation itself has been defined as an illogical adherence to a perceived set of ideas or limitations - this illogical adherence may well be explained through the rationalising function of Type 2 processing. If designers feel drawn to continuing a particular idea, this desire to persist with the concept may well lend itself to illogical justification that it is an idea worth pursuing. This presents a promising path for future design research building on a DPT foundation particularly for fixation.

8.3 Methodological development of DPT in design cognition research

The theoretical development resulting from this work requires strengthening beyond the initial cycle of theory building and testing, such that further ‘spirals’ of this cycle are carried out and the scientific knowledge is strengthened (Cash, 2018, 2020). While the theoretical insights from this work need this future iteration, the methodological development is this work’s strength. This thesis stands with direct insight to give guidance to similar research in design cognition and, potentially, beyond. Methodologically, this work develops the landscape of design cognition research by addressing several of the challenges identified throughout this thesis. Specifically, it advances calls to diversify methods beyond traditional qualitative approaches, like protocol analysis, and to establish stronger links between cognitive theory and empirical design observation.

This work exemplifies construct and theory mapping between psychology and design cognition. By operationalising DPT constructs within an empirical design context, it contributes to the broader methodological challenge of aligning design cognition constructs with established psychological frameworks. This responds to the need for clearer mapping and comparability of constructs and the adoption of theoretical models from cognitive psychology.

The lack of methods suitable to accounting for the complex, contextual, and temporal aspects central to designing has also been identified as a key area for future work in design cognition research. Hay et al. (2020) discussed methodological moves towards accounting for these aspects that centred on developing a deeper and more detailed understanding of design cognition as it proceeds naturally. That is, in real-world design scenarios rather than controlled, time-bound, experimental lab setups. This thesis relies heavily on experimental lab research. However, this does not contradict such initiatives for design cognition research. Rather, it presents an avenue towards it - that of developing and testing theories in the lab, where factors can be closely controlled and monitored such that the theories can be subsequently validated in real-world contexts with greater ecological validity. Indeed, the approach taken in this work of focusing on individual differences may provide a powerful foundation of

knowledge from future work through which to examine teams - through the interactions of different individual characteristics.

This work has targeted critiques of design research regarding focusing on description and neglecting theory testing and refinement. While, theory development and testing support impact, they also present challenges that must be supported by methodological rigour. The work of this thesis presents an example of how these challenges might be tackled through developing cognitively informed theory and methods. In this section, the developments regarding our understanding of challenges and considerations for psychometric testing in design, evaluation of the DCT as a prototype psychometric test for design, and connecting dual-process theory constructs to linkography are discussed.

8.3.1 The DCT as an example of challenges and considerations for psychometric testing in design research

The beginnings of this thesis discussed the methods and constructs used in design cognition research (see Chapter 3). In this, it was found that mixed methods are increasingly being used in design cognition research. However, methodological development of tests and metrics to advance quantitative measures in design cognition as a field has been limited. This was identified as one of the key challenges to be tackled in this work (see Section 1.1.1). To address this, DS I presented a novel test - the Design Conflict Test - with significant promise for providing more direct insights into design cognition. Additionally, it acts as an example of how, as a field, we may begin to construct such tests and measures.

This demonstration of how psychometric principles can be adapted to design cognition context provides constructive guidance on considerations, challenges, and direction for the field. Indeed, the performance on cognitive reflection (CRT) and working memory capacity (PASAT) presented less behavioural variation in DS II than design conflict resolution ability (DCT) which suggests that tailoring tests to design contexts is a valuable approach. As such, transferring psychometric formats into design may not be a matter of simple adaptation. Conventional reasoning tests, such as the Cognitive Reflection Test (CRT), rely on abstract, deductive, decontextualised scenarios. In contrast, design cognition is inherently situated: it involves visual

reasoning, knowledge of physical principles, and satisficing judgments.

8.3.1.1 *Mindware*

Domain specific factors of design present challenges for psychometric testing in the field. Taking FBS conflict tasks as an example - these inherently require some understanding of physical principles, or, mindware. While the sample in DS I consisted of students trained in these principles, variation in retention and comprehension is unavoidable. Thus, when a participant selects an incorrect response, multiple interpretations are possible: they may have lacked relevant knowledge, misapplied it, or detected conflict but failed to engage analytic reasoning. Distinguishing among these explanations is critical for interpreting test scores. In contrast to this, reasoning tests like the CRT rely on mathematical skills that, for most participants, are stable and resistant to forgetting. Therefore, the DCT highlights an important methodological point: tests of design cognition must carefully disentangle reasoning tendencies from knowledge gaps, potentially through careful sampling of expertise, use of principles that are intuitive even to those untrained in the domain, control items, or prior domain-knowledge assessments. This could be further explored through versions of the test that do not provide multiple-choice answers - akin to the CRT to see if the spontaneously generated answers of designers align with the intuitive lure and analytic response intended with the item design.

8.3.1.2 *Sampling*

These aspects relating to required mindware for psychometric tests leads on to considerations relating to sampling. Testing early methodological developments with relatively homogenous samples, such as the student cohort used here, is both typical and necessary. Homogeneity reduces variability in expertise, helping isolate the cognitive construct of interest. Nevertheless, establishing the generalisability of design psychometrics across novices, advanced students, and expert practitioners will be required. Expertise interacts strongly with dual-processing pathways (Purcell et al., 2020), while the tendency to engage Type 2 processing depends on the individual, the ability to reach the correct answer in lure problems can transition from effortful (Type 2) to intuitive (Type 1) processing with greater domain-specific expertise. This is a

necessary factor to consider in future work if testing across expertise in the same study.

8.3.1.3 *Visual reasoning*

As discussed, these domain-specific considerations (e.g. visual interpretation of artefacts, familiarity with mechanical principles) distinguish product design psychometrics from traditional reasoning tests. Much reflection during the design process occurs through a cycle of creating representations, perceiving the representations, and generating new insights through this perception (e.g. reflection-in-action/-on-action (Schön, 1983)). Therefore, this visual aspect of design should have a central role in the development of such avenues in design cognition research, with the potential for parallel exploration of written tasks more akin to classical reasoning tasks (e.g. design briefs that induce an incorrect intuitive response). For example, could a test equivalent to the Wason Selection Task - be created whereby it assesses confirmation bias in understanding design requirements?

Alongside potential in written tasks for design psychometrics, thinking dispositions (a component of DCT construct measurement) could be another avenue for future works. Thinking dispositions are typically measured through questionnaires (e.g. actively open-minded thinking, need for cognition, superstitious thinking). Could there be a design thinking disposition questionnaire that captures designers' tendency towards designerly thinking - assessing the capacity to create novel and functional products, or the likelihood of following a more descriptive or prescriptive approach? Alternatively, there could be questionnaire that combines the visual and written aspects of design within a questionnaire. For example, mental imagery questionnaires (e.g. mental rotation tests (Peters et al., 1995) combine written questionnaire aspects with visual reasoning abilities.

8.3.1.4 *Eye-tracking*

Eye-tracking as a physiological measure is a further methodological consideration highlighted by this work. Here, eye-tracking was used as a complementary measure in the development and evaluation of psychometric tests for design cognition. In conventional psychometric testing, validity evidence is often inferred solely from response accuracy, response time, or correlations with other measures. However, when

adapting such approaches to design cognition, reliance on behavioural measures alone limits the depth of understanding of the cognitive processes generating such outcomes. Eye-tracking offers a means of partially addressing this limitation by providing further evidence about how participants engage with stimuli during task performance.

In DS I, eye-tracking was not used as a primary metric of ability or performance, but as a supporting method to examine whether the Design Conflict Test (DCT) elicited attentional and processing patterns consistent with theoretical expectations derived from dual-process theory. Measures such as fixation distribution and dwell time on intuitive lure versus analytic responses were interpreted as indicators of conflict detection and analytic engagement. In this way, eye-tracking contributed to substantive validity by helping to assess whether the intended cognitive mechanisms were plausibly engaged during task performance, rather than merely inferred from correctness. This approach was directly informed by recent developments in dual-process research using eye movements to examine cognitive pathways and uncertainty, particularly the work of Purcell et al. (2021) on the Cognitive Reflection Test.

Findings also highlighted several challenges associated with the use of eye-tracking in design psychometrics. Eye-movement measures are inherently indirect indicators of cognition. Fixations and dwell times cannot be directly equated with Type 1 or Type 2 processing. This necessitates cautious interpretation and reinforces the importance of theory-driven hypotheses when using eye-tracking data. Without a strong theoretical framework, such data risk becoming descriptive rather than explanatory.

Furthermore, design-focused tasks introduce additional complexity compared to traditional reasoning paradigms. Visual artefacts in the DCT required participants to interpret structure, behaviour, and function through spatial reasoning, meaning that longer fixations could reflect perceptual decoding rather than analytic intervention. This complicates attempts to distinguish between cognitive effort arising from conflict resolution and effort arising from representational complexity. As such, eye-tracking metrics in design psychometrics must be interpreted relative to carefully controlled item design and supported by complementary measures such as uncertainty ratings or behavioural outcomes.

Despite these challenges, the use of eye-tracking in this thesis demonstrates its value as part of a mixed-method validation strategy rather than as a standalone indicator of cognitive processing. When combined with psychometric performance data and self-report measures, eye-tracking can strengthen claims about construct engagement by triangulating across different levels of analysis. In particular, its use aligns with Messick's substantive validity by providing evidence that the processes assumed by theory are plausibly enacted during assessment.

For future work, eye-tracking could play an even stronger role in refining design-specific psychometric instruments. More tightly controlled manipulation of conflict strength, variation in representational complexity, and larger samples would enable clearer differentiation between perceptual and analytic sources of visual attention. Additionally, combining eye-tracking with other methods, such as protocol analysis, may further support robust inference about cognitive mechanisms in design reasoning. Eye-tracking use could even be expanded to assessing DPT constructs in more naturalistic design. For example, eye-tracking has been used in design fixation research which could be tied to the fundamental analytic bias from DPT (Starkey et al., 2018; Wu et al., 2023). Additionally, eye-tracking use regarding expertise through a DPT lens has shown experts have a greater dependency on Type 1 processing regarding the processing of visual information than novices (e.g. Gegenfurtner et al., 2011; Warren et al., 2018) suggesting a promising avenue for future design research.

8.3.1.5 *Item design for design psychometrics*

In this thesis, each DCT item functioned as a bounded micro-design problem capable of eliciting both intuitive and analytic interpretations. The DCT item-level issues observed in DS I (e.g. variation in conflict strength across items) motivate a broader reflection on item design in design cognition research. As previously discussed, design reasoning follows a satisficing rather than an optimising principle (Lawson, 2005; Simon, 1972). Due to this satisficing nature, unlike conventional reasoning items, design problems may not have a single unambiguously correct solution (Simon, 1972). The determination of whether this satisficing level has been reached adds another layer of complexity to the item design for psychometric tests in design. That is, analytic override may not occur even when an intuitive response is

suboptimal.

This challenge presents two potential paths: closed-form items, where normative correctness is well defined, and open-interpretation items, which allow variation in how designers perceive conflict and decide whether to intervene. That is, items where a clearly heuristic lure and a normatively correct answer exist, allowing for stronger statistical discrimination of cognitive tendencies (e.g., the wine glass item in the DCT). Alternatively, items where correctness is ambiguous, potentially allowing researchers more nuance in capturing where and how designers perceive conflict, determine if the concept is satisficing, and choose to intervene.

Determining which of these methods provides the greatest predictive capacity in terms of real design behaviour is also crucial. Through this we can consider that conflict detection in design may not necessarily signal an error to be corrected, as in CRT tasks, but a cue to reframe or refine the evolving representation. Indeed, interpretation and reorientation are interspersed within more associative generation (Cash & Maier, 2021; Gonçalves et al., 2016). Perhaps it is the cues that trigger such a shift that will give us more insight into design reasoning and Type 1 and 2 processing. Future psychometric tools may need to integrate both forms, balancing standardisation with representational fidelity.

In summary, this work demonstrates both the promise and complexity of developing psychometric tests for design cognition research. The DCT illustrates that cognitive psychology methods can be meaningfully adapted to design cognition research, but only when key design-specific considerations are addressed (e.g. mindware requirements, sampling constraints, visual reasoning demands, and the satisficing nature of design problems). Together, these issues highlight that test development in design cognition may not be able to rely on direct translation of existing reasoning paradigms. Instead, it requires the integration of cognitive theory with the epistemic and representational characteristics of design practice. As such, the methodological insights generated here provide an initial foundation for a design-focused psychometric framework, one that balances ecological fidelity with experimental control and offers a pathway toward robust, scalable measurement tools capable of supporting future theory-driven research in design cognition.

8.3.2 Evaluating the Design Conflict Test

The factors relevant to developing psychometric instruments in design cognition research also hold relevance to the validity of such instruments. Messick (1995) proposed a - now well-established - unified theory of validity of psychological assessment integrating content, criteria, and consequences centring on construct validity. This theory aimed to incorporate how scores on psychological assessments were interpreted and used such that different sources of validity evidence are considered jointly - not separately. Construct validity in this unified consideration is considered in six aspects - content, substantive, structural, generalisability, external, and consequential (Messick, 1995).

The following discusses the validity of the DCT as it relates to these six aspects and the surrounding work in the thesis. Table 8-1 presents an overview of validity relating to this work which is subsequently expanded upon.

Table 8-1 - Messick's aspects of construct validity within this thesis

Messick's aspects of construct validity	Definition (Messick, 1995)	Relevance to DCT	Evidence in Thesis (DS I/DS II)
Content	Evidence that the content of test items accurately represents the construct the test is designed to measure.	Items must instantiate FBS-based cognitive conflict	<ul style="list-style-type: none"> • Item rationale • Pilot testing • Item behaviour patterns
Substantive	Rationale that the cognitive processes engaged during testing match the theoretical processes that define the construct.	Should induce intuitive defaults, potential conflict, and optional Type 2 override	<ul style="list-style-type: none"> • Eye-tracking AOIs • FOR/uncertainty • Fixation and dwell patterns
Structural	Fidelity of the scoring model reflecting the structure of the psychological construct.	Scores should reflect thinking disposition, not ability or accidental difficulty	<ul style="list-style-type: none"> • Independence from WMC • Item difficulty patterns due to conflict strength
Generalisability	The extent to which the test scores and their interpretation remain stable across different people, situations, and tasks.	DCT must be expandable to different expertise levels, and provide insights for different tasks and settings.	<ul style="list-style-type: none"> • Current limits acknowledged • Future expansion to experts/domains proposed
External	Whether the test relates to other measures and outcomes in ways predicted by theory.	Should diverge from general analytic measures; predict design behaviour	<ul style="list-style-type: none"> • Non-correlation with CRT/WMC • DS II linkography alignment
Consequential	The consequences for action and use of the test being appropriate, ethical, and theoretically justified.	Must avoid misuse as ability/expertise assessment.	<ul style="list-style-type: none"> • Thesis explicitly limits scope • Emphasised ethical interpretation

8.3.2.1 *Content Validity*

Content validity concerns the degree to which the test items adequately represent the theoretical construct and its domain (Messick, 1995). The DCT aims to measure and how individuals resolve cognitive conflict triggered by FBS belief bias. This required that each item have the capacity to trigger a clear form of Function-Behaviour-Structure (FBS) conflict, such that intuitive structural cues invite a Type 1 response that conflicts with an analytically correct interpretation (Type 1 or Type 2). The theoretical demand was that items must specifically elicit the cognitive pattern predicted by the default-interventionist account: an intuitive default, an opportunity to detect conflict, and the possibility of override.

If an item were to instead test engineering knowledge, working memory, or maths skills - this would undermine content validity. Item development therefore centred on selecting physical scenarios whose intuitive interpretation is plausible yet misleading under deeper functional, behavioural, or structural analysis. The physical scenarios were based on engineering concepts taught in the education of the sample. Pilot studies reinforced item relevance, although DS I revealed variation in item quality (e.g. Item 5 producing stronger conflict than Item 3), which informs future refinement of the test. This variation was expected at what is an exploratory stage of such work and strengthens the content validity claim by demonstrating which items most faithfully instantiate the theoretical construct.

8.3.2.2 *Substantive Validity*

Substantive validity refers to the degree to which the test elicits the cognitive processes theorised to underlie performance (Messick, 1995). For the DCT, this involves demonstrating that responses emerge from the sequence of intuitive activation, conflict monitoring, and analytic intervention assumed in default-interventionist dual-process theory. DS I provided several lines of empirical support for this aspect of validity. Eye-tracking analysis showed differential attention to intuitive lure options versus analytic alternatives, consistent with conflict detection (not always statistically significant and a key aspect to ensure is stronger in future iterations of the DCT). Uncertainty ratings (feelings of rightness) indicated that

participants often sensed conflict even when giving incorrect intuitive responses. Dwell-time and AOI patterns revealed deeper processing for analytic choices in correct trials and less deep consideration of analytic conflict in heuristic trials. (see sections 7.2. and 7.3)

Together, these findings suggest that DCT items reliably engage the theoretical processes of Type 1 activation and optional Type 2 override, supporting substantive validity. However, a focus of future work on editing the DCT should be strengthening the effects of findings regarding these mechanisms and underlying theory.

8.3.2.3 *Structural Validity*

Structural validity evaluates whether the scoring structure reflects the theoretical structure of the construct, rather than unintended difficulty or unrelated abilities (Messick, 1995). While, for the DCT, content validity relates to choosing the right kinds of conflict items, structural validity is whether people respond to those items in ways predicted by the underlying theory. In the DCT, this means that performance should vary according to conflict strength and cognitive processing tendencies, not according to working-memory capacity, or domain-specific knowledge unrelated to conflict resolution.

The data support this requirement in several ways. First, DCT scores were only weakly correlated to working-memory capacity - as predicted - ruling out the possibility that performance reflects cognitive resources rather than disposition. Second, differences in item performance aligned with theoretical differences in intuitive strength and analytic demand. Given that all participants were educated in the same knowledge, items differed based on the cognitive conflict they elicited. Item-level variation is relevant to structural validity not because it critiques item design, but because it demonstrates that differences in scores arise from conflict strength rather than irrelevant difficulty. These differences in conflict strength can be seen in the lower feelings of rightness seen in correct trials for Item 5 - which shows a stronger capacity to elicit conflict. This pattern supports the argument that the DCT's scoring structure reflects the underlying construct of conflict resolution tendencies in design.

8.3.2.4 *Generalisability Validity*

Generalisability validity concerns whether score interpretations hold across populations, tasks, and contexts (Messick, 1995). As an exploratory study, the limits in sample size and expertise range are acknowledged. Participants were of the same intermediate level designers, and items covered a restricted set of FBS conflict scenarios.

However, this work's foundation in a theory of FBS cognitive conflict in design should be generalisable to various expertise levels - given that foundation knowledge on the engineering principles is known. However, expertise-level generalisation cannot be assumed to be linear. Research on domain-specific experience and dual-process thinking shows that experts may solve similar problems using automated Type 1 reasoning, whereas intermediates rely more on effortful Type 2 processing, and novices may engage in either intuitive shortcuts or ineffective Type 2 reasoning (Purcell et al., 2020).

This means that as designers move from novice to expert, the cognitive processes elicited by the DCT may shift, potentially altering how conflict is experienced and whether intervention is triggered. Therefore, while the theoretical foundation of the DCT suggests it should generalise across experience levels, shifts in automation, conflict detection, and reasoning strategy may also shift with expertise. Future validation must therefore examine whether the test functions equivalently across novice, intermediate, and expert designers.

8.3.2.5 *External Validity*

External validity evaluates the extent to which test scores relate appropriately to other measures (Messick, 1995). For the DCT, this involved three forms of validity: convergent, discriminant, and predictive. The DCT was initially expected to behave in parallel to classical belief-bias reasoning tasks - correlating positively with general analytic reasoning (CRT) but weakly with cognitive capacity (working memory - PASAT). However, DS I showed weak correlation between the DCT and both the CRT and the PASAT. Rather, than undermining validity, this pattern provides meaningful evidence regarding the type of external validity that the DCT demonstrates.

A critical insight from the DCT-CRT comparison is that lack of correlation may not necessarily indicate invalidity. In design cognition, divergence from traditional cognitive tests may signify domain-specific constructs rather than measurement error. Indeed, the DCT's independence from working memory capacity supports its alignment with design-specific reasoning rather than general analytic ability. That is, the absence of correlation with the CRT indicates that the DCT does not measure domain-general analytic reasoning. This suggests the underlying construct of DCT performance is not equivalent to the constructs accessed by the CRT. In DPT, analytic override is typically treated as a domain-general disposition, but DS I indicates that conflict resolution in design draws on cognitive processes that differ from those engaged in abstract reasoning tasks. The independence of working memory capacity further supports discriminant validity in showing that DCT performance is not driven by cognitive capacity.

Taking another type of external validity - convergent validity, this can be seen emerging not from correlations with standard psychometric tools, but from alignment with design-specific indicators of cognitive processing. Eye-tracking signatures of conflict detection (e.g., increased dwell time on analytic alternatives), and uncertainty markers (FOR) consistent with Type 1/Type 2 conflict, converge with the patterns predicted by the FBS conflict theory. These findings show that the DCT elicits and detects the processes it was theoretically designed to measure, even if they do not converge with generic reasoning tests.

A stronger test of external validity comes from predictive validity demonstrated in DS II, where DCT performance predicted meaningful variation in design behaviour as revealed by linkographic analysis. Participants with different DCT profiles demonstrated recognisably distinct patterns in critical moves, fixation, bidirectionality, and entropy measures. These patterns consistently aligned with theoretical expectations of Type 1 versus Type 2 processing tendencies. Although tentative given the necessary future redesign of the DCT, this provides promising early evidence that the DCT captures cognitive dispositions relevant to actual design practice.

Participants with different DCT profiles produced distinct patterns of: temporal

distribution of critical moves, proportions of forelinks vs backlinks, fixation levels, bidirectionality, and horizonlink entropy. These differences align with dual-process accounts of design: greater reliance on early cues (Dyad 1) reflected a fundamental heuristic bias; linear, analytic persistence (Dyad 2) resembled a fundamental analytic bias; and distributed, iterative synthesis (Dyad 3) indicated balanced or metacognitively regulated engagement of both modes. This mapping provides predictive evidence that DCT scores may relate to real design behaviour, not merely to performance on artificial tasks.

8.3.2.6 *Consequential Validity*

Consequential validity concerns the appropriateness, impact, and ethical implications of score interpretation (Messick, 1995). A key requirement is that test scores should not be misused to draw evaluative or normative conclusions beyond what the construct supports.

The thesis explicitly positions the DCT as an exploratory research instrument, not a tool for ranking designers, diagnosing ability, or defining expertise. Limitations are acknowledged, and findings are interpreted cautiously to avoid conflating cognitive disposition with design ability or talent, and to avoid overstating conclusions. The careful articulation of boundaries ensures that DCT scores are used responsibly, fulfilling the consequential validity criterion.

In summary, evaluating the Design Conflict Test (DCT) through Messick's unified framework demonstrates its validity extending beyond the correlations with established cognitive measures in DS I. Content and substantive evidence indicate that items instantiate FBS-based conflict and elicit the dual-process dynamics central to the intended construct. While some items trigger stronger lure answers than others (e.g. the wine glass) - this provides important guidance for future iterations of the test. Structural evidence shows that test scores reflect conflict-resolution tendencies rather than extraneous abilities, while the discussion of generalisability clarifies how expertise-related shifts in reasoning may affect future applications across broader populations. Although the DCT does not correlate with classical measures such as the

CRT or working-memory capacity, its external validity emerges through theoretically meaningful alignment with design-specific behavioural indicators and its predictive association with linkographic process patterns. Finally, explicit reflection on the ethical and interpretive boundaries of the instrument supports its consequential validity. Together, these forms of evidence position the DCT as a theoretically grounded yet exploratory psychometric prototype whose divergence from traditional reasoning tests is not a weakness but a potential indicator of its sensitivity to the unique cognitive demands of design.

8.3.3 Linkography in DPT design research

The mixed-method approach of this work - through combining more objective quantitative psychometric testing and physiological measures (eye-tracking) in DS I, with more subjective qualitative transcript data through linkographic analysis in DS II furthers the methodological development of DPT in design cognition research from this work. Gonçalves and Cash (2021) were the first to connect dual-process theory with linkography in design ideation through using a network-based approach informed by linkographic principles. The present work extends this by using a methodology that spans both individual-difference measurement and design process analysis to capture unique patterns of thought that can be linked to DPT constructs. While specific insights linking linkographic features to DPT construct were presented in the Discussion of DS II (see Section 7.6), broader insights for the field can be considered.

Linkography presents a strong basis as methodology for future DPT research in design cognition. It has characteristics that lend itself both to depth of enquiry and the discussed wider goals of design cognition research. There has been an emphasis on increasing quantitative approaches to promote robust hypothesis testing with large samples (Hay et al., 2017a, 2020). While linkography itself repeats familiar challenges to the design cognition field present in the resource intensive and time-consuming nature of protocol analysis, it provides additional benefits within DPT research. That is, it involves the analysis of design at a highly granular level - assessing design move by design move which provides excellent flexibility for DPT enquiry based on identified individual differences. Researchers can code and link moves based on the focus of the study. The flexible length of linkographs enables researchers to select key

segments to analyse, and the flexible number of designers that can be studied allows selective sampling in both individual and teams settings. These factors allow precisely the methodology taken in this work which, when scaled up, could provide significant advancements to the field. That is, analysing the metrics of many designers through DPT (or other cognitively informed theoretical foundation), and selecting key participants (extremes, averages etc.) at which to look more closely. Indeed, through this, these factors provide researchers the flexibility of enquiry based on DPT through many different individual differences and design process stages.

Most of all, however, linkography is an analysis of patterns. This is the strength of linkography in a DPT context considering the complexities involved in identifying correctly specific instances of Type 1 and Type 2 thought. As a field, we can work towards identifying a set of individual (or team dynamic) differences that affect design through a DPT lens and correlating these with patterns that appear in these individuals' (or teams') design sessions. With this, a solid foundation of knowledge can be built. Upon this, we can potentially identify these specific instances with more certainty and push design cognition work onto a more rigorous and theory driven stage.

Even so, this work only touches the surface of depths possible with such mixed-methods, multi-study approaches. Here, this work has focused on exploring the combination of quantitative and qualitative measures in DPT founded design research. However, while linkography requires qualitative analysis of transcripts data to determine design moves and link ideas together, metrics that emerge from the linkograph can be analysed quantitatively. Indeed, such quantitative analysis was done in this work (see Section 7.5). However, the qualitative aspects of linkography can be stretched further. Through coding design moves and analysing protocols alongside linkographic patterns and features, even further depths of understanding may be reached. Indeed, such qualitative analysis could be one of the main links in connecting enquiry regarding patterns of thought (i.e. thinking dispositions) in identifying specific instances of Type 1 and Type 2 processing. Although, such insights should be considered with caution until the body of evidence is strong enough to substantiate claims of specific instances of dual-processing thought in design.

Qualitative insights from such linkography use could be expanded through

analysing the generated ideas themselves. While linkography gives insight into patterns of thought, insight into the consequences of this thought is limited. Through analysing creativity metrics we could understand how different patterns of Type 1 and Type 2 processing affect design outputs (e.g. sketches, concepts). For example, the effect of a reliance on Type 2 processing on novelty, variety, quantity, and quality could be determined. These are an example of such creativity metrics, proposed by Shah et al. (2002) and respectively denote how comparatively unexpected and idea is (novelty), the depth of solution exploration (variety), the number of ideas (quantity), and the feasibility of an idea (quality). Through these metrics the link between design theory and design practice could be strengthened.

Ultimately, this work advances the field toward what Hay et al. (2020) describe as the necessary “major methodological paradigm shift, bringing new perspectives in addition to classical protocol analysis approaches”. Therefore, while the present work marks an early step in aligning linkographic analysis with DPT, it establishes a viable methodological pathway that future research can refine, validate, and extend toward increasingly reliable and theoretically grounded insights.

8.4 Implications of DPT in design cognition for design research, practice, and education

The findings of this thesis have several implications for how design cognition is studied, taught, and supported in practice. At the core is the recognition that designers differ in how they balance intuitive (Type 1) and analytic (Type 2) processing, and that these differences shape the structure and quality of their design activity. Rather than treating designing as a homogeneous cognitive process, the work suggests that individual cognitive profiles and metacognitive regulation deserve greater attention in both research and practice.

8.4.1 Implications for design research

8.4.1.1 Understanding Individual Differences

A first implication is the need to foreground individual differences in design cognition research. DS II showed that designers with different DCT × CRT profiles exhibited recognisably different linkographic patterns: some relied heavily on early intuitive cues and showed limited synthesis, others displayed more linear and narrow analytic progression, and others demonstrated a more balanced and iterative interplay between divergent and convergent activity. These behavioural differences emerged even when designers were working on the same task, within the same constraints, and at similar levels of formal expertise. This indicates that the way designers coordinate Type 1 and Type 2 processing is not just a function of the task, but an individual-difference variable with tangible process consequences. For design cognition research, this emphasises the importance of approaches that explicitly model cognitive profiles, thinking dispositions, and metacognitive tendencies.

Methodologically, this supports the use of individual-difference measures such as design-specific tests like the DCT alongside process-tracing methods (e.g. variation in linkographic patterns) such that data can be interpreted in light of underlying cognitive tendencies rather than solely descriptive analysis. For future work, this points to the value of sampling strategies that deliberately contrast different cognitive profiles, as well as longitudinal studies that track how these profiles evolve with experience and training.

Individual differences have been researched in design cognition (e.g. Christiaans & Dorst, 1992; E. J. Kim & Kim, 2015; Liikkanen & Perttula, 2009; Puente-Díaz et al., 2021). Indeed, some of this work has moved toward more neurocognitive methods to ensure individual differences are considered (Goel, 2014). However, such research has been largely descriptive - identifying cognitive- or designer-types (Kruger & Cross, 2006), and has involved limited exploration or cognitive theory to explain these differences. Indeed, others have identified that while clear individual differences have been found in design cognition research, they have largely been linked to expertise (Ball & Christensen, 2019). The nature of cognitive processing behind attentional shifts, problem formulation to solution development, and decision making remains underexplored (Ball & Christensen, 2019). This lack of underlying explanatory theory limits the use of much design cognition research. In contrast, the strong theoretical underpinning of the work presented in this thesis provides a basis on which these differences can be considered, tailored for, and utilised in the design process - aspects which are explored in the following sections.

8.4.1.2 *Cognitive models of design*

This work provides an initial basis for developing a DPT founded model of design cognition. Indeed, DPT - as presented by Evans (2019) - which incorporates cognitive capacity, mindware, competing tasks, available time, decision importance, thinking dispositions, metacognitive aspects like feelings of rightness, and context provides an excellent range of well-established factors that affect design. Developing our understanding of these factors through a DPT lens holds significant potential for developing a general model of design. Here advances have been made in understanding thinking dispositions, feelings of rightness, and working memory capacity within conceptual design. Furthermore, an understanding of the biases, and their effects in design, may well provide greater support and depth to such models. Beyond the DCT and FBS conflict theory, there will exist a range of cognitive biases related to dual-processing that affect the design process. Are there yet uncovered biases related to visual reasoning or situated cognition (perhaps that the DCT already instantiates)? From this, would a battery of design-focused bias tests be valuable in unlocking the inner workings of design cognition and how we might use these to

design better? Alternatively, do existing tests of reasoning from cognitive psychology hold descriptive or predictive value in strengthening our understanding design cognition? Such questions may need to be asked when developing cognitive models of design.

Cognitive models evolve with the supporting knowledge available. Indeed, the Intervention Model proposed by Evans originally in 2011 underwent development for its subsequent presentation in 2019 (Evans, 2011, 2019). That is the set of factors affecting default-interventionist processing changed (see Table 8-2).

Table 8-2 - Evolution of factors in the Intervention Model

Model Presented	Motivational Factors	Cognitive Resources	Situational Factors
Evans, 2011	<ul style="list-style-type: none"> • Instructional set • Thinking disposition • Feelings of Rightness 	<ul style="list-style-type: none"> • Time available • Competing tasks • Mindware • Working memory capacity 	
Evans, 2019	<ul style="list-style-type: none"> • Thinking disposition • Feelings of Rightness • Importance of decision 	<ul style="list-style-type: none"> • Mindware • Working memory capacity 	<ul style="list-style-type: none"> • Time available • Competing tasks • Context

The evolution of the Intervention Model helps to visualise changes that could be relevant for application in design cognition research. For example, importance of decision proposed in Evans (2019) may well present with a range of subfactors relevant to the design such as the stage of the design process or the level of requirements/constraints. Measuring the ongoing appraisal of this importance of decision could also enable us to assess its effect on the design process in different stages and, therefore, where there is increased Type 2 engagement - revealing further design cognition insights from DPT. Context, another factor included in the latest iteration of the Intervention Model, is often discussed in design and is central to much research and existing accounts (e.g. the FBS framework). Indeed, Cash & Maier

(2021) identify that further work is needed to understand dual-processing mechanisms and Type 1 and 2 interactions alongside situating this within contextual factors that influence design practice. The adoption of existing work on design contexts into the advancement of DPT research in design is another avenue for exploration.

The centrality of metacognition within DPT research (see section 8.2.2) - particularly given its increasing focus in design (see section 3.6), highlights the need to make metacognitive (Type 3) processes explicit within DPT based design cognition models. Indeed, research working toward such support for design cognition research could clarify how designers manage cognitive effort and attention over time. It could also provide a framework for strengthening the connection between cognitive psychology and design theory with the management of reflection, iteration, and satisficing being understood as manifestations of metacognitive control. Indeed, such work could build on existing metacognitive focused dual-process theory model of cognition such as Thompson's (2009) "Metacognitive framework of reasoning".

The evidence from DS II not only demonstrates the operation of metacognitive regulation and control in design but also positions design as a rich context for advancing the growing research on metacognition. Understanding how designers monitor, control, and adapt their reasoning across the design process provides both a deeper theoretical integration of dual-process theory and a foundation for future empirical work on metacognitive adaptability in creative expertise.

8.4.2 Implications for design methods and tools

The focus on individual differences in this work has implications for the development of design methods and tools. If designers differ in how they engage and regulate intuitive and analytic thought, then design processes and methods that assume uniform cognitive behaviour may inadvertently support some profiles more than others. One implication is the development of adaptive or flexible design methods that can be tuned to support different processing tendencies. Methods that emphasise rapid sketching and broad associative thinking in both concept exploration and evaluation may help highly analytic designers engage more freely with conceptual design. Conversely, methods that emphasise structured approaches in evaluation or synthesis

may help highly intuitive designers avoid premature convergence.

Digital tools also present opportunities. Sketching or CAD environments could incorporate prompts that encourage users to shift modes, for example inviting them to generate alternatives after a period of refinement or prompting them to revisit earlier concepts when signs of fixation appear. In collaborative contexts, awareness of individual dual-processing profiles could support team composition and coordination, allowing different tendencies to complement one another rather than conflict. Having a strong foundation in theory for considering such individual differences provides much needed support for developing design methods and tools that not only to suit the task but also to support designers in using the strengths and range of their cognitive capabilities.

8.4.3 Implications for teaching design tools

The findings also have implications for teaching design tools, particularly in relation to how students come to understand and regulate their own thinking. While the DCT is not yet suited for rigorous evaluative use, it demonstrates potential value as a formative or reflective educational tool. A refined version could help students recognise whether they tend to rely on early intuitive responses, persist analytically without sufficient exploration, or move more flexibly between different modes of thinking. Making these tendencies explicit could support reflective practice. Students could be encouraged to notice when they are prematurely converging, when they are over-justifying (rationalising) weak ideas, or when they are avoiding the cognitive effort required for analytic evaluation.

The prominence of metacognitive regulation in DS II implies that teaching should not only focus on methods and tools but also on helping students understand how to manage their own cognitive biases. Educational strategies might include structured reflection on how a design was developed, or tasks that make students consciously attend to their own feelings of rightness or uncertainty. Such approaches can foster the ability to shift between divergent and convergent thinking more effectively, aligning with the more expert-like patterns observed in Dyad 3. Ultimately, design teaching may benefit from treating dual-processing and metacognitive regulation as explicit

learning outcomes alongside traditional outcomes such as creativity, technical competence, and communication.

8.4.4 Broader Relevance Beyond Design

Although this thesis is grounded in product design engineering, the theoretical mechanisms explored, such as conflict detection, metacognitive regulation, and interaction between intuitive and analytic reasoning, may also hold relevance for other domains involving open-ended problem solving. These possibilities remain speculative and require domain-specific investigation, but suggest potential avenues for extending DPT-informed approaches beyond design cognition research. For example, from the perspective of cognitive psychology, the results suggest that domain-specific thinking dispositions and mindware can compensate for weaker performance on domain-general analytic tasks. For example, high DCT but low CRT performers in DS II produced cohesive and productive design behaviour despite low working memory capacity, indicating that dual-processing constructs and tendencies relevant to design may support effective conflict resolution even when general analytic ability is lower. This this emphasises the importance of domain-investigations in exploring dual-process theory further.

This has further relevance for domains such as architecture, mechanical engineering, and engineering management, where professionals also reason with incomplete information, ambiguous constraints, and evolving representations. The mechanisms studied here, such as conflict detection, metacognitive regulation, and the interplay between intuitive and analytic thought, may be able to be strengthened in their understanding through parallel work in such fields. The work therefore develops our applied understanding of dual-process theory, showing how intuitive and analytic processes function in practice within specialised domains. It suggests that dual-processing in more complex reasoning is shaped by representational practices, domain knowledge, and task context in ways that extend beyond the traditional laboratory paradigm - but that can still be explored through tailoring such paradigms.

8.5 Summary

This thesis set out to improve understanding of intuitive (Type 1) and analytic (Type 2) cognitive processes in conceptual design, and to address three challenges identified in the field: the limited alignment of design cognition with established cognitive psychology, the lack of suitable tests and metrics for individual differences, and the limited integration of quantitative and qualitative methods.

Across theory building (Part 1) and theory evaluation (Part 2), the work developed three main aspects of design cognition research. Firstly, theoretical development, providing a novel theory of cognitive conflict in design, deepening our understanding of the role of metacognition in design through a DPT lens, and connecting fundamental biases of DPT to design behaviour - strengthening our predictive capacity for understanding design cognition. Methodological development was also central, using this work as an example to map challenges and considerations that face psychometric testing in design, proposing the DCT as a novel prototype psychometric test for design cognition research, and focusing the field on pattern identification (rather than identifying specific Type 1 and Type 2 instances) through individual differences by proposing linkography as a method for advancing DPT research in design. Beyond this, implications for design practice, research, and education are addressed - highlighting a direction for future work to apply an individual differences approach to address challenges regarding impact and theory development in the field.

Given the exploratory and theory-building nature of this thesis, these contributions are not claimed to be statistically generalisable across all designers, design domains, or forms of design activity. Instead, generality is considered in terms of theoretical transferability and methodological extensibility. That is, the work establishes clearly defined constructs, mechanisms, and methods that can be applied, refined, and tested across broader design contexts in future research.

The proposed FBS conflict theory and Design Conflict Test are specifically bounded to conceptual design contexts involving visual representations. Establishing theory with the potential for strong predictive capacity in such contexts, enabled design-specific dual-processing mechanisms to be operationalised and linked to

observable design behaviour. This foundation acts as a theoretically grounded base for generality in theorising and researching other contexts and mechanisms behind design behaviour beyond this.

Generality is therefore addressed through the grounding of the work in established dual-process theory, the alignment of this theory with design-specific constructs, and the use of methods that can be extended to other samples, domains, and design tasks. The significance of the work lies not in claiming universal findings, but in demonstrating a feasible pathway for future research into dual-processing in design cognition.

The key insights regarding research findings, research approach, and research methods that were outlined throughout this discussion are presented in summary in Table 8-3.

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Table 8-3 - Summary of research findings, approach, and methods

STRENGTHS	LIMITATIONS	FUTURE WORK
Research Findings		
FBS theory of cognitive conflict		
<ul style="list-style-type: none"> • Provided a design-specific mechanism for cognitive conflict grounded in the FBS ontology. • Integrated dual-process theory with established design cognition frameworks. • Generated clear, testable predictions about conflict detection and intervention in design. • Provided a basis for assessing visual reasoning a priori. 	<ul style="list-style-type: none"> • Developed and tested primarily through bounded, experimentally constructed scenarios. • Unclear how explicitly FBS conflict manifests in naturalistic, evolving design processes. • Represents only one possible source of cognitive conflict in design. 	<ul style="list-style-type: none"> • Investigate FBS conflict in situated, real-world design activity. • Compare FBS conflict with other conflict triggers. • Examine how FBS conflict unfolds temporally during extended design episodes.
Metacognitive regulation and control in design		
<ul style="list-style-type: none"> • Highlighted metacognitive regulation as central to effective design cognition. • Supported by behavioural patterns observed in linkographic analysis. • Aligned with broader theories of reflection-in-action and expert performance. 	<ul style="list-style-type: none"> • Metacognitive processes inferred indirectly rather than measured directly. • Limited number of participants restricts generalisability. 	<ul style="list-style-type: none"> • Explore methods for capturing metacognition in situ, e.g. intervention prompts (asking for FORs after a concept is generated), capturing regulation and control in protocol data. • Examine development of metacognitive regulation across expertise levels. • Explore training interventions that support adaptive switching between processing modes. • Explicitly incorporate metacognition into models of design cognition.

STRENGTHS	LIMITATIONS	FUTURE WORK
Fundamental biases in design cognition		
<ul style="list-style-type: none"> • Reframed fixation and premature convergence as cognitive biases through a DPT lens. • Grounded design behaviour in established dual-process bias theory. • Empirical patterns in DS II aligned with theoretical expectations. 	<ul style="list-style-type: none"> • Evidence for the fundamental analytic bias in design remains tentative. 	<ul style="list-style-type: none"> • Explore linking thinking disposition to the fundamental biases with larger samples. • Examine how justification and rationalisation contribute to fixation. • Study bias mitigation strategies through metacognitive interventions.
The DCT as a prototype psychometric test for design		
<ul style="list-style-type: none"> • Demonstrated that design-specific cognitive conflict can be experimentally induced and measured. • Showed independence from working-memory capacity and general analytic reasoning. • Predicted meaningful differences in design behaviour. • Serves as a concrete example of psychometric adaptation to design cognition. 	<ul style="list-style-type: none"> • Item set is small with variable conflict strength. • Performance may reflect both reasoning disposition and domain knowledge. 	<ul style="list-style-type: none"> • Iterative item calibration, difficulty balancing, and ensuring items generate intended intuitive and analytic responses without multiple-choice answers,. • Determining the most effective items for predicting design behaviour e.g. the CRT only has 3 questions but is a powerful indicator of performance on other tasks. • Add pre-checks for required knowledge of engineering principles or embed control items. • Validate across larger and more diverse designer populations.

STRENGTHS	LIMITATIONS	FUTURE WORK
Test validity		
<ul style="list-style-type: none"> • Attention to validity supported careful interpretation of test outcomes • Demonstrated aspects of content, substantive, structural, external, and consequential validity. • Treated non-correlation with CRT as theoretically meaningful rather than problematic. • Used converging evidence from psychometrics, eye-tracking, and behavioural data. 	<ul style="list-style-type: none"> • Generalisability limited by sample size. • Design students are not representative of design professionals • Some validity claims remain provisional. 	<ul style="list-style-type: none"> • Investigate the role of expertise within test performance and design behaviour. • Expand sample to strengthen validity of future DCT iterations.
Individual differences in design education, research, and practice		
<ul style="list-style-type: none"> • Demonstrated that cognitive dispositions shape design behaviour. • Provided a theoretically grounded framework for person-centred design cognition research. • Offered explanatory depth beyond descriptive designer typologies. 	<ul style="list-style-type: none"> • Educational and professional implications remain conceptual. • Risk of misinterpreting disposition as ability if applied uncritically. • DCT not yet suitable for evaluative use. 	<ul style="list-style-type: none"> • Develop formative tools for reflective design education. • Study interactions between cognitive profiles in design teams. • Examine how individual differences evolve with training and experience.

STRENGTHS	LIMITATIONS	FUTURE WORK
Research Approach		
DRM + theory building and testing cycle methodology		
<ul style="list-style-type: none"> • Provided a coherent and rigorous structure linking theory development, empirical testing, and interpretation, directly addressing calls for stronger theory-driven design cognition research. • Positioned the thesis as an initial iteration within a cumulative theory-building process. 	<ul style="list-style-type: none"> • Only a single iteration of the theory building/testing cycle was completed, limiting the strength of theoretical claims. • The adapted DRM focuses on descriptive rather than prescriptive outcomes, limiting direct practical application. 	<ul style="list-style-type: none"> • Conduct further iterations of the theory building/testing cycle to refine, test, and extend and strengthen the proposed theory/methodology. • Introduce prescriptive studies to translate theoretical insights into design methods or interventions.
Research Philosophy		
<ul style="list-style-type: none"> • Critical realism provided a robust foundation for studying unobservable cognitive mechanisms through observable design behaviour. • Methodological pluralism supported the integration of quantitative and qualitative methods needed to study complex design cognition. 	<ul style="list-style-type: none"> • Cognitive mechanisms remain inferred rather than directly observable, limiting the strength of causal claims. • The philosophical stance requires careful interpretation to avoid overclaiming explanatory certainty. 	<ul style="list-style-type: none"> • Further formalise links between observed behaviour and hypothesised cognitive mechanisms.

STRENGTHS	LIMITATIONS	FUTURE WORK
Research Methods		
Literature review		
<ul style="list-style-type: none"> • Enabled identification of theoretical, methodological, and ontological gaps in design cognition research. • Provided a rigorous foundation for theory selection, construct mapping, and subsequent theory building. 	<ul style="list-style-type: none"> • Narrative in nature, limiting claims of completeness and reproducibility. • Synthesis is shaped by the dual-process theoretical lens adopted. 	<ul style="list-style-type: none"> • Extend reviews to adjacent design domains to assess generalisability of findings.
Psychometric Methods		
<ul style="list-style-type: none"> • Enabled quantitative measurement of individual differences in dual-process tendencies using controlled, theory-driven tasks. • Supported hypothesis testing and comparison with established cognitive measures, strengthening methodological rigour. 	<ul style="list-style-type: none"> • Psychometric tasks necessarily simplify design cognition, limiting ecological validity. • Performance may be influenced by domain knowledge or task interpretation rather than thinking disposition and cognitive capacity. 	<ul style="list-style-type: none"> • Refine item design to better isolate cognitive conflict from knowledge effects. • Extend psychometric testing across broader populations and design domains.

STRENGTHS	LIMITATIONS	FUTURE WORK
Eye-tracking		
<ul style="list-style-type: none"> Supported theoretical claims about conflict detection and analytic engagement. Offered convergent validity beyond response accuracy alone. Demonstrated the strength of conflict in items. 	<ul style="list-style-type: none"> Eye-tracking metrics are indirect indicators of cognition and require careful interpretation. Effects were subtle due to sample size and exploratory item design. 	<ul style="list-style-type: none"> Use eye-tracking to refine item design for DCT iteration
Linkography		
<ul style="list-style-type: none"> Enabled qualitative and quantitative fine-grained analysis of temporal and structural patterns in design reasoning. Well suited to analysing individual differences. Complements psychometric approaches in mixed-methods research. 	<ul style="list-style-type: none"> Time-intensive and reliant on interpretive coding decisions. Limited scalability without automation or sampling strategies. 	<ul style="list-style-type: none"> Further experimental work to validate and expand DPT construct manifestations presented in DS II linkography analysis.
Mixed-methods integration		
<ul style="list-style-type: none"> Allowed theoretical constructs to be examined across complementary levels of analysis. Strengthened explanatory power by linking individual differences to design behaviour. 	<ul style="list-style-type: none"> Sequential design limited direct statistical integration of quantitative and qualitative datasets. Integration relied primarily on theoretical rather than formal mixed-model analyses. 	<ul style="list-style-type: none"> Develop designs that allow direct statistical linking between psychometric scores and process metrics.

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9 CONCLUSIONS

The aim of this thesis, was to provide a greater understanding of intuitive and analytic cognitive processes of designers during the conceptual design phase. The thesis was structured around a deliberate progression from theory development to theory evaluation. The adapted Design Research Methodology and Theory Building/Cycle (see Section 2.2), were used to guide the work. Several objectives led this work within this methodology. Firstly, Part 1 – Theory Building synthesised literature from design cognition and cognitive psychology to identify conceptual gaps and establish a theoretical foundation for investigating dual-processing in design. Through building from the Intervention Model of DPT, this culminated in the proposal of FBS Conflict Theory as a design-specific mechanism for cognitive conflict and tackled Objectives 1 & 2:

- O1.** Identify challenges facing conceptual design cognition research to define the research focus and determine a theory as a means of tackling these challenges.
- O2.** Determine a model from the chosen theory and align it with design cognition insights as foundation for investigating conceptual design cognition.

Part 2 – Theory Evaluation then evaluated this theoretical account empirically through two complementary descriptive studies. Descriptive Study I operationalised the theory through the Design Conflict Test, providing initial evidence that design-relevant cognitive conflict can be elicited and measured using psychometric principles.

Descriptive Study II extended this evaluation into situated design activity, using linkographic analysis to examine how individual dual-process tendencies manifest in observable design behaviour. These two empirical studies were led by Objective 3:

- O3.** Assess the validity and utility of the model through both quantitative and qualitative methods.

Together, these stages form a coherent theory building and testing cycle, through which the thesis arrives at its conclusions regarding the nature of dual-processing, metacognitive regulation, and individual differences in design cognition. Objective 4 is the focus of this chapter, which draws together the findings of DS I and DS II and considers their broader implications:

- O4.** Evaluate the work to recognise the advantages, disadvantages, and potential areas for future research.

Motivated by persistent challenges in design cognition research, including weak alignment with cognitive theory, limited quantitative measurement of individual differences, and insufficient integration of qualitative and quantitative methods, this work pursued a theory-driven investigation grounded in dual-process theory. Through a structured approach of theory building and theory testing, the thesis demonstrates that dual-processing constructs can be meaningfully adapted to the design domain, operationalised through developing design-specific measures following established approaches in cognitive psychology, and linked to observable patterns of design behaviour. In doing so, it contributes both theoretical and methodological foundations for studying cognitive conflict, metacognitive regulation, and individual differences in design reasoning, while opening new pathways for future research at the intersection of cognitive psychology and design cognition.

On this basis, the contributions of the thesis can be summarised in terms of three advances to knowledge. First, the thesis advances theoretical understanding through the formulation of a design-specific account of cognitive conflict grounded in the FBS framework (K1). Second, it contributes methodologically through the development and initial validation of the Design Conflict Test as a prototype psychometric

instrument for studying individual differences in design cognition (K2). Third, it provides empirical insights into how dual-processing dispositions and metacognitive regulation may shape observable design behaviour in practice (K3). Together, these contributions demonstrate how cognitively grounded theory, purpose-built measurement, and mixed-method empirical analysis can be integrated to advance design cognition research in a systematic and cumulative manner. These contributions are visualised within this theory building and testing cycle in Figure 9-1, and detailed further in the following section.

The initial theory building stage was addressed through reviews of design cognition and dual-process theory literature. Through this, gaps in ontological alignment and methodological consistency were identified - leading directly to the proposal of the FBS Conflict Theory (K1). This theory was then operationalised through the development of the Design Conflict Test as a prototype psychometric instrument (K2), aiming to build a predictive account of design behaviour through testing, and validation. The combination of controlled experimental methods in DS I with analysis of more naturalistic design behaviour in DS II allowed the theory to be examined. This methodological progression enabled the refinement and extension of the theoretical claims by demonstrating how individual dual-processing dispositions manifest in observable design behaviour (K3). In this way, the use of the DRM and the engagement with the theory building and testing cycle did more than structuring the research process, in that it shaped the nature and coherence of the contributions, ensuring that theoretical development, methodological innovation, and empirical insight advanced together rather than in isolation.

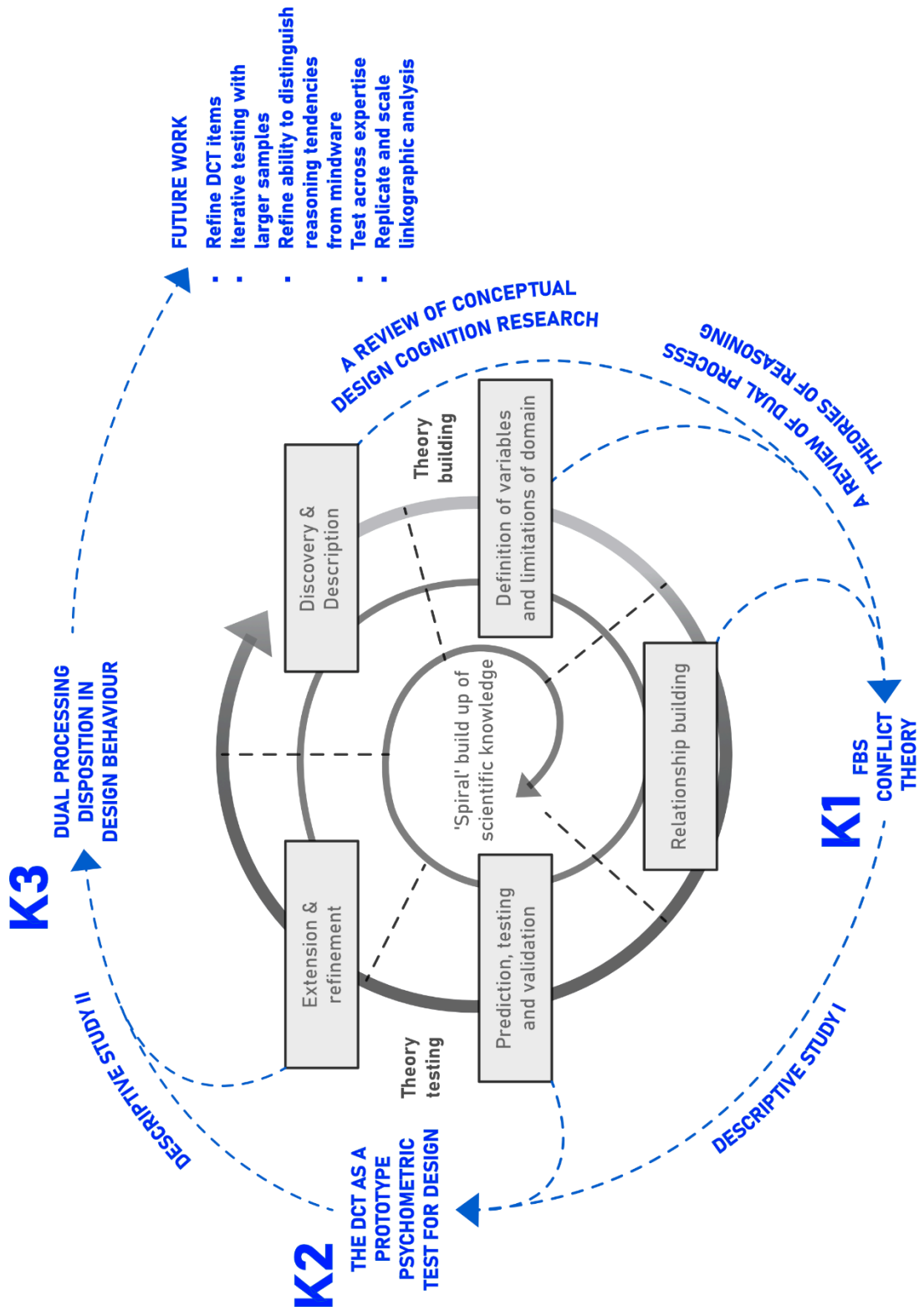


Figure 9-1 - The alignment of the contributions of this thesis within theory building/testing cycle

Revisiting the DRM in more detail, the criteria set out in the reference model developed during research clarification (see Figure 5-1) played a central role in structuring and justifying the methodology of this thesis. In line with DRM, the model articulated both the desired success criterion of improved understanding of design cognition and the measurable success criterion of establishing suitable tests and metrics for investigating cognitive processes in design. The literature review identified a set of key factors that constrain progress toward these criteria, most notably fragmentation in design terminology, the adoption of theory and methods from established fields, and the effective combination of quantitative and qualitative methods. These factors informed the choice to prioritise descriptive rather than prescriptive studies and to focus on methodological development as a necessity for theoretical progress. The subsequent empirical studies can therefore be understood as targeted responses to the reference model: the Design Conflict Test directly addresses the measurable success criterion by proposing a prototype psychometric instrument. Although the test remains at a prototype stage whereby further iteration is needed to refine the test for wider use - it provides much potential from initial results with tangible areas for improvement. In this respect, a clear contribution to establishing suitable tests and metrics for investigating cognitive processes in design has been made. Furthermore, the mixed-methods evaluation strategy responds to the broader success criterion by strengthening the basis for cumulative, theory-driven understanding of design cognition. Through this, the reference model can be seen both as an initial diagnostic tool and as a link between identified research challenges, methodological choices, and the contributions ultimately delivered by this thesis.

9.1 Summary of contributions to knowledge

9.1.1 K1 - A FBS theory of conflict

The first contribution is the development of an FBS-based theory of cognitive conflict in design. Building on the Function-Behaviour-Structure (FBS) framework, the thesis proposes that a trigger of cognitive conflict in design occurs when perceiving the function, behaviour, and structure of a concept. That is, an intuitive interpretation could contrast to an analytic interpretation (Type 1-Type 2 conflict), or two competing intuitive interpretations could arise (Type 1-Type 1 conflict). This extends the default-interventionist account of dual-process theory into a design-specific mechanism by specifying how intuitive defaults, conflict detection, and potential analytic override are instantiated in visual and physical representations rather than in abstract verbal or numerical problems.

The FBS theory of conflict contributes conceptually by (1) linking a core design theory (FBS) with a core cognitive theory (DPT); (2) specifying one plausible mechanism through which Type 2 processing is engaged in design; and (3) opening up a wider space of possible conflict sources, including representational conflict, requirement-solution mismatches, and metacognitive triggers such as feelings of rightness or lack of progress. In doing so, it provides a theoretically grounded way of talking about cognitive conflict in design that can be operationalised in empirical work, as demonstrated in DS I.

9.1.2 K2 - The Design Conflict Test

The second contribution is methodological and concerns the development and initial evaluation of the Design Conflict Test. The DCT translates the logic of heuristics-and-biases tasks into a design context by using FBS-based items that elicit an intuitive lure response alongside a normatively superior alternative that requires deeper analytic engagement. The test was constructed to position designers along a spectrum of conflict-resolution tendencies in design, rather than to measure general intelligence or working-memory capacity.

Empirically, DS I shows that the DCT can induce design-relevant cognitive

conflict. Eye-tracking measures, feelings-of-rightness, and response patterns are consistent with the activation of intuitive responses, detection of conflict in at least some cases, and optional engagement of more effortful reasoning. The independence of DCT scores from working-memory capacity and the lack of correlation with the CRT indicate that the test does not simply reproduce existing measures of analytic ability but taps into a more design-specific disposition toward detecting and resolving FBS conflict. Using Messick's unified framework, the thesis provides initial evidence for content, substantive, structural, and predictive aspects of validity, while being explicit about the current limits of generalisability and the exploratory nature of the instrument.

As such, the DCT is a contribution not only as a specific prototype tool but as a proof of concept and template for design psychometrics. It illustrates how domain-specific constructs can be operationalised using psychometric principles, how process data (eye-tracking, metacognitive judgements) can support validity arguments, and how such instruments can be linked to richer process analyses in subsequent studies.

9.1.3 K3 - Dual-processing dispositions in design behaviour

The third contribution concerns what dual-process theory reveals about design cognition when applied through the lens of FBS conflict, psychometric testing, and linkographic analysis. Taken together, DS I and DS II show that dual-process constructs are observable in design and that they help to explain meaningful variation in design behaviour.

First, the work supports the view that intuitive and analytic processes interact throughout conceptual design, rather than being cleanly separated into generative and evaluative phases. Designers in DS II showed different patterns in how they relied on early intuitive cues, sustained analytic exploration, or balanced iterative switching. These patterns appeared even under identical task conditions and similar levels of formal expertise, highlighting that the coordination of Type 1 and Type 2 processing is an individual-difference variable with process consequences.

Second, the thesis suggests that design cognition involves domain-specific thinking dispositions or mindware that are not captured by domain-general measures

like the CRT. The dissociation between DCT and CRT scores, combined with the effective but low-CRT performance of Dyad 3, indicates that well-internalised design knowledge, visual reasoning, and sensitivity to FBS conflict can support productive behaviour even when general analytic scores and working-memory capacity are relatively low. This points to a form of design-specific rationality that is grounded in situated, representational reasoning rather than purely abstract logic.

Third, the work highlights the central role of metacognitive regulation in effective designing. The most productive dyad showed signs of more adaptive switching between divergent and convergent activity, more distributed critical moves, and higher integration of ideas, consistent with more sensitive and better calibrated metacognitive control over when to trust intuition, when to intervene analytically, and when to reframe. By connecting these observations with fundamental heuristic and analytic biases, the thesis offers a psychologically grounded account of phenomena such as fixation, premature convergence, and iterative synthesis.

Table 9-1 - Summary of contributions

Challenges	Contribution	Description
Lack of alignment with ontology and methodological standards with established fields	K1 - FBS Conflict theory	Proposes one, of potentially many, mechanisms for conflict in design, integrating DPT with the FBS framework
Lack of suitable tests and metrics for design cognition research	K2 - The DCT as a prototype psychometric test for DPT in design	Demonstrates how DPT constructs can be operationalised in design; contributes item-design principles, mindware considerations, visual reasoning considerations, and multi-aspect validity evidence for the DCT.
Lack of quantitative and qualitative method combination	K3 - Dual-process dispositions in design behaviour	Integrates quantitative psychometric profiles with more qualitative linkographic patterns; identifies alignment of Type 1/Type 2 cognitive tendencies in design with fundamental DPT biases; discusses the role of metacognition from a DPT perspective.

9.2 Future work, strengths, and limitations

Objective 4 was to evaluate the overall contribution of the research, recognising its strengths, limitations, and future directions. This was done through the discussion presented in Chapter 8. This thesis has presented largely exploratory work into addressing current challenges in consistency and rigour in the field of design cognition. Indeed, this is visualised in Figure 9-1 whereby this work and its contributions are situated within a single initial spiral in the theory building and testing cycle. This work, therefore, leaves a broad scope for directing future work in design cognition research, presents strengths in its drive towards novel theory and methods, and is limited by its exploratory nature. While the discussion focused on broader insights and implications, here, the key strengths, limitations, and more immediate future work are discussed.

A central strength of this research lies in its theory-driven integration of cognitive psychology and design cognition. This thesis anchors its theoretical development in an established dual-process framework and adapts it to the epistemic and representational characteristics of design (FBS conflict theory and the DCT). Methodologically, the combined use of psychometric testing, eye-tracking, and linkographic analysis represents a further strength, demonstrating how individual-difference measures can be meaningfully connected to observable design behaviour. This mixed-methods strategy responds directly to calls for greater rigour, comparability, and theoretical grounding in design cognition research.

Alongside strengths in novel theory and method development, several limitations constrain the scope and strength of the claims that can be made. Most prominently, the Design Conflict Test remains a prototype instrument. Being built as a design-focused variation of the belief-bias test, the DCT operationalised FBS conflict as a proposed trigger of Type 2 engagement in design. While DS I provided encouraging evidence that DCT items elicit cognitive conflict and engage both intuitive and analytic processing, the divergence from predicted correlations, and divergence in item metrics indicate that further refinement is required. This divergence may be due to limitations in item design, such as uneven conflict strength across items. It may also reflect a genuine dissociation between design-specific conflict resolution and domain-general analytic reasoning. At this stage, the data do not permit a definitive conclusion between

these explanations. In addition, the use of a relatively homogeneous and small student sample limits claims regarding generalisability across levels of expertise, and the small number of dyads analysed in DS II necessarily constrains the strength of predictive inferences drawn from linkographic patterns.

Immediate future work (outlined in Figure 9-1) should, therefore, prioritise refinement, calibration, and replication. For the DCT, this includes item revision guided by empirical indicators of conflict strength, such as feelings of rightness and eye-tracking metrics, alongside the removal or redesign of weaker items. Iterative pilot testing with larger samples would enable more robust assessment of internal consistency and item discrimination. Additionally, psychometric tests in cognitive psychology often manipulate conditions such as time constraints or cognitive load to preferentially activate Type 1 or Type 2 processing. Similar manipulations hold substantial potential for design cognition research and would enhance construct validity by making the cognitive processes driving performance more transparent. In parallel, assessing relevant domain knowledge explicitly, or applying more intuitive engineering principles would help disentangle reasoning tendencies from knowledge gaps.

Testing across different samples should be a further focus of immediate future work. Applying the DCT across novice, intermediate, and expert designers would allow examination of how intuitive processing, conflict detection, and analytic intervention shift with experience. Analysing how tendencies within this present in the design process would add further insight. Indeed, replicating the linkographic analysis with a larger and more diverse sample would strengthen the evidential basis for linking DCT profiles to design process patterns and fundamental biases. Future work should retain the individual-differences sampling logic used here, as this proved critical for revealing tentative relationships between cognitive capacity, design-specific disposition, and observed behaviour.

This work presents a realistic pathway for future research to move from identifying patterns of dual processing in design toward more precise accounts of when and how specific instances of intuitive and analytic processing are engaged. However, such ambitions depend on methodological refinement alongside strong theoretical

grounding. The principal strength of this thesis is, therefore, not that it resolves around questions of optimal ratios of Type 1 and Type 2 processing or prescribes ideal design behaviour, but that it establishes a credible empirical and theoretical platform from which such questions can now be asked with greater precision and rigour. From this, could we determine which ratio of Type 1 to Type 2 processing is most productive or novel in design? Do these ideal ratios differ at each stage of the design process? And can these ideals be manufactured through design methods and tools developed or applied accordingly? The future of such work holds exciting possibility.

Ultimately, design cognition research is under pressure to strengthen its impact and theory development. Here, dual-process theory has been used to provide new theoretical insights, methodological tools, and an example of how we can approach current challenges in the field. While dual-process theory is subject to nuanced debate - it provides much utility to the broader picture of design research. It is clear that the vast majority of our behaviour - including in design - is controlled by intuitive and automatic processing. This processing is often very effective and balances out limitations in our effortful cognitive capacity. Further, the central working memory system is involved in successfully performing a wide range of cognitive functions in design. These two proposals are well-founded in the literature and mean that our overall cognitive processing must be explained by some form of dual-processing theory accounting for these autonomous and executive processes. The fundamental nature of this idea contrasts the design field's significant lack of research and descriptive investigations on the topic. The need for greater research impact and theory development in design may, therefore, depend on the incorporation of such concepts and underlying research approaches involved in dual-process theory.

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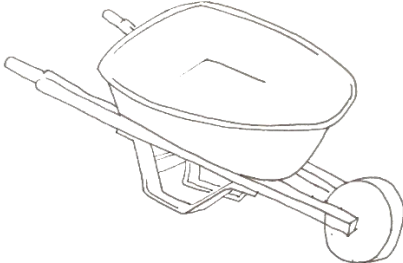

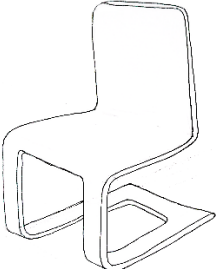
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APPENDICES

Appendix 1: No conflict DCT items

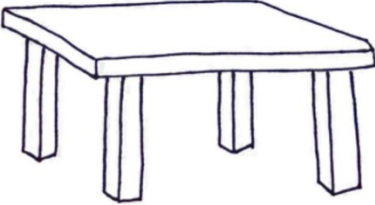
The table below presents the 4 no conflict items presented as control items in the DCT administered in Descriptive Study I. Inspiration was taken from The Uncomfortable (<https://www.theuncomfortable.com>) - a collection of deliberately inconvenient everyday objects by architect Katerina Kamprani.

Item	Sketch image	Looks like it works and does	Looks like it does not work and does not
Fork			X
Wheelbarrow		X	
Teapot			X
Chair		X	

Appendix 2: Full DCT

Here the full Design Conflict Test, items, multiple choice answers, and control items are given. These were presented with the example question first, followed by the opportunity to ask the researcher any questions, then the DCT items and control items were presented followed by the confidence rating screen after each.

Example question:

Works: Table would hold expected weights	<p>Example question</p>  <p>Table</p>	Fails: Table would fail under expected weights
Fails: Objects would easily slide off the table		Works: Users would sit comfortably at the table

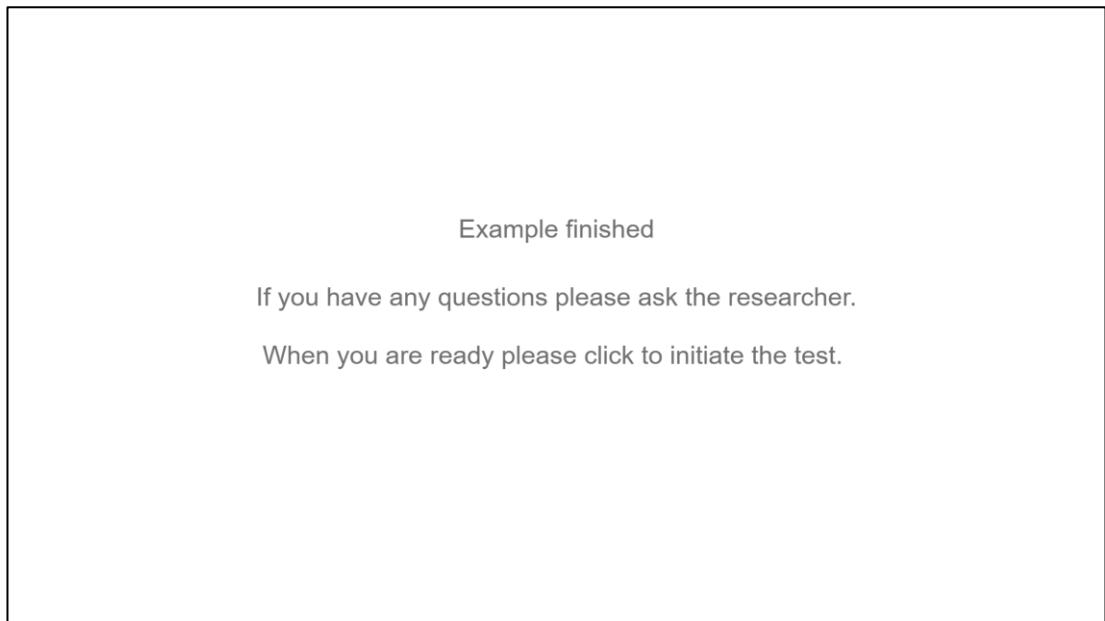
Question confidence rating:

Please state verbally your confidence
in your response on a scale of 0-100?

0 (no confidence) - 100 (high confidence)

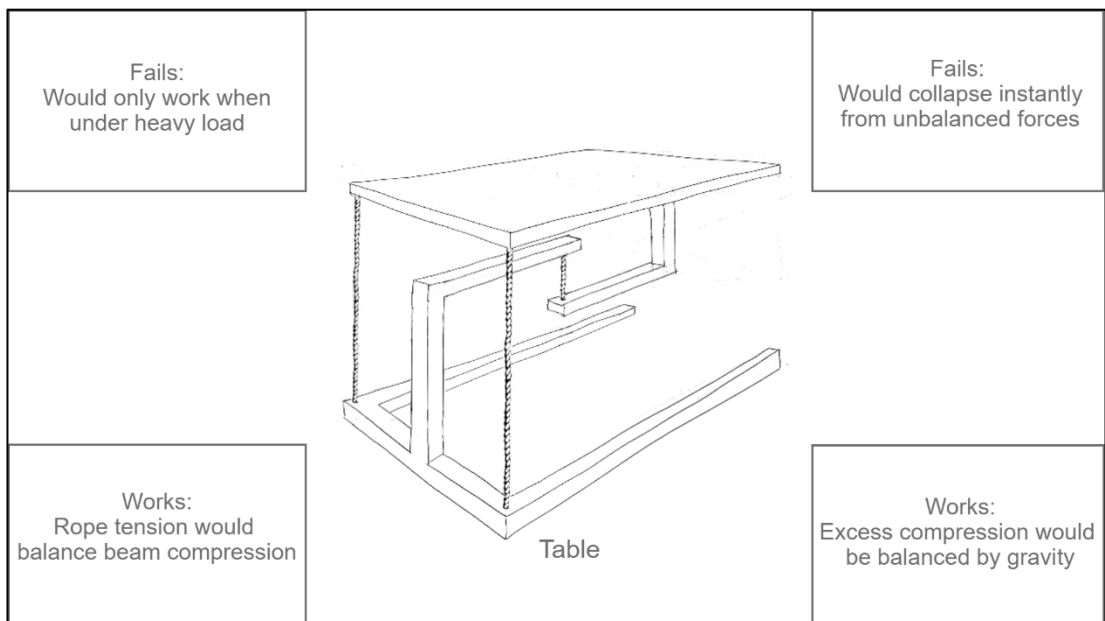
Click to continue when ready

Example finished screen:

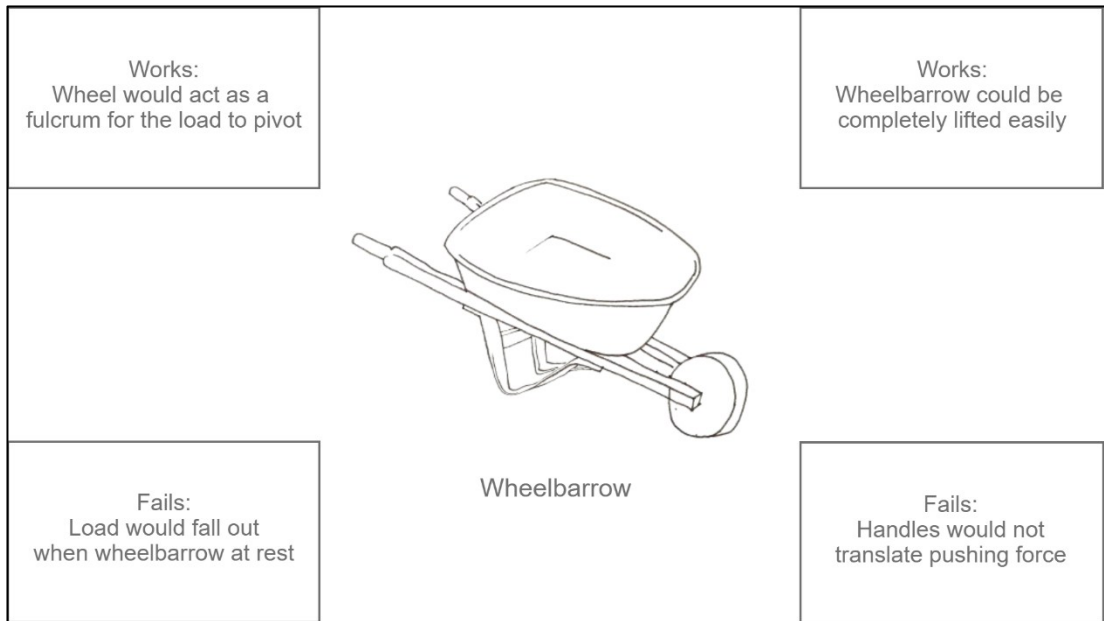


Subsequent questions were randomised and with each item followed by a confidence rating screen.

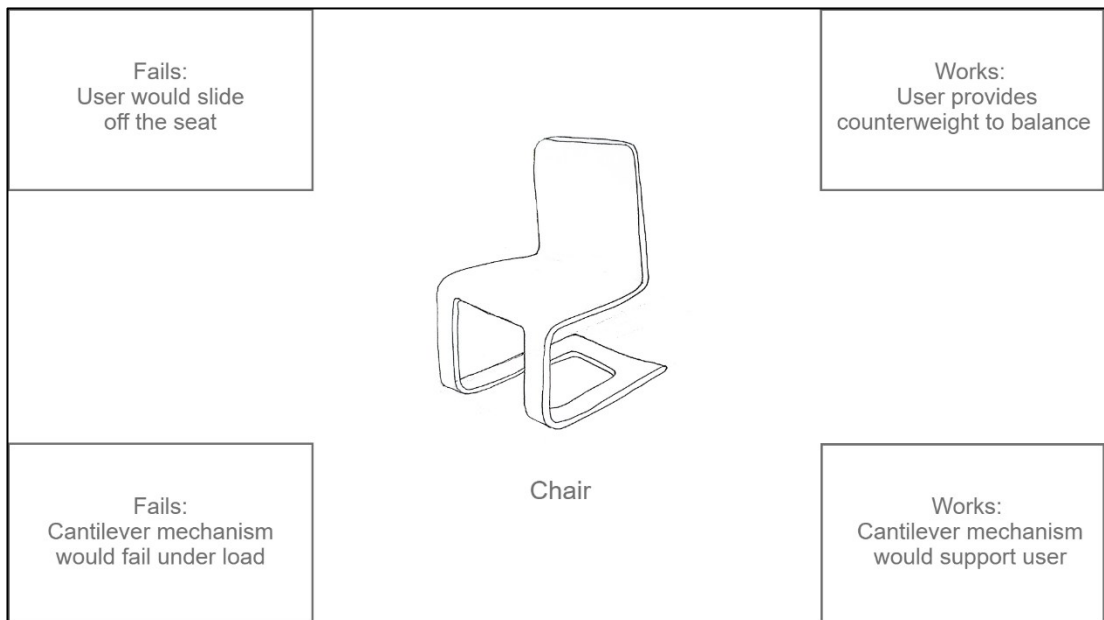
Table Item:



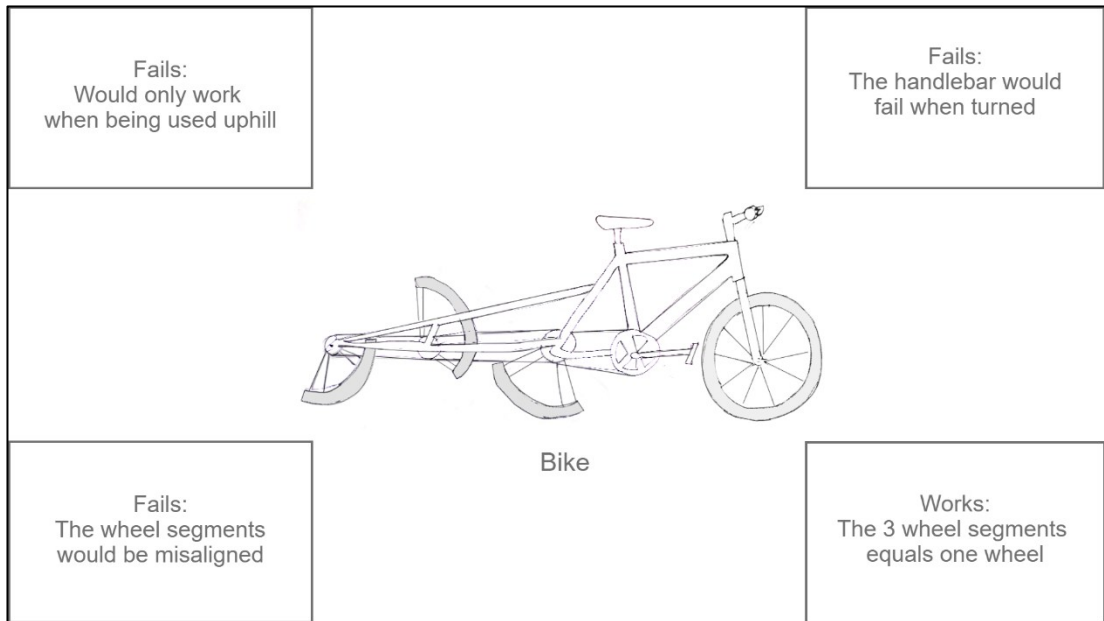
Wheelbarrow control item:



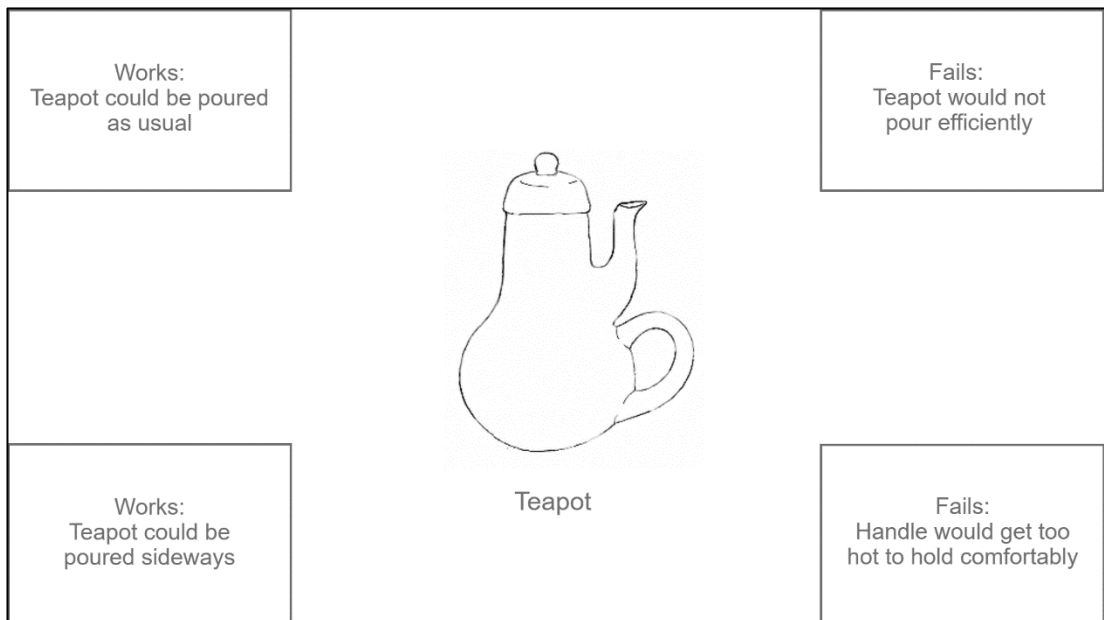
Chair control item:



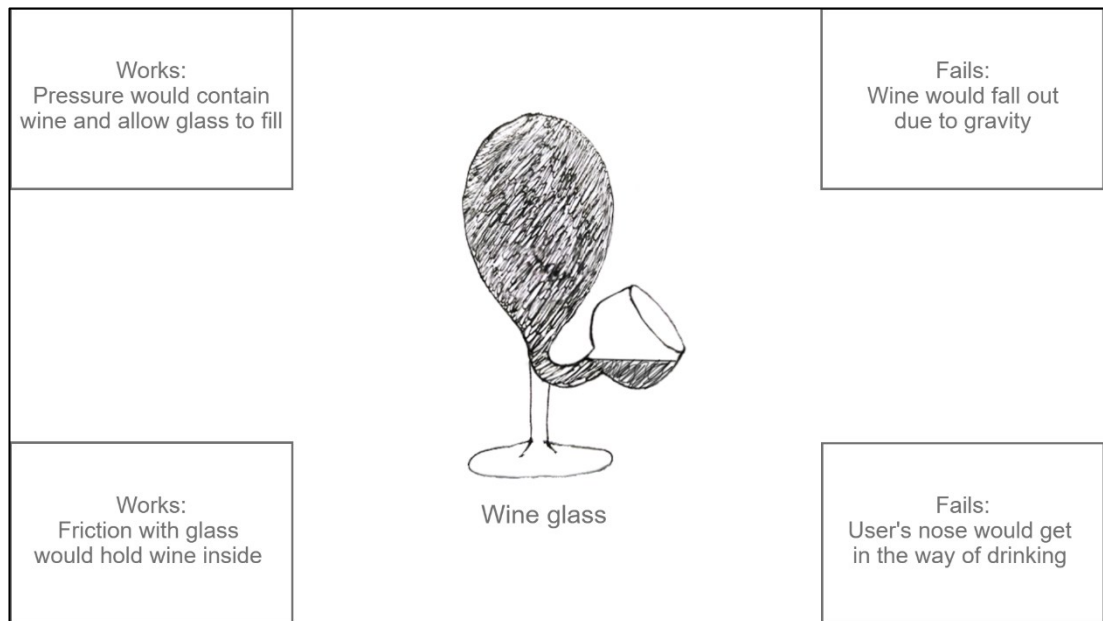
Bike item:



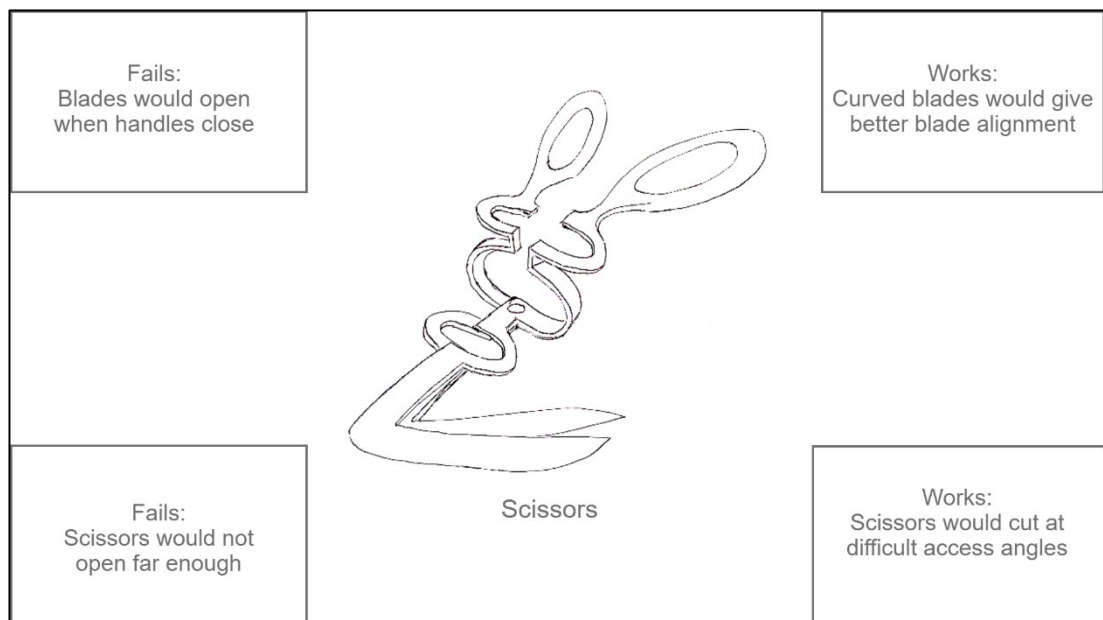
Teapot control item:



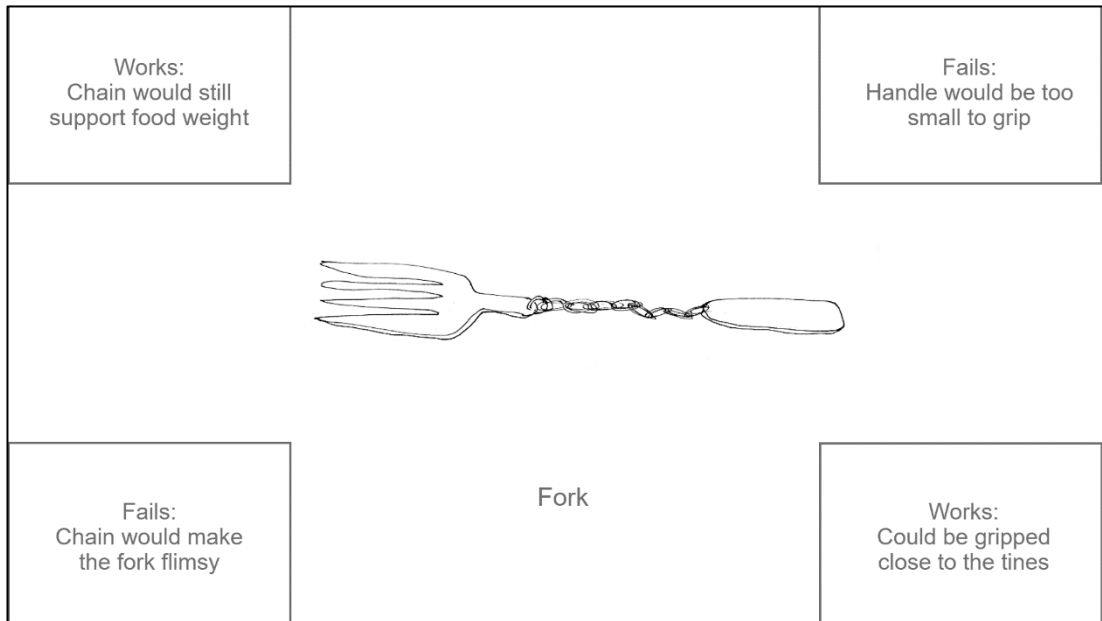
Wine glass item:



Scissors item:



Fork control item:



Appendix 3: DS I participant information and instructions

Written information sheet:

Name of department: Design, Manufacturing, and Engineering Management

Title of the study: Design Thinking Study

Introduction

Researcher: Emma Lawrie

Position: PhD Candidate, Department of DMEM

Email: emma.lawrie.2015@uni.strath.ac.uk

What is the purpose of this research?

This research aims to discover new knowledge on how designers think. This knowledge can ultimately be used to improve design teaching, methodology, and practice through building a solid theoretical foundation of design.

Do you have to take part?

It is your decision whether to take part in the research or not (participation is voluntary). You are allowed to refuse to participate or withdraw participation at any time with no negative consequences.

What will you do in the project?

You will be asked to complete a short design task while speaking your design process and thoughts aloud. This will be followed by a short break and then you will be asked to perform a series of screen-based and verbal tests. The total experiment time will be roughly 1 hour and 15 minutes including the break.

Why have you been invited to take part?

You have been asked to take part because of a design and engineering background as a student in the DMEM department at the university of Strathclyde.

What information is being collected in the project?

Information is being collected on your test responses, eye-tracking data, audio and video recording of your voice and sketching during the design task (no video of your face will be taken), and video recording of your eyes during the eye-tracking.

Who will have access to the information?

Information will be anonymised, kept confidential, and only accessible by the primary researcher.

Where will the information be stored and how long will it be kept for?

Information will be stored according to the University of Strathclyde Data Management Policy. The data will be stored for a minimum of 5 years.

Thank you for reading this information – please ask any questions if you are unsure

about what is written here.

All personal data will be processed in accordance with data protection legislation. Please read our Privacy Notice for Research Participants [provided](#) for more information about your rights under the legislation.

What happens next?

If you would like to participate, please continue reading and sign the consent form overleaf. If you would not like to participate, thank you for your attention.

Verbal instructions:

This study will consist of two main parts. The first is a design task where you will be given 30 minutes to narrow down to a final concept from a given brief. You will then be given a 10-minute break and then asked to come back for the second part which involves some screen-based tests and the eye-tracking equipment.

You are welcome to stop the experiment at any time. Are you happy to continue?

Protocol Explanation:

During the design task I would like you to voice all your thoughts. Think aloud as you are designing. Try to say as much as possible on your thoughts, actions and feelings.

Here is the design brief. Let me know if you have any questions. Feel free to familiarise yourself with the drawing tools in front of you.

Please try to speak clearly and not too quietly. You have 30 minutes, I will let you know when you are at 15 minutes and when you have 5 minutes left.

Tests:

This second part of the experiment has three sections – two sets of screen-based questions and then a verbal test without the screen. We are now going to set up the eye-tracking equipment.

When you are ready please click to begin and follow the instructions on the screen.

On this tape you are going to hear a series of single digit numbers that will be presented at the rate of one every 3 seconds. Listen for the first two numbers, add them up, and tell me your answer. When you hear the next number, add it to the one you heard on the tape right before it. Continue to add the next number to each preceding one. Remember, you are not being asked to give me a running total, but rather the sum of the last two numbers that were spoken on the tape.

For example, if the first two numbers were '5' and '7,' you would say '12.' If the next number were '3,' you would say '10.' Then if the next number were '2,' you would say '5.' (If the participant was having difficulty understanding these instructions, the numbers 5, 7, 3, and 2 were written on a sheet of paper and instructions repeated, demonstrating how the task was done).

This is a challenging task. If you lose your place, just jump right back in - listen for two numbers in a row and add them up and keep going. There are some practice items at the beginning of the tape. Let's try those first. Do not count on your fingers

You will now have the same experiment but with a 2 second interval between numbers instead of 3. This is faster so more challenging, but again, if you lose your place just jump back in. You will get a short practice round now.

Now you will be presented with the full 2 second interval test.

Appendix 4: CRT and DCT monitor instructions:

CRT instruction page:

You will be presented with a series of 3 questions.
Please take as much time as you need to answer, then
give this answer verbally.

Click when you are ready to proceed

DCT instruction page:

You will now be presented with a series of product sketches and be asked
to determine if they look like they WORK or would FAIL.

Please click the answer and given reasoning you think is **most accurate**.

There is not necessarily only one correct answer.

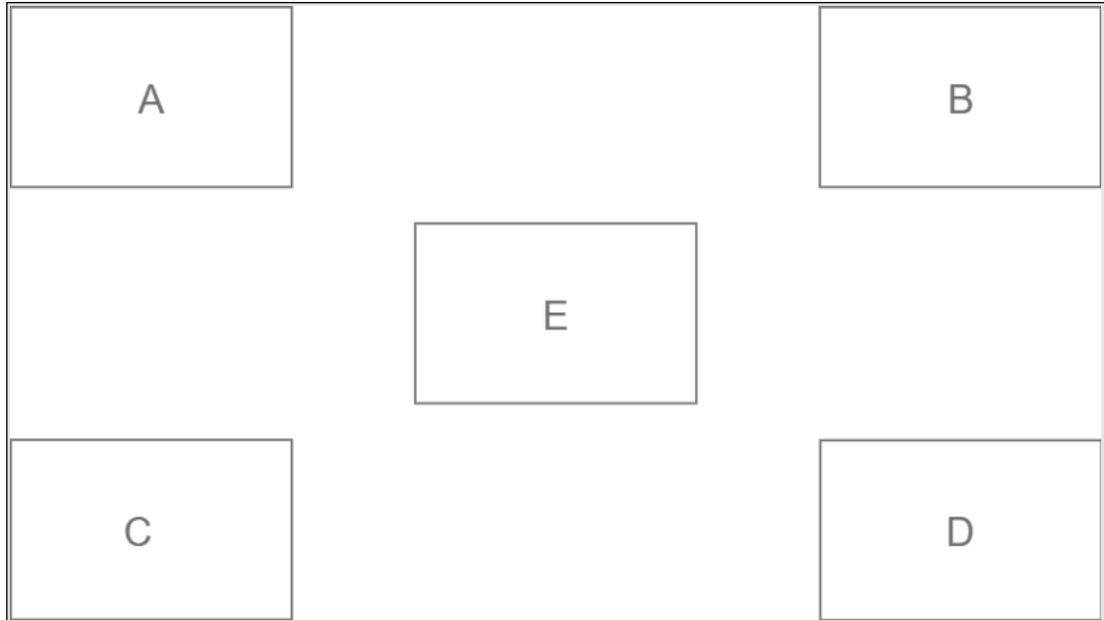
After each, you will be asked to rate your confidence in your answer on a
scale from 0-100, where 0 is low confidence and 100 is high confidence.

Take as much time as you need.

Please click when you are ready to see an example.

Appendix 5: DCT eye-tracking calibration screen

Before completing the DCT, participants were instructed to look at each letter to confirm if the calibration was accurate. If it was not, the calibration was repeated and this screen was shown again to test the accuracy. This process was repeated until the calibration was accurate with the screen shown below.



Appendix 6: DS I Statistical tests and assumptions

Here tables and graphs of the statistical tests performed on DS I data are displayed. All tests were performed on SPSS guided by Laerd Statistics guides.

Normality assessment of psychometrics:

Here it can be seen that the only normally distributed variable is the PASAT.

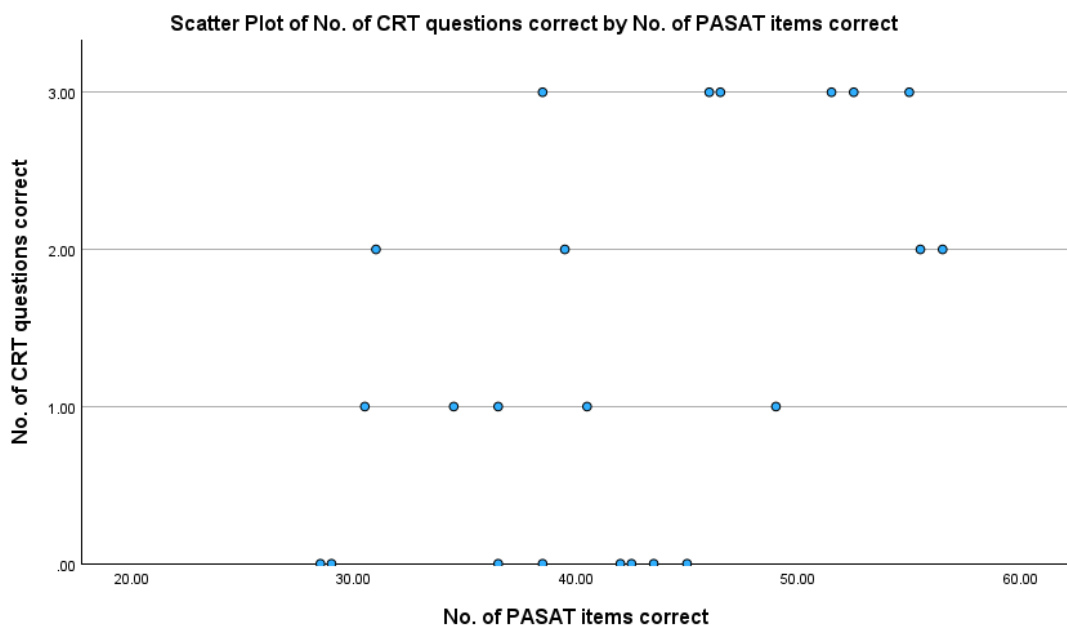
	Tests of Normality					
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
No. of CRT questions correct	.211	23	.009	.824	23	<.001
No. of PASAT items correct	.080	23	.200*	.960	23	.473
No. of DCT questions correct	.225	23	.004	.902	23	.028

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Correlational analyses of psychometrics:

CRT and PASAT Monotonic relationship:



CRT and PASAT Spearman's Rank Order Correlation:

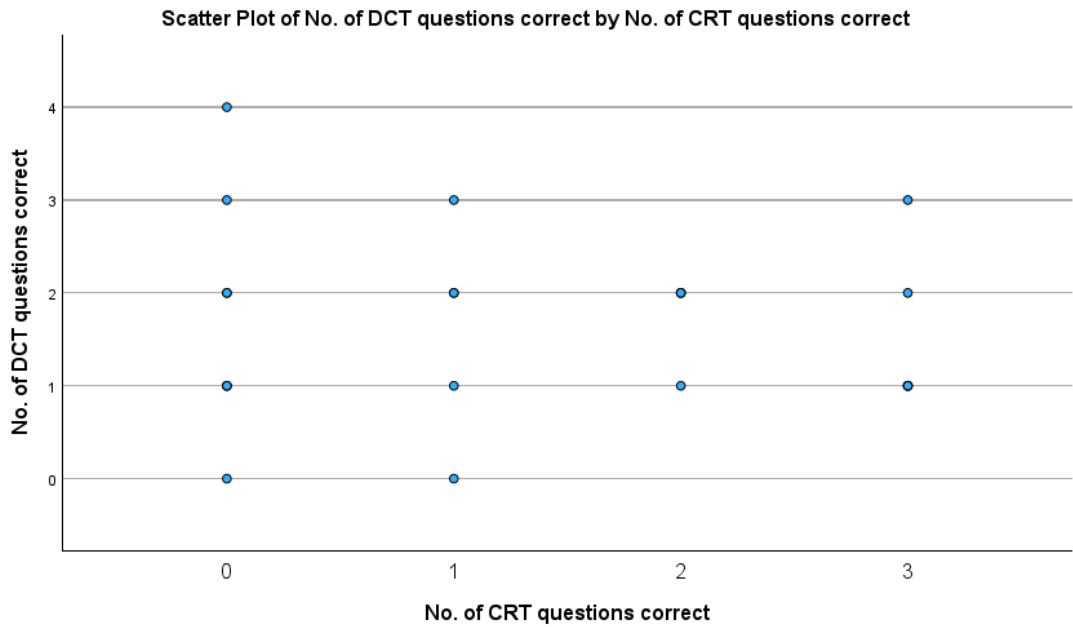
Nonparametric Correlations

Correlations

			No. of CRT questions correct	No. of PASAT items correct
Spearman's rho	No. of CRT questions correct	Correlation Coefficient	1.000	.499*
		Sig. (2-tailed)	.	.015
		N	23	23
	No. of PASAT items correct	Correlation Coefficient	.499*	1.000
		Sig. (2-tailed)	.015	.
		N	23	23

*. Correlation is significant at the 0.05 level (2-tailed).

CRT and DCT Non-Monotonic relationship:



CRT and DCT Linear regression model:

No. of CRT questions correct

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.084	.007	-.040	1.253

The independent variable is No. of DCT questions correct.

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.232	1	.232	.148	.705
Residual	32.986	21	1.571		
Total	33.217	22			

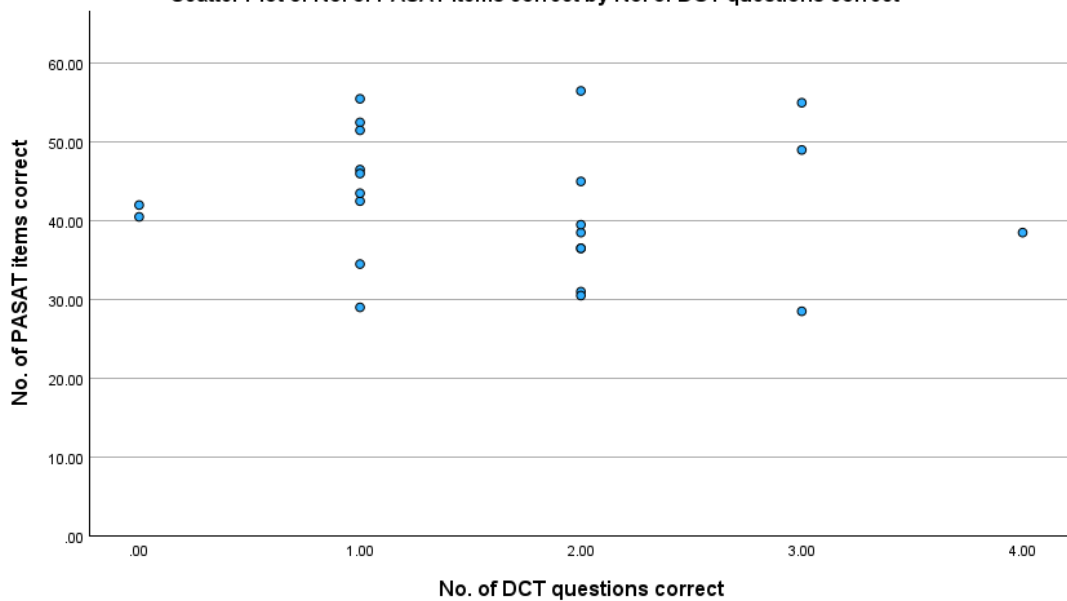
The independent variable is No. of DCT questions correct.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
No. of DCT questions correct	-.105	.272	-.084	-.384	.705
(Constant)	1.520	.520		2.924	.008

9.2.1.1 *DCT and PASAT Non-Monotonic relationship*

Scatter Plot of No. of PASAT items correct by No. of DCT questions correct



DCT and PASAT Linear regression model:

No. of PASAT items correct

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.108	.012	-.035	8.712

The independent variable is No. of DCT questions correct.

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	18.771	1	18.771	.247	.624
Residual	1593.838	21	75.897		
Total	1612.609	22			

The independent variable is No. of DCT questions correct.

Coefficients

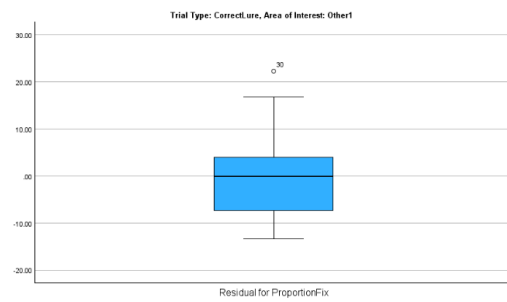
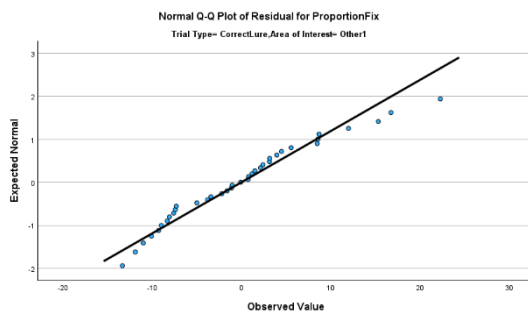
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
No. of DCT questions correct	-.941	1.891	-.108	-.497	.624
(Constant)	43.684	3.614		12.086	<.001

Two-way Anova Fixations:

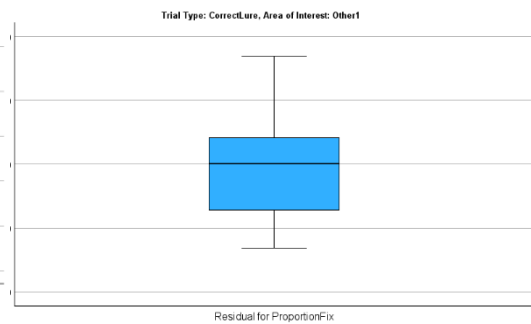
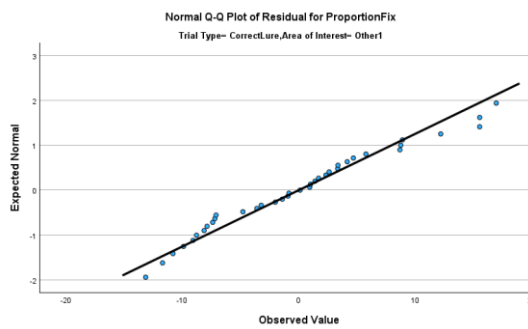
Outliers:

Correct Conflict Trial – Other 1:

Pre-outlier modification:

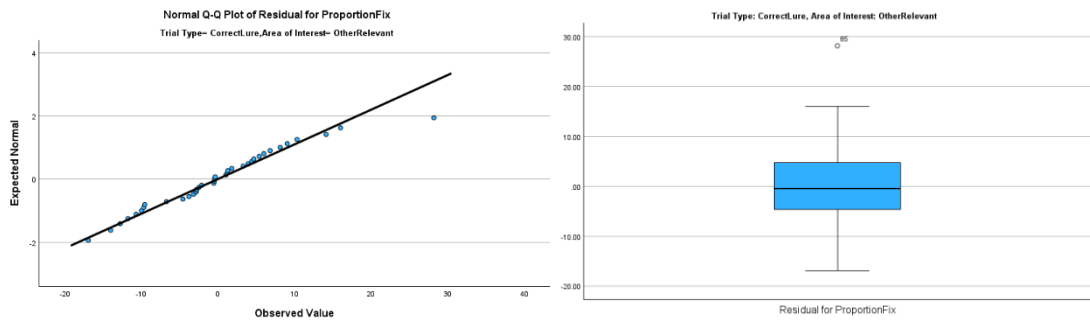


Post-outlier modification:

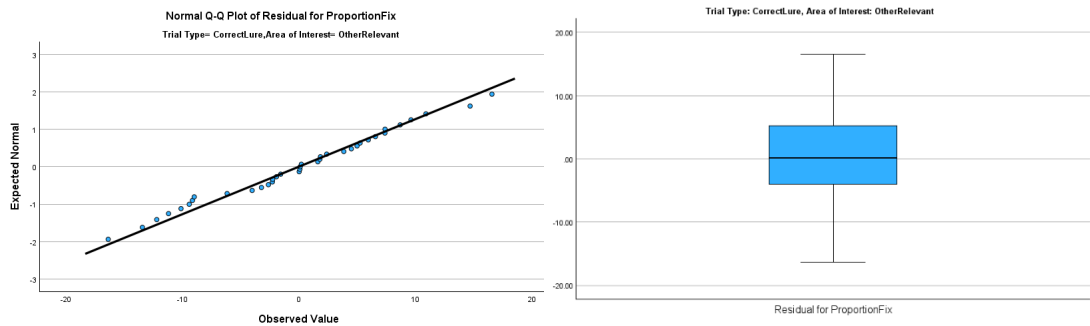


Correct Conflict – Other Relevant:

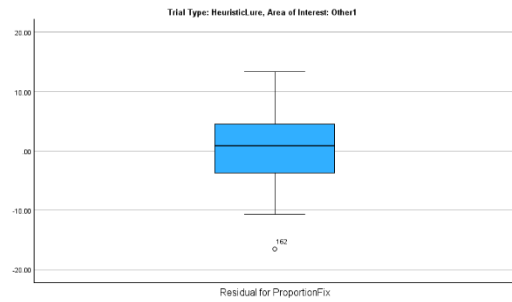
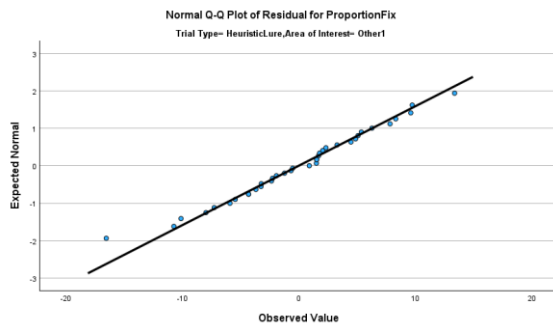
Pre-outlier modification:



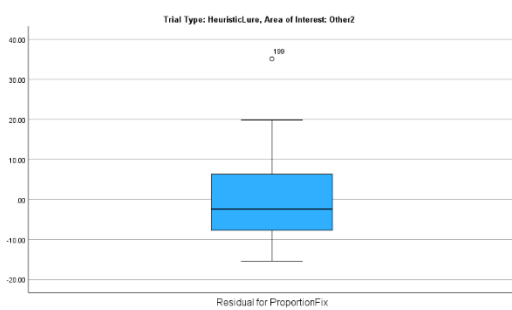
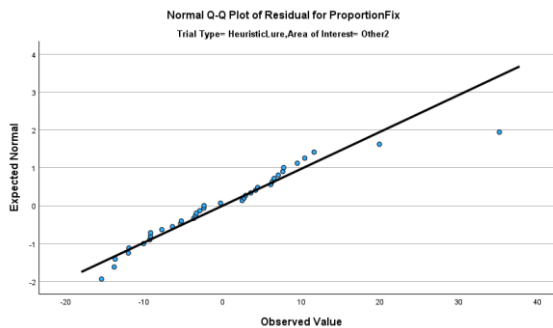
Post-outlier modification:



Heuristic Conflict – Other 1:



Heuristic Conflict – Other 2:



Normality:

For the two-way ANOVA on fixations - proportion of fixations across AOI and Trial Type - Data was normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$).

Tests of Normality

Trial Type	Area of Interest	Residual for ProportionFix	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
			Statistic	df	Sig.	Statistic	df	Sig.
CorrectLure	Other1	Residual for ProportionFix	.111	37	.200*	.963	37	.256
	Other2	Residual for ProportionFix	.072	37	.200*	.972	37	.451
	OtherRelevant	Residual for ProportionFix	.089	37	.200*	.985	37	.893
	Selected	Residual for ProportionFix	.075	37	.200*	.988	37	.960
HeuristicLure	Other1	Residual for ProportionFix	.071	37	.200*	.988	37	.959
	Other2	Residual for ProportionFix	.100	37	.200*	.966	37	.312
	OtherRelevant	Residual for ProportionFix	.073	37	.200*	.986	37	.908
	Selected	Residual for ProportionFix	.104	37	.200*	.971	37	.431

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Homogeneity of variances:

Levene's Test of Equality of Error Variances^{a,b}

		Levene Statistic	df1	df2	Sig.
Proportion of Fixations	Based on Mean	2.977	7	288	.005
	Based on Median	2.771	7	288	.008
	Based on Median and with adjusted df	2.771	7	256.487	.009
	Based on trimmed mean	2.946	7	288	.005

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Dependent variable: Proportion of Fixations

b. Design: Intercept + TrialType + AOI + TrialType * AOI

Interaction Effect of Trial Type and AOI:

Tests of Between-Subjects Effects

Dependent Variable: Proportion of Fixations

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	9328.985 ^a	7	1332.712	17.435	<.001	.298
Intercept	183354.587	1	183354.587	2398.676	<.001	.893
TrialType	1.895	1	1.895	.025	.875	.000
AOI	8884.358	3	2961.453	38.742	<.001	.288
TrialType * AOI	442.733	3	147.578	1.931	.125	.020
Error	22014.695	288	76.440			
Total	214698.267	296				
Corrected Total	31343.680	295				

a. R Squared = .298 (Adjusted R Squared = .281)

Main effects – unbalanced design – unweighted marginal means:

Unweighted marginal means of Area of Interest:

Estimates

Dependent Variable: Proportion of Fixations

Area of Interest	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Other1	20.351	1.016	18.350	22.351
Other2	20.815	1.016	18.815	22.816
OtherRelevant	24.409	1.016	22.408	26.409
Selected	33.979	1.016	31.979	35.980

Unweighted marginal means of Trial Type:

Estimates

Dependent Variable: Proportion of Fixations

Trial Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
CorrectLure	24.809	.719	23.394	26.223
HeuristicLure	24.969	.719	23.554	26.383

Main effect of AOI and Trial Type:

Tests of Between-Subjects Effects

Dependent Variable: Proportion of Fixations

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	9328.985 ^a	7	1332.712	17.435	<.001	.298
Intercept	183354.587	1	183354.587	2398.676	<.001	.893
TrialType	1.895	1	1.895	.025	.875	.000
AOI	8884.358	3	2961.453	38.742	<.001	.288
TrialType * AOI	442.733	3	147.578	1.931	.125	.020
Error	22014.695	288	76.440			
Total	214698.267	296				
Corrected Total	31343.680	295				

a. R Squared = .298 (Adjusted R Squared = .281)

Differences between marginal means for AOI:

Pairwise Comparisons

Dependent Variable: Proportion of Fixations

(I) Area of Interest	(J) Area of Interest	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference ^b	
					Lower Bound	Upper Bound
Other1	Other2	-.464	1.437	1.000	-4.283	3.354
	OtherRelevant	-4.058*	1.437	.031	-7.876	-.240
	Selected	-13.629*	1.437	<.001	-17.447	-9.810
Other2	Other1	.464	1.437	1.000	-3.354	4.283
	OtherRelevant	-3.594	1.437	.078	-7.412	.225
	Selected	-13.164*	1.437	<.001	-16.983	-9.346
OtherRelevant	Other1	4.058*	1.437	.031	.240	7.876
	Other2	3.594	1.437	.078	-.225	7.412
	Selected	-9.571*	1.437	<.001	-13.389	-5.752
Selected	Other1	13.629*	1.437	<.001	9.810	17.447
	Other2	13.164*	1.437	<.001	9.346	16.983
	OtherRelevant	9.571*	1.437	<.001	5.752	13.389

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

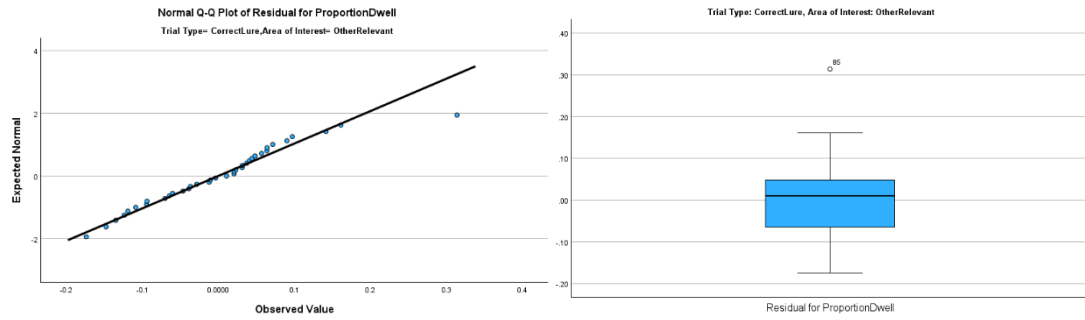
b. Adjustment for multiple comparisons: Bonferroni.

Two-way Anova Dwell:

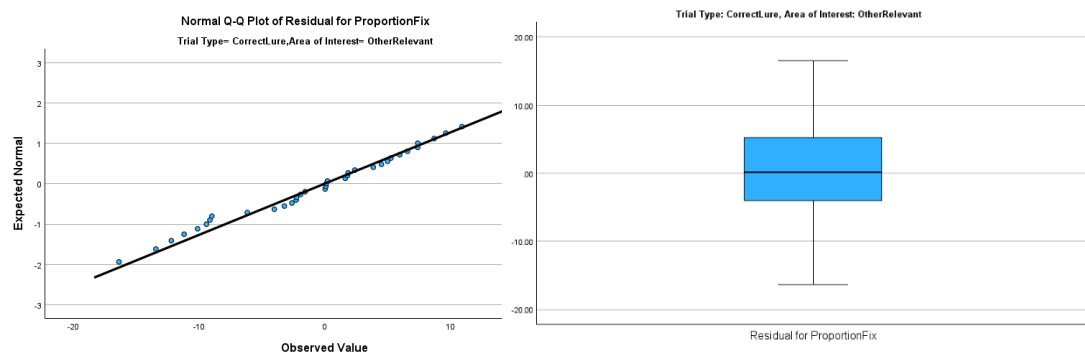
Outliers:

Correct Conflict – Other Relevant:

Pre-outlier modification:

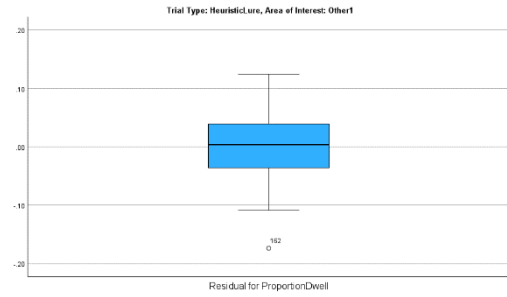
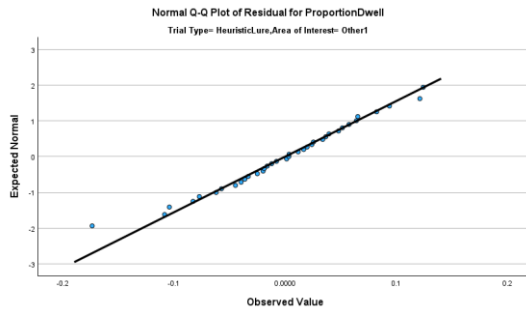


Post-outlier modification:

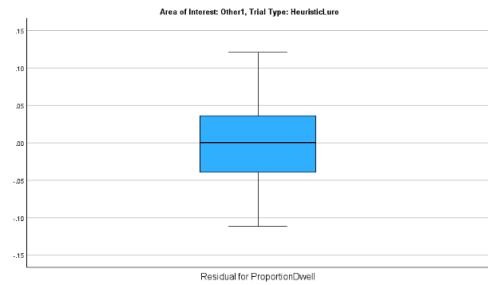
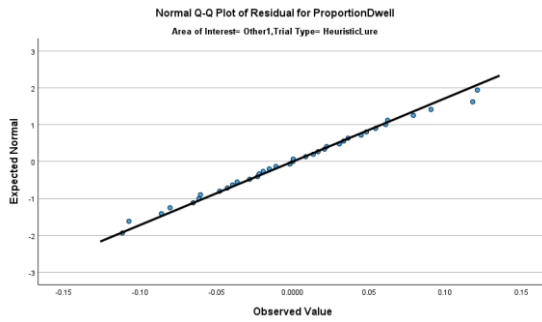


Heuristic Conflict – Other 1

Pre-outlier modification:

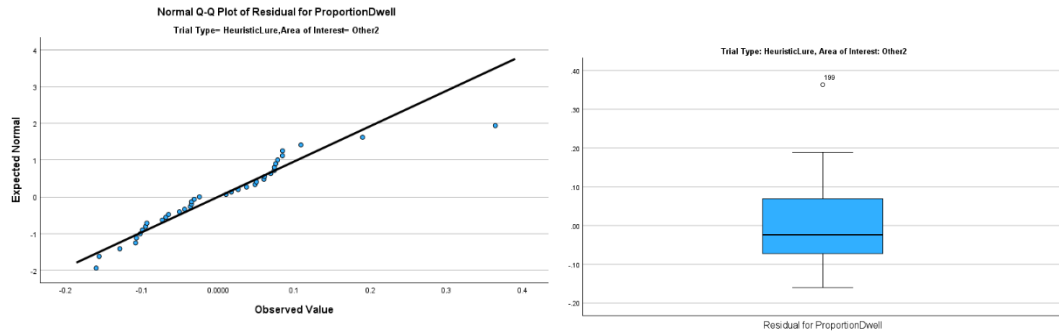


Post-outlier modification:

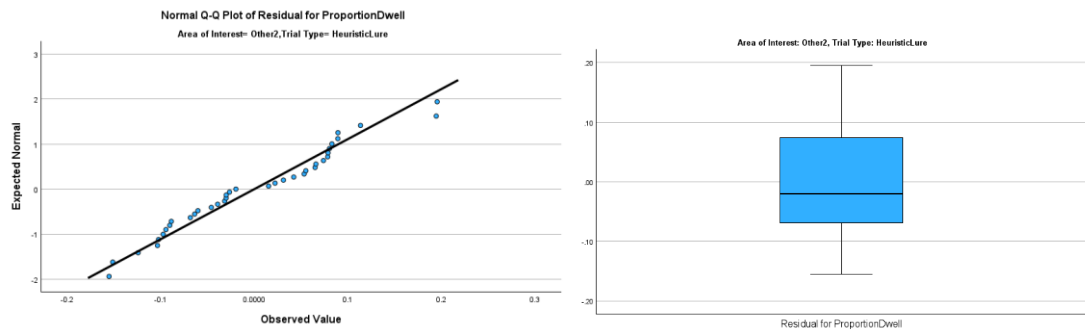


Heuristic Conflict – Other 2

Pre-outlier modification:

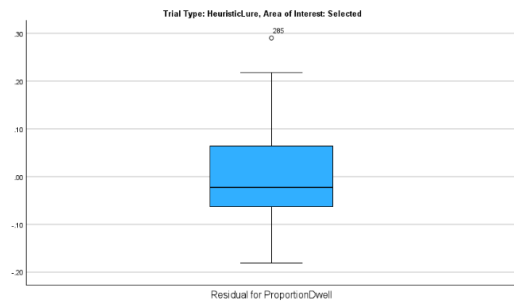
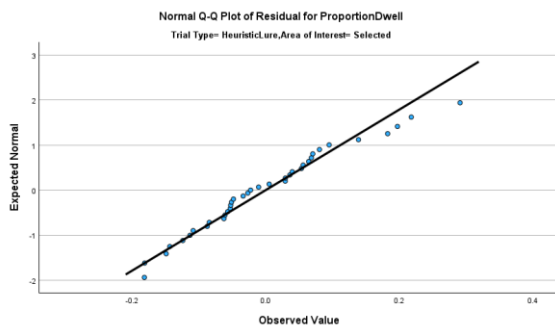


Post-outlier modification:

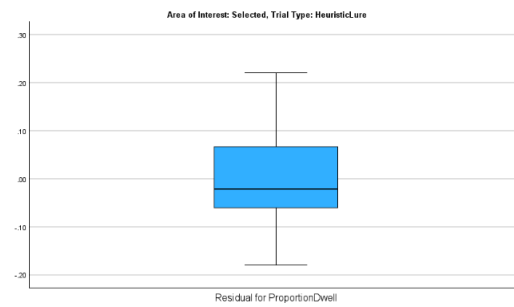
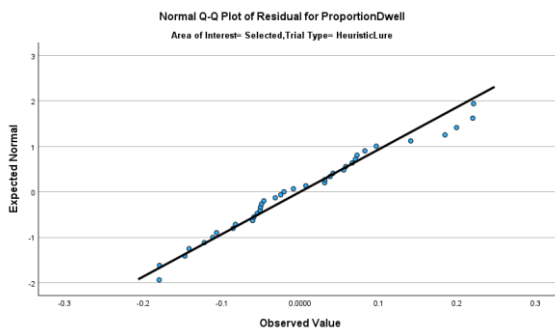


9.2.1.2 Heuristic Conflict – Selected

Pre-outlier modification:



Post-outlier modification:



Normality:

Proportion of Dwell across AOI and Trial Type - Data was normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$).

Tests of Normality

Area of Interest	Trial Type		Kolmogorov-Smirnov ^a			Shapiro-Wilk		
			Statistic	df	Sig.	Statistic	df	Sig.
Other1	CorrectLure	Residual for ProportionDwell	.103	37	.200*	.959	37	.187
	HeuristicLure	Residual for ProportionDwell	.040	37	.200*	.988	37	.960
Other2	CorrectLure	Residual for ProportionDwell	.073	37	.200*	.976	37	.602
	HeuristicLure	Residual for ProportionDwell	.103	37	.200*	.960	37	.195
OtherRelevant	CorrectLure	Residual for ProportionDwell	.117	37	.200*	.977	37	.641
	HeuristicLure	Residual for ProportionDwell	.086	37	.200*	.976	37	.608
Selected	CorrectLure	Residual for ProportionDwell	.104	37	.200*	.984	37	.852
	HeuristicLure	Residual for ProportionDwell	.100	37	.200*	.964	37	.267

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Homogeneity of variances:

Levene's test for Proportion of Dwell - the assumption of homogeneity of variances was violated, as assessed by Levene's test for equality of variances, $p = .004$.

Levene's Test of Equality of Error Variances^{a,b}

		Levene Statistic	df1	df2	Sig.
Proportion of Dwell	Based on Mean	3.107	7	288	.004
	Based on Median	2.789	7	288	.008
	Based on Median and with adjusted df	2.789	7	258.882	.008
	Based on trimmed mean	3.083	7	288	.004

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Dependent variable: Proportion of Dwell

b. Design: Intercept + TrialType + AOI + TrialType * AOI

Interaction Effect of Trial Type and AOI:

Interaction effect of trial type and AOI - there interaction between trial type and AOI for "Proportion of Dwell" was approaching significance, $F(3, 288) = 2.471$, $p = .062$, partial $\eta^2 = .025$.

Tests of Between-Subjects Effects

Dependent Variable: Proportion of Dwell

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.915 ^a	7	.131	15.818	<.001	.278
Intercept	18.311	1	18.311	2214.813	<.001	.885
TrialType	4.772E-5	1	4.772E-5	.006	.939	.000
AOI	.854	3	.285	34.435	<.001	.264
TrialType * AOI	.061	3	.020	2.471	.062	.025
Error	2.381	288	.008			
Total	21.608	296				
Corrected Total	3.296	295				

a. R Squared = .278 (Adjusted R Squared = .260)

Simple main effects for Trial Type:

For correct conflict and heuristic conflict trials in the Other Relevant AOI, mean "Proportion of Dwell" for heuristic conflict trials was 26.96 ± 11.54 and 22.61 ± 8.19 for correct conflict trials, a statistically significant mean difference of 4.3 (95% CI, 0.20 to 8.50), $F(1, 288) = 4.23$, $p = 0.041$, partial $\eta^2 = .014$.

Univariate tests for Proportion of dwell in the simple main effects of trial type:

Univariate Tests

Dependent Variable: Proportion of Dwell

Area of Interest		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Other1	Contrast	.001	1	.001	.075	.784	.000
	Error	2.381	288	.008			
Other2	Contrast	.002	1	.002	.231	.631	.001
	Error	2.381	288	.008			
OtherRelevant	Contrast	.035	1	.035	4.229	.041	.014
	Error	2.381	288	.008			
Selected	Contrast	.024	1	.024	2.885	.091	.010
	Error	2.381	288	.008			

Each F tests the simple effects of Trial Type within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Pairwise comparisons for proportion of dwell in the simple main effects of trial type:

Pairwise Comparisons

Dependent Variable: Proportion of Dwell

Area of Interest	(I) Trial Type	(J) Trial Type	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference ^b	
						Lower Bound	Upper Bound
Other1	CorrectLure	HeuristicLure	-.006	.021	.784	-.047	.036
	HeuristicLure	CorrectLure	.006	.021	.784	-.036	.047
Other2	CorrectLure	HeuristicLure	.010	.021	.631	-.031	.052
	HeuristicLure	CorrectLure	-.010	.021	.631	-.052	.031
OtherRelevant	CorrectLure	HeuristicLure	-.043 [*]	.021	.041	-.085	-.002
	HeuristicLure	CorrectLure	.043 [*]	.021	.041	.002	.085
Selected	CorrectLure	HeuristicLure	.036	.021	.091	-.006	.078
	HeuristicLure	CorrectLure	-.036	.021	.091	-.078	.006

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Descriptive statistics for proportion of dwell in the simple main effects of trial type:

Descriptive Statistics

Dependent Variable: Proportion of Dwell

Trial Type	Area of Interest	Mean	Std. Deviation	N
CorrectLure	Other1	.201149081	.0891426392	37
	Other2	.211342319	.0929566972	37
	OtherRelevant	.226116627	.0819190313	37
	Selected	.354665918	.0808348476	37
	Total	.248318486	.1057392429	148
HeuristicLure	Other1	.206951391	.0581615176	37
	Other2	.201182496	.0900676368	37
	OtherRelevant	.269590452	.1153953913	37
	Selected	.318761583	.1072235494	37
	Total	.249121481	.1060373839	148
Total	Other1	.204050236	.0748032155	74
	Other2	.206262408	.0910383157	74
	OtherRelevant	.247853539	.1017605418	74
	Selected	.336713750	.0960144523	74
	Total	.248719983	.1057095592	296

Simple main effects for AOI

There were no other statistically significant differences in mean “Proportion of Dwell” between correct conflict and heuristic conflict trials for the Selected, Other 1, or Other 2 AOIs.

Univariate tests for proportion of dwell in the simple main effects of AOI:

Univariate Tests

Dependent Variable: Proportion of Dwell

Trial Type		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
CorrectLure	Contrast	.570	3	.190	22.966	<.001	.193
	Error	2.381	288	.008			
HeuristicLure	Contrast	.346	3	.115	13.941	<.001	.127
	Error	2.381	288	.008			

Each F tests the simple effects of Area of Interest within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Pairwise comparisons for proportion of dwell in the simple main effects of AOI:

Pairwise Comparisons

Dependent Variable: Proportion of Dwell

Trial Type	(I) Area of Interest	(J) Area of Interest	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference ^b	
						Lower Bound	Upper Bound
CorrectLure	Other1	Other2	-.01019	.02114	1.00000	-.06635	.04597
		OtherRelevant	-.02497	.02114	1.00000	-.08113	.03119
		Selected	-.15352 [*]	.02114	<.001	-.20968	-.09736
	Other2	Other1	.01019	.02114	1.00000	-.04597	.06635
		OtherRelevant	-.01477	.02114	1.00000	-.07093	.04139
		Selected	-.14332 [*]	.02114	<.001	-.19948	-.08716
	OtherRelevant	Other1	.02497	.02114	1.00000	-.03119	.08113
		Other2	.01477	.02114	1.00000	-.04139	.07093
		Selected	-.12855 [*]	.02114	<.001	-.18471	-.07239
	Selected	Other1	.15352 [*]	.02114	<.001	.09736	.20968
		Other2	.14332 [*]	.02114	<.001	.08716	.19948
		OtherRelevant	.12855 [*]	.02114	<.001	.07239	.18471
HeuristicLure	Other1	Other2	.00577	.02114	1.00000	-.05039	.06193
		OtherRelevant	-.06264 [*]	.02114	.01980	-.11880	-.00648
		Selected	-.11181 [*]	.02114	<.001	-.16797	-.05565
	Other2	Other1	-.00577	.02114	1.00000	-.06193	.05039
		OtherRelevant	-.06841 [*]	.02114	.00812	-.12457	-.01225
		Selected	-.11758 [*]	.02114	<.001	-.17374	-.06142
	OtherRelevant	Other1	.06264 [*]	.02114	.01980	.00648	.11880
		Other2	.06841 [*]	.02114	.00812	.01225	.12457
		Selected	-.04917	.02114	.12428	-.10533	.00699
	Selected	Other1	.11181 [*]	.02114	<.001	.05565	.16797
		Other2	.11758 [*]	.02114	<.001	.06142	.17374
		OtherRelevant	.04917	.02114	.12428	-.00699	.10533

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Descriptive statistics for proportion of dwell in the simple main effects of AOI

Descriptive Statistics

Dependent Variable: Proportion of Dwell

Trial Type	Area of Interest	Mean	Std. Deviation	N
CorrectLure	Other1	.201149081	.0891426392	37
	Other2	.211342319	.0929566972	37
	OtherRelevant	.226116627	.0819190313	37
	Selected	.354665918	.0808348476	37
	Total	.248318486	.1057392429	148
HeuristicLure	Other1	.206951391	.0581615176	37
	Other2	.201182496	.0900676368	37
	OtherRelevant	.269590452	.1153953913	37
	Selected	.318761583	.1072235494	37
	Total	.249121481	.1060373839	148
Total	Other1	.204050236	.0748032155	74
	Other2	.206262408	.0910383157	74
	OtherRelevant	.247853539	.1017605418	74
	Selected	.336713750	.0960144523	74
	Total	.248719983	.1057095592	296

Interaction contrasts for Proportion of Dwell between Other Relevant and Selected for correct conflict and heuristic conflict trials:

Contrast Results (K Matrix)^a

Contrast		Dependent Variable Proportion of Dwell	
L1	Contrast Estimate	.07938	
	Hypothesized Value	.00000	
	Difference (Estimate - Hypothesized)	.07938	
	Std. Error	.02990	
	Sig.	.00837	
	95% Confidence Interval for Difference	Lower Bound	.02054
		Upper Bound	.13822

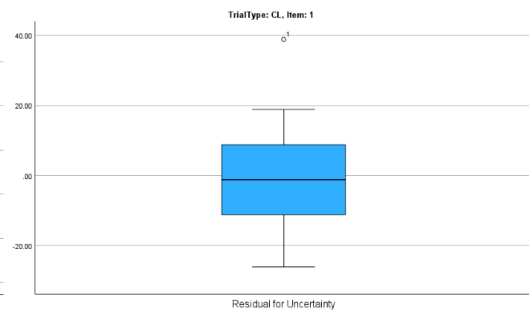
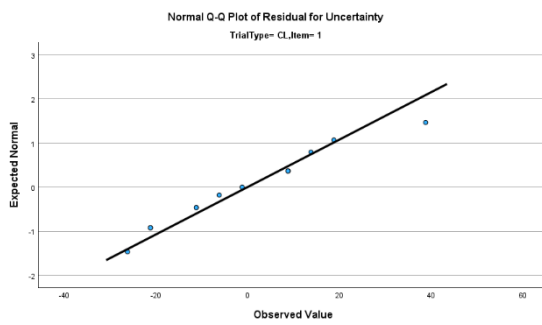
a. Based on the user-specified contrast coefficients (L') matrix number 1

Two-way ANOVA: Uncertainty

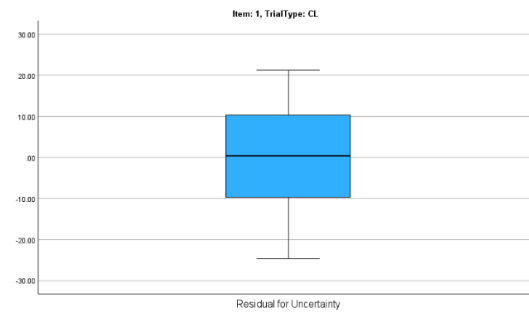
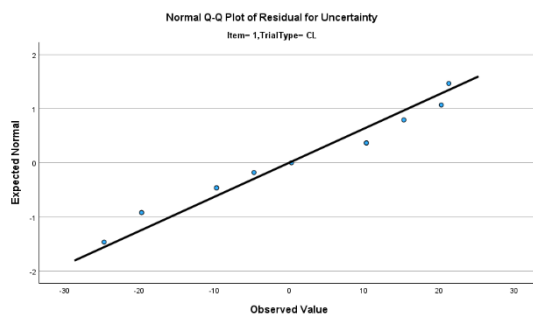
Outliers:

Correct Conflict – Item 1:

Pre-modification:



Post-modification:



Normality

Tests of Normality

Item	TrialType		Kolmogorov-Smirnov ^a			Shapiro-Wilk		
			Statistic	df	Sig.	Statistic	df	Sig.
1	CL	Residual for Uncertainty	.204	13	.143	.925	13	.294
	HL	Residual for Uncertainty	.138	8	.200*	.962	8	.833
2	CL	Residual for Uncertainty	.157	9	.200*	.975	9	.935
	HL	Residual for Uncertainty	.175	3	.	1.000	3	1.000
3	CL	Residual for Uncertainty	.202	12	.188	.923	12	.312
	HL	Residual for Uncertainty	.206	10	.200*	.905	10	.247
5	CL	Residual for Uncertainty	.253	3	.	.964	3	.637
	HL	Residual for Uncertainty	.154	16	.200*	.905	16	.096

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Homogeneity of variances:

Levene's Test of Equality of Error Variances^{a,b}

		Levene Statistic	df1	df2	Sig.
Uncertainty	Based on Mean	1.243	7	66	.292
	Based on Median	1.166	7	66	.334
	Based on Median and with adjusted df	1.166	7	58.027	.336
	Based on trimmed mean	1.226	7	66	.301

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Dependent variable: Uncertainty

b. Design: Intercept + Item + TrialType + Item * TrialType

Interaction effect of Trial Type and Item:

Tests of Between-Subjects Effects

Dependent Variable: Uncertainty

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	5258.971 ^a	7	751.282	2.248	.041	.193
Intercept	56617.935	1	56617.935	169.397	<.001	.720
Item	1708.327	3	569.442	1.704	.175	.072
TrialType	682.192	1	682.192	2.041	.158	.030
Item * TrialType	3555.568	3	1185.189	3.546	.019	.139
Error	22059.366	66	334.233			
Total	89147.000	74				
Corrected Total	27318.338	73				

a. R Squared = .193 (Adjusted R Squared = .107)

Simple main effects for Trial Type:

Univariate Tests

Dependent Variable: Uncertainty

TrialType		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
CL	Contrast	3411.191	3	1137.064	3.402	.023	.134
	Error	22059.366	66	334.233			
HL	Contrast	1405.064	3	468.355	1.401	.250	.060
	Error	22059.366	66	334.233			

Each F tests the simple effects of Item within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Pairwise comparisons for uncertainty in the simple main effects of trial type:

Pairwise Comparisons

Dependent Variable: Uncertainty

Item	(I) TrialType	(J) TrialType	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference ^b	
						Lower Bound	Upper Bound
1	CL	HL	-4.933	8.215	.550	-21.335	11.469
	HL	CL	4.933	8.215	.550	-11.469	21.335
2	CL	HL	2.889	12.188	.813	-21.445	27.223
	HL	CL	-2.889	12.188	.813	-27.223	21.445
3	CL	HL	-5.583	7.828	.478	-21.212	10.046
	HL	CL	5.583	7.828	.478	-10.046	21.212
5	CL	HL	36.542 [*]	11.502	.002	13.577	59.507
	HL	CL	-36.542 [*]	11.502	.002	-59.507	-13.577

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Simple main effects for Item:

Univariate Tests

Dependent Variable: Uncertainty

Item		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
1	Contrast	120.499	1	120.499	.361	.550	.005
	Error	22059.366	66	334.233			
2	Contrast	18.778	1	18.778	.056	.813	.001
	Error	22059.366	66	334.233			
3	Contrast	170.038	1	170.038	.509	.478	.008
	Error	22059.366	66	334.233			
5	Contrast	3373.373	1	3373.373	10.093	.002	.133
	Error	22059.366	66	334.233			

Each F tests the simple effects of TrialType within each level combination of the other effects shown. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Pairwise comparisons for uncertainty in the simple main effects of item:

Pairwise Comparisons

Dependent Variable: Uncertainty

TrialType	(I) Item	(J) Item	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference ^b		
						Lower Bound	Upper Bound	
CL	1	2	-8.197	7.928	1.000	-29.761	13.367	
		3	7.776	7.319	1.000	-12.132	27.683	
		5	-26.974	11.710	.146	-58.826	4.878	
	2	1	8.197	7.928	1.000	-13.367	29.761	
		3	15.972	8.062	.310	-5.956	37.901	
		5	-18.778	12.188	.769	-51.931	14.375	
	3	1	-7.776	7.319	1.000	-27.683	12.132	
		2	-15.972	8.062	.310	-37.901	5.956	
		5	-34.750*	11.801	.027	-66.850	-2.650	
	5	1	26.974	11.710	.146	-4.878	58.826	
		2	18.778	12.188	.769	-14.375	51.931	
		3	34.750*	11.801	.027	2.650	66.850	
	HL	1	2	-.375	12.377	1.000	-34.042	33.292
			3	7.125	8.672	1.000	-16.464	30.714
			5	14.500	7.916	.429	-7.033	36.033
2		1	.375	12.377	1.000	-33.292	34.042	
		3	7.500	12.035	1.000	-25.236	40.236	
		5	14.875	11.502	1.000	-16.412	46.162	
3		1	-7.125	8.672	1.000	-30.714	16.464	
		2	-7.500	12.035	1.000	-40.236	25.236	
		5	7.375	7.370	1.000	-12.671	27.421	
5		1	-14.500	7.916	.429	-36.033	7.033	
		2	-14.875	11.502	1.000	-46.162	16.412	
		3	-7.375	7.370	1.000	-27.421	12.671	

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Descriptive statistics for uncertainty in the simple main effects of trial type:

Descriptive Statistics

Dependent Variable: Uncertainty

Item	TrialType	Mean	Std. Deviation	N
1	CL	29.6923	15.85026	13
	HL	34.6250	18.96566	8
	Total	31.5714	16.81241	21
2	CL	37.8889	20.85932	9
	HL	35.0000	5.00000	3
	Total	37.1667	17.96377	12
3	CL	21.9167	14.28577	12
	HL	27.5000	23.12406	10
	Total	24.4545	18.55167	22
5	CL	56.6667	15.27525	3
	HL	20.1250	19.09930	16
	Total	25.8947	22.74471	19
Total	CL	31.3514	18.72197	37
	HL	26.4595	19.90058	37
	Total	28.9054	19.34487	74

Exploratory Analyses: Binomial logistic regressions:

Logistic regression on all items:

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	1.253	2	.534
	Block	1.253	2	.534
	Model	1.253	2	.534

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	101.332 ^a	.017	.022

a. Estimation terminated at iteration number 3 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	5.495	8	.704

Classification Table^a

Observed		Predicted		Percentage Correct
		Trial 0	Trial 1	
Step 1	Trial 0	17	20	45.9
	Trial 1	16	21	56.8
Overall Percentage				51.4

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for EXP(B)	
								Lower	Upper
Step 1 ^a	CRT	-.042	.196	.047	1	.829	.959	.653	1.407
	Uncertainty	.013	.012	1.148	1	.284	1.013	.989	1.038
	Constant	-.328	.506	.420	1	.517	.720		

a. Variable(s) entered on step 1: CRT, Uncertainty.

Logistic regression on items 1-3

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	.233	2	.890
	Block	.233	2	.890
	Model	.233	2	.890

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	72.911 ^a	.004	.006

a. Estimation terminated at iteration number 3 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	6.814	7	.448

Classification Table^a

Observed		Predicted		Percentage Correct
		Trial 0	Trial 1	
Step 1	Trial 0	0	21	.0
	Trial 1	0	34	100.0
Overall Percentage				61.8

a. The cut value is .500

Variables in the Equation

Step 1 ^a		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for EXP(B)	
								Lower	Upper
	Uncertainty	-.007	.016	.210	1	.647	.993	.963	1.024
	CRT	-.049	.232	.044	1	.833	.952	.605	1.499
	Constant	.759	.653	1.353	1	.245	2.136		

a. Variable(s) entered on step 1: Uncertainty, CRT.

Logistic regression on item 5

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	8.227	2	.016
	Block	8.227	2	.016
	Model	8.227	2	.016

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	8.347 ^a	.351	.604

a. Estimation terminated at iteration number 7 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.985	8	.998

Classification Table^a

		Predicted		Percentage Correct
		Trial 0	Trial 1	
Step 1	Observed 0	15	1	93.8
	Observed 1	2	1	33.3
Overall Percentage				84.2

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for EXP(B)	
								Lower	Upper
Step 1 ^a	CRT	-.574	.876	.429	1	.512	.563	.101	3.137
	Uncertainty	.124	.069	3.254	1	.071	1.132	.989	1.296
	Constant	-5.930	3.145	3.555	1	.059	.003		

a. Variable(s) entered on step 1: CRT, Uncertainty.

Appendix 7: DCT Eye-tracking raw data

Raw eye tracking data for fixations and dwell - selected answer with bold outlines

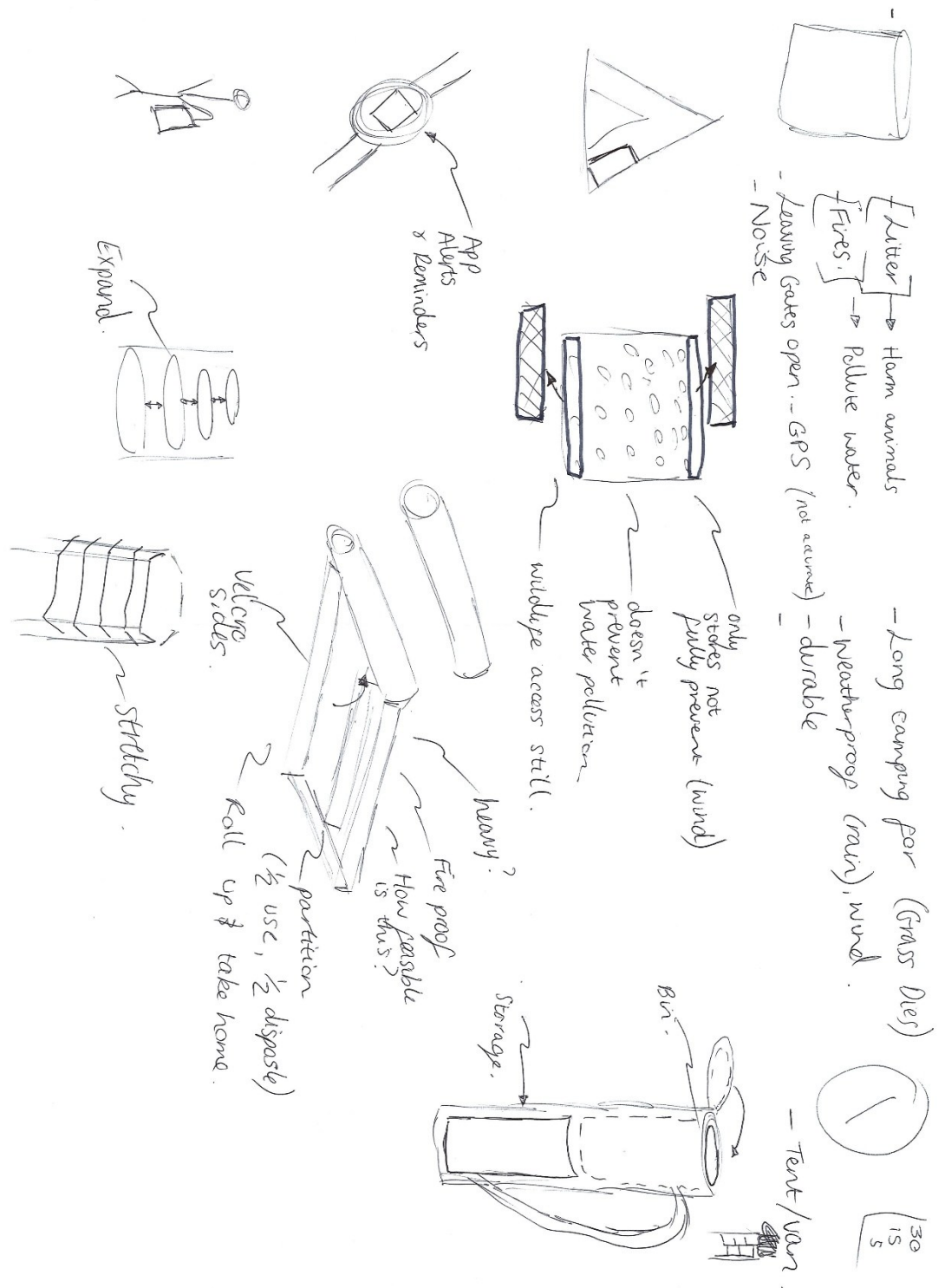
Participant	Question Measure	1		1		2		2		3		3		5		5	
		Correct	Lure	Other1	Other2	Correct	Lure	Other1	Other2	Correct	Lure	Other1	Other2	Correct	Lure	Other1	Other2
P01	Fixations	66	189	132	51	21	52	53	19	52	68	28	85	46	32	46	28
P01	Dwell	11.511	27.1	21.95	7.0044	2.9637	6.8076	6.747	2.6143	7.28	9.916	3.8474	12.384	13.835	4.1319	7.14	4.6103
P02	Fixations	29	16	11	17	9	19	29	5	10	21	10	4	2	21	20	16
P02	Dwell	4.5022	2.2748	1.745	2.4498	1.3897	3.2268	4.291	0.8759	1.6129	2.6011	1.4342	0.6106	0.2887	3.481	3.051	2.4843
P03	Fixations	32	32	29	25	31	25	26	15	32	28	29	23	26	28	31	15
P03	Dwell	3.9962	5.0526	4.664	3.7286	5.1341	3.6666	2.945	1.9253	3.8738	4.1731	4.6244	3.4985	3.3928	4.4481	5.319	2.3876
P04	Fixations	26	9	19	12	10	22	22	11	23	5	6	14	9	27	19	12
P04	Dwell	3.1562	1.0838	2.185	1.3757	1.2319	2.4293	2.919	1.3124	2.9938	0.6227	0.79	1.9543	1.2556	3.2632	2.522	1.4364
P05	Fixations	14	12	9	5	59	60	32	28	8	12	2	28	8	22	8	5
P05	Dwell	1.7317	1.7963	1.618	0.9059	7.7904	6.9349	4.247	3.8143	1.1991	1.7293	0.2208	4.1723	0.9668	3.304	1.175	0.6893
P06	Fixations	41	46	28	26	39	21	11	15	36	19	16	24	6	31	9	6
P06	Dwell	5.2296	5.9238	3.728	3.2979	4.2868	2.5494	1.08	1.5202	4.4762	1.8995	1.8524	2.8343	0.5672	3.6968	1.184	0.5965
P08	Fixations	13	8	3	9	22	12	11	13	8	26	14	33	15	14	9	7
P08	Dwell	2.0459	1.3959	0.589	1.2462	3.3528	1.548	1.554	1.8501	1.4093	4.5597	1.9092	5.1561	2.2353	2.1327	1.629	1.1586
P09	Fixations	23	11	9	11	14	20	17	10	26	12	28	71	9	33	16	12
P09	Dwell	3.4848	1.8326	1.383	1.6028	1.8443	2.5096	2.661	1.4388	2.9669	1.548	4.0779	10.653	1.4098	5.9055	2.139	1.9501
P10	Fixations	20	22	11	4	35	49	39	29	18	23	21	20	60	24	29	65
P10	Dwell	3.2015	3.5028	1.609	0.6921	6.1307	8.1565	6.289	4.6728	2.6097	3.5988	3.5931	3.5529	9.3722	3.5714	4.782	11.053
P11	Fixations	37	25	21	10	49	69	15	20	22	52	19	37	15	21	16	11
P11	Dwell	5.2855	3.6055	3.325	1.4578	7.5058	11.2	2.323	3.3462	3.5829	7.527	3.2792	5.5937	2.5417	2.7267	2.424	1.5872
P12	Fixations	65	47	39	89	42	67	72	22	23	9	28	38	56	78	28	61
P12	Dwell	10.467	7.7569	5.745	14.563	7.1183	10.736	10.41	3.1458	3.5256	1.2875	4.4155	5.9026	9.2429	12.787	3.533	9.9197
P13	Fixations	10	19	6	2	31	16	20	19	23	13	19	24	30	27	13	28
P13	Dwell	1.5262	2.9172	1.066	0.2884	4.7529	2.3067	3.259	3.0506	3.2874	1.8048	2.6788	3.3244	4.9844	3.8953	1.898	4.2217
P14	Fixations	11	12	21	13	40	21	33	42	32	28	21	17	22	16	12	24
P14	Dwell	1.6273	1.903	3.62	2.1603	6.2152	3.0834	5.516	6.9155	4.6281	4.0451	3.8064	2.6391	3.9588	2.5316	1.691	3.7558
P15	Fixations	23	9	10	3	7	25	13	14	14	4	7	10	30	17	15	6
P15	Dwell	3.0167	0.994	1.39	0.5081	1.2647	3.858	2.343	2.3995	2.3108	0.6041	1.0715	1.556	4.5231	2.3494	2.089	1.1158
P16	Fixations	39	23	20	12	16	62	28	17	68	45	11	39	34	22	19	29
P16	Dwell	5.9569	3.734	3.152	1.8783	2.6057	9.5021	4.213	2.8068	10.826	7.3958	1.8269	6.6491	5.3338	3.1944	3.005	4.7196
P17	Fixations	68	42	53	22	43	42	28	34	41	27	12	22	58	50	17	9
P17	Dwell	11.655	6.9843	8.703	4.0853	7.1798	6.7668	4.712	5.4176	7.1813	4.8715	2.21	3.5485	10.099	8.7244	2.861	1.6239
P19	Fixations	23	7	8	15	14	18	23	17	14	23	15	16	15	12	14	16
P19	Dwell	3.9145	1.2257	1.412	2.3126	2.1927	2.8671	3.844	2.6487	2.2119	3.9253	2.4711	2.6038	2.1629	1.939	2.37	2.2601
P20	Fixations	6	10	21	26	26	29	8	11	28	38	29	35	23	11	12	20
P20	Dwell	0.7719	1.3961	2.932	3.9239	4.2413	4.5593	0.872	1.8989	4.4416	6.4892	4.678	5.3246	3.9555	1.9357	1.864	3.1755
P21	Fixations	24	37	8	3	29	21	17	25	19	12	25	3	7	22	21	20
P21	Dwell	4.0156	6.6415	0.95	0.5419	4.2434	3.4482	2.77	3.6946	3.126	1.8426	4.0488	0.3802	1.176	2.9556	3.02	3.1218
P22	Fixations	50	13	26	15	48	34	10	30	38	31	23	7	9	15	15	13
P22	Dwell	7.7875	2.2966	4.205	2.1861	8.0938	5.1422	1.518	4.7199	5.8916	5.0237	3.3178	0.9839	1.3399	2.0766	2.042	2.1659
P23	Fixations	9	5	2	4	6	8	12	4	8	3	5	8	19	12	17	5
P23	Dwell	1.3939	0.6378	0.248	0.5022	1.0705	1.216	1.832	0.3964	1.2839	0.4157	0.6744	1.2783	2.6003	1.9179	2.366	0.6101
P24	Fixations	12	16	5	15	8	4	15	10	14	3	17	14	19	10	10	3
P24	Dwell	1.7972	2.5928	0.879	1.9986	1.313	0.6179	2.128	1.4372	2.3553	0.4476	2.7477	2.0189	2.883	1.7967	1.296	0.287
P25	Fixations	20	13	14	20	17	38	35	21	26	20	19	23	36	11	29	14
P25	Dwell	2.9894	1.9707	2.191	3.0073	2.6737	5.5499	4.4851	3.1904	3.384	3.3348	2.727	3.7194	5.9367	1.7342	3.904	2.6631

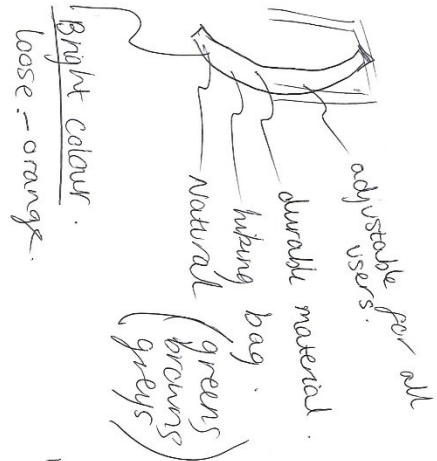
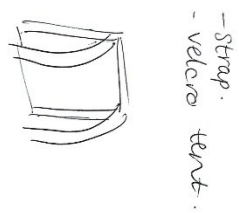
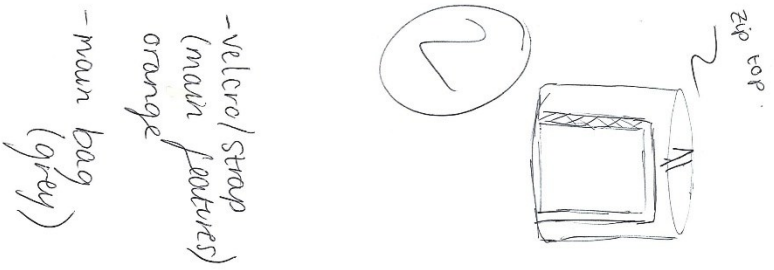
Appendix 8: Participant psychometric scores

Participant ID	CRT Score	DCT Score	PASAT Score
1	3	1	46.5
2	1	0	40.5
3	0	1	29
4	0	2	45
5	0	2	36.5
6	0	1	42.5
8	2	2	31
9	3	1	52.5
10	3	3	55
11	0	0	42
12	1	1	34.5
13	3	2	38.5
14	3	1	51.5
15	2	2	56.5
16	1	2	36.5
17	0	4	38.5
19	3	1	46
20	2	1	55.5
21	0	3	28.5
22	1	2	30.5
23	1	3	49
24	0	1	43.5
25	2	2	39.5

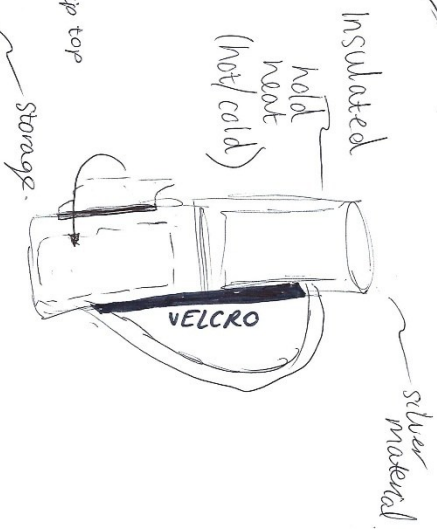
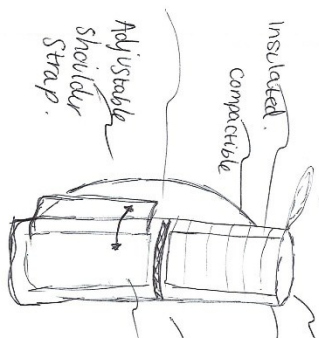
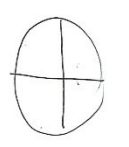
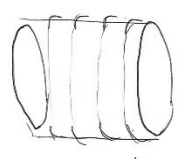
Appendix 9: DS II Participant Sketches

P11 Sketches:



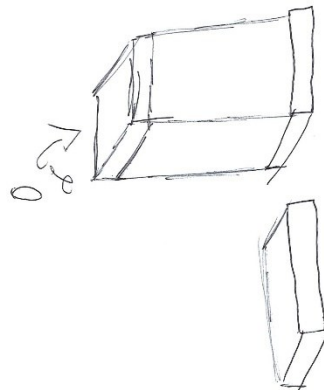
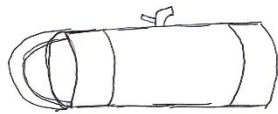
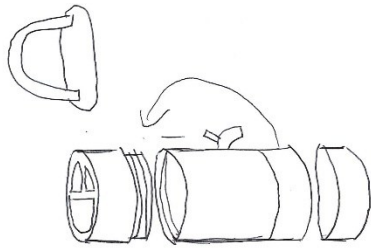
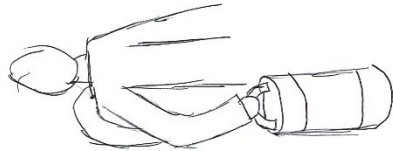
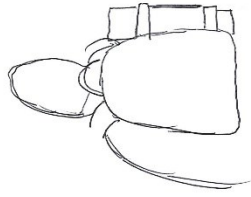


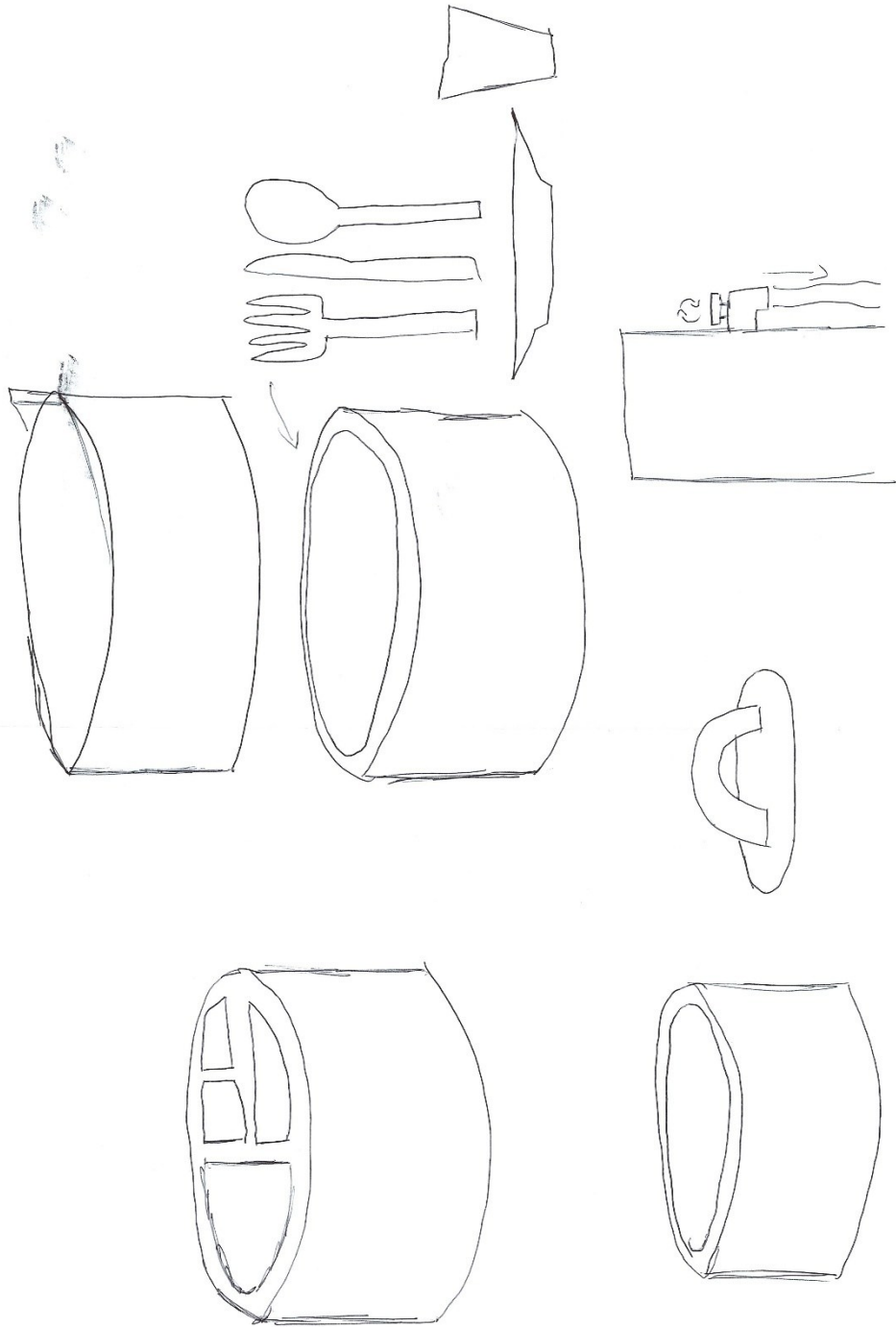
Zip easy access to clean

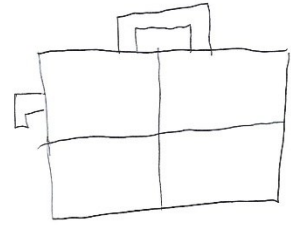
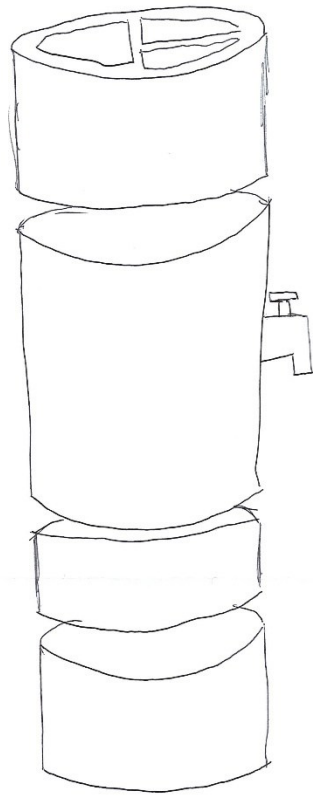


- Prevents & Encourages users to not leave litter lying around, take home.
- Reduces chance wildlife themselves on litter.

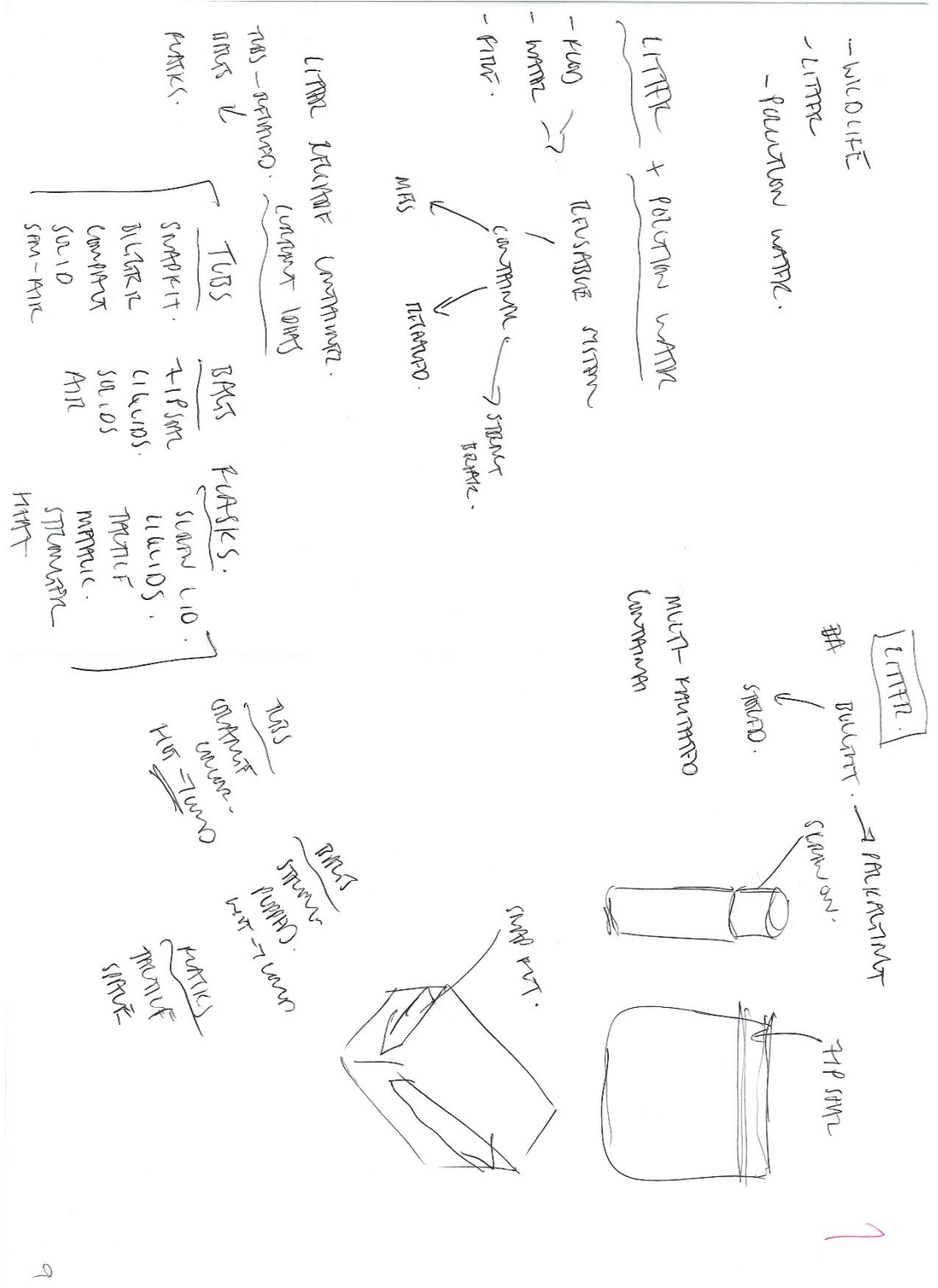
P24 Sketches:

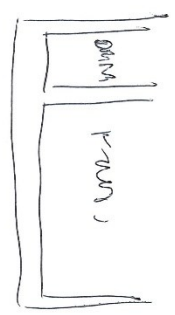
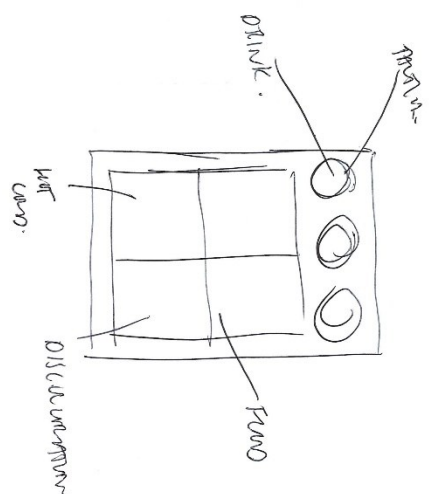
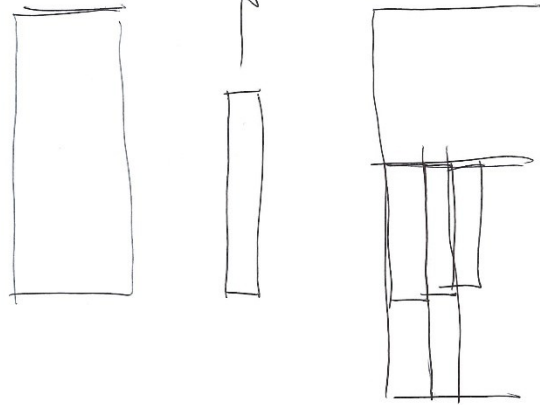
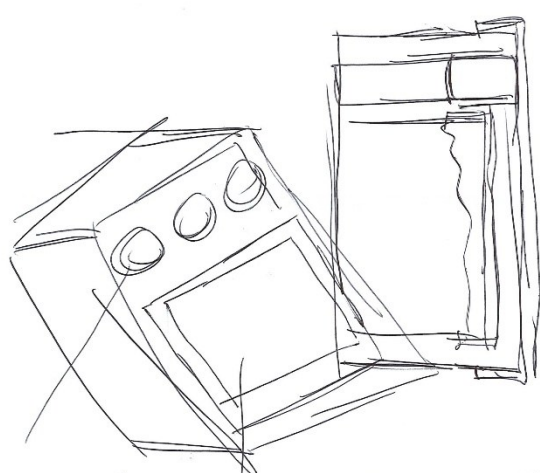
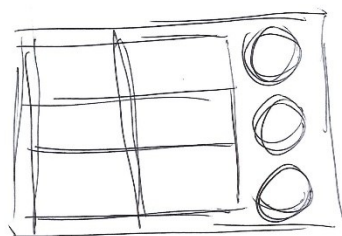
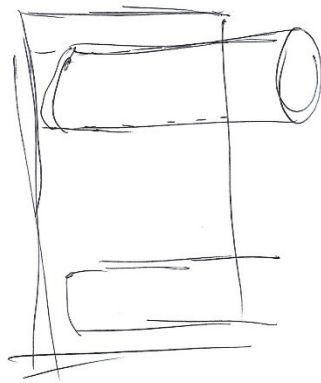




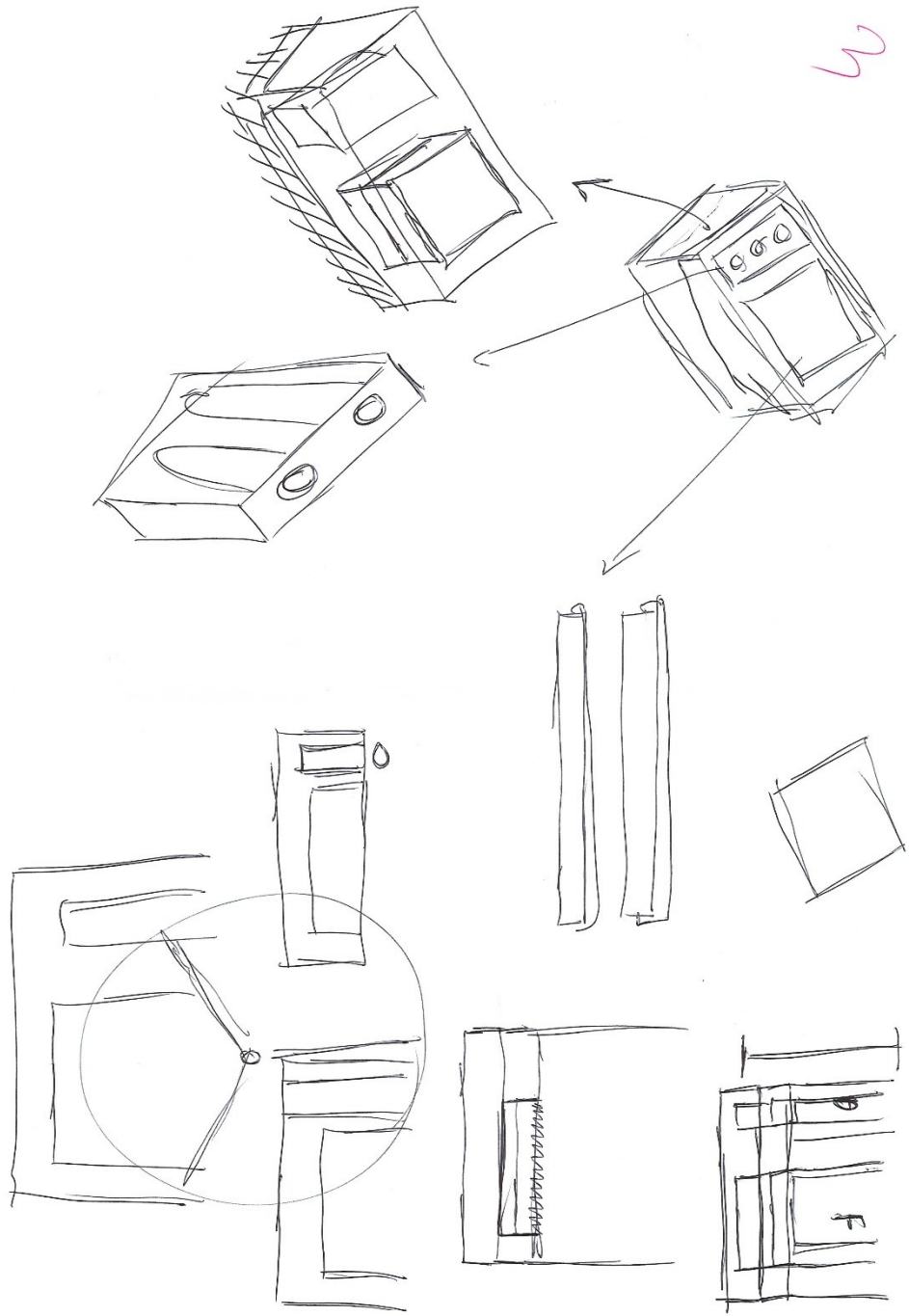


P09 Sketches:

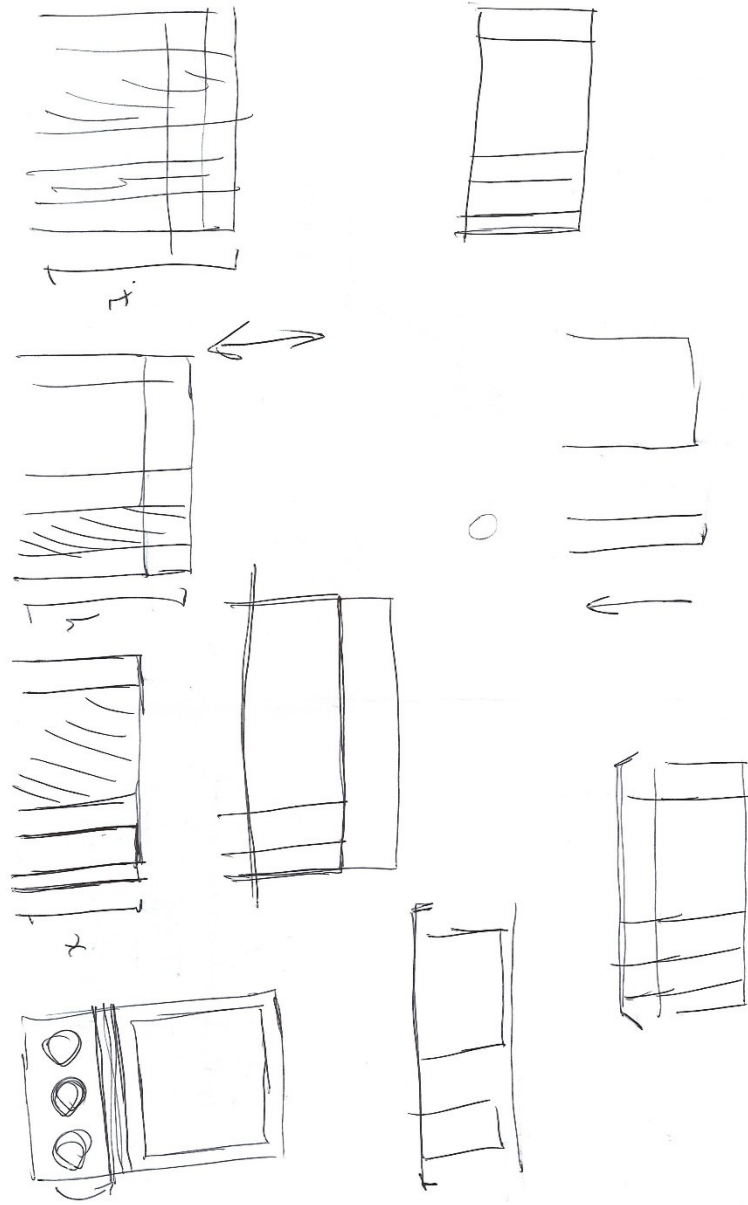




9



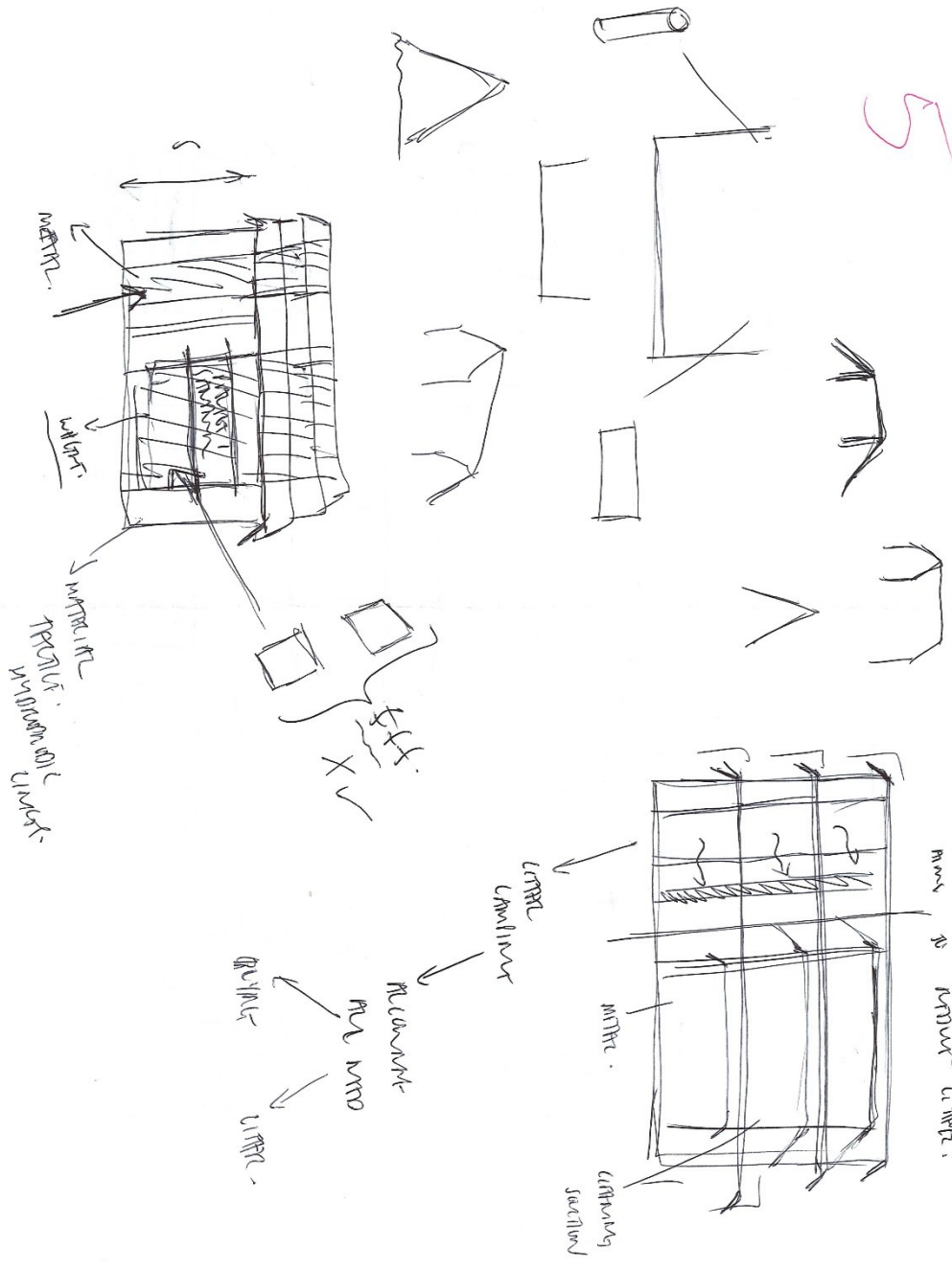
b



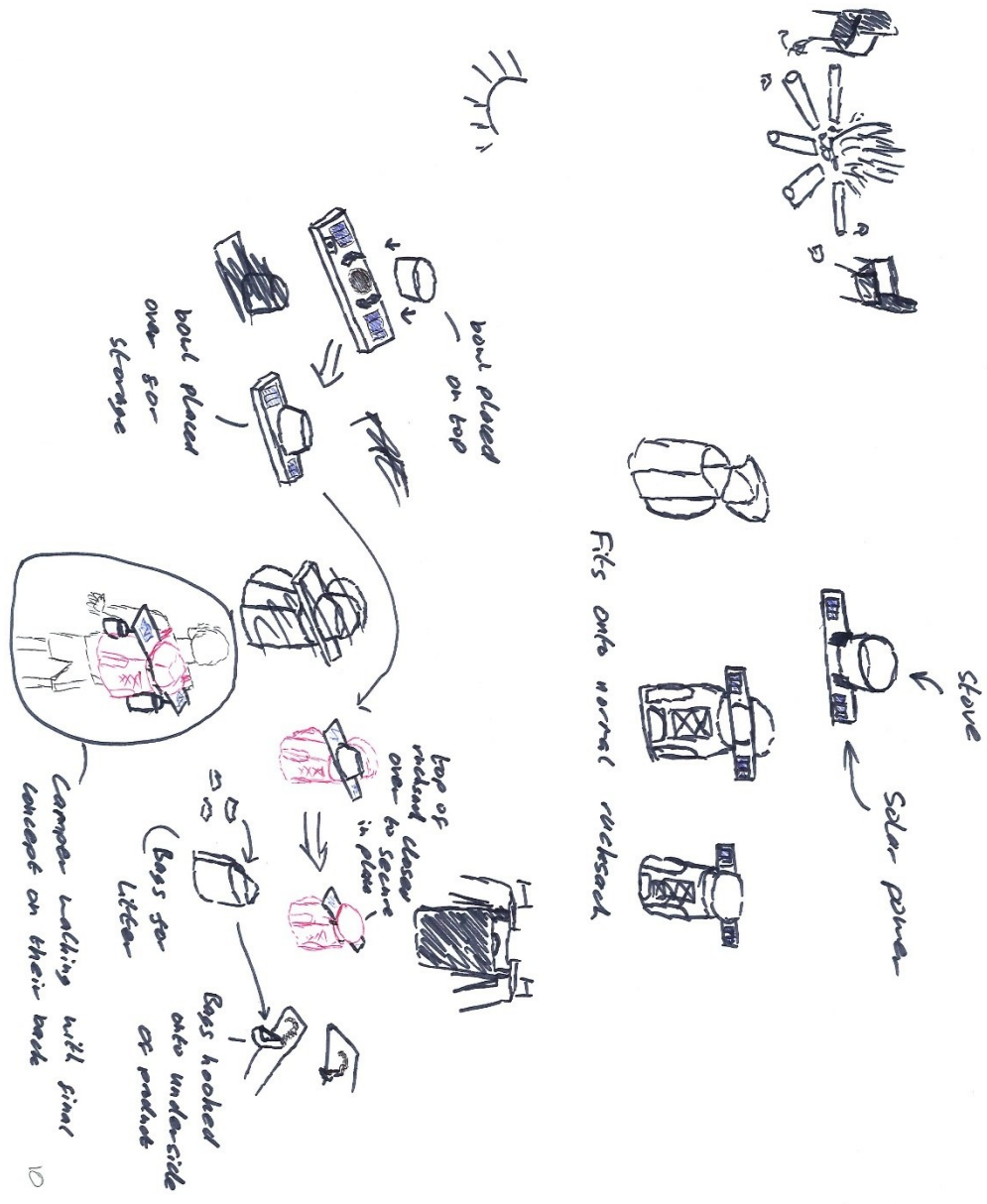
b

ct

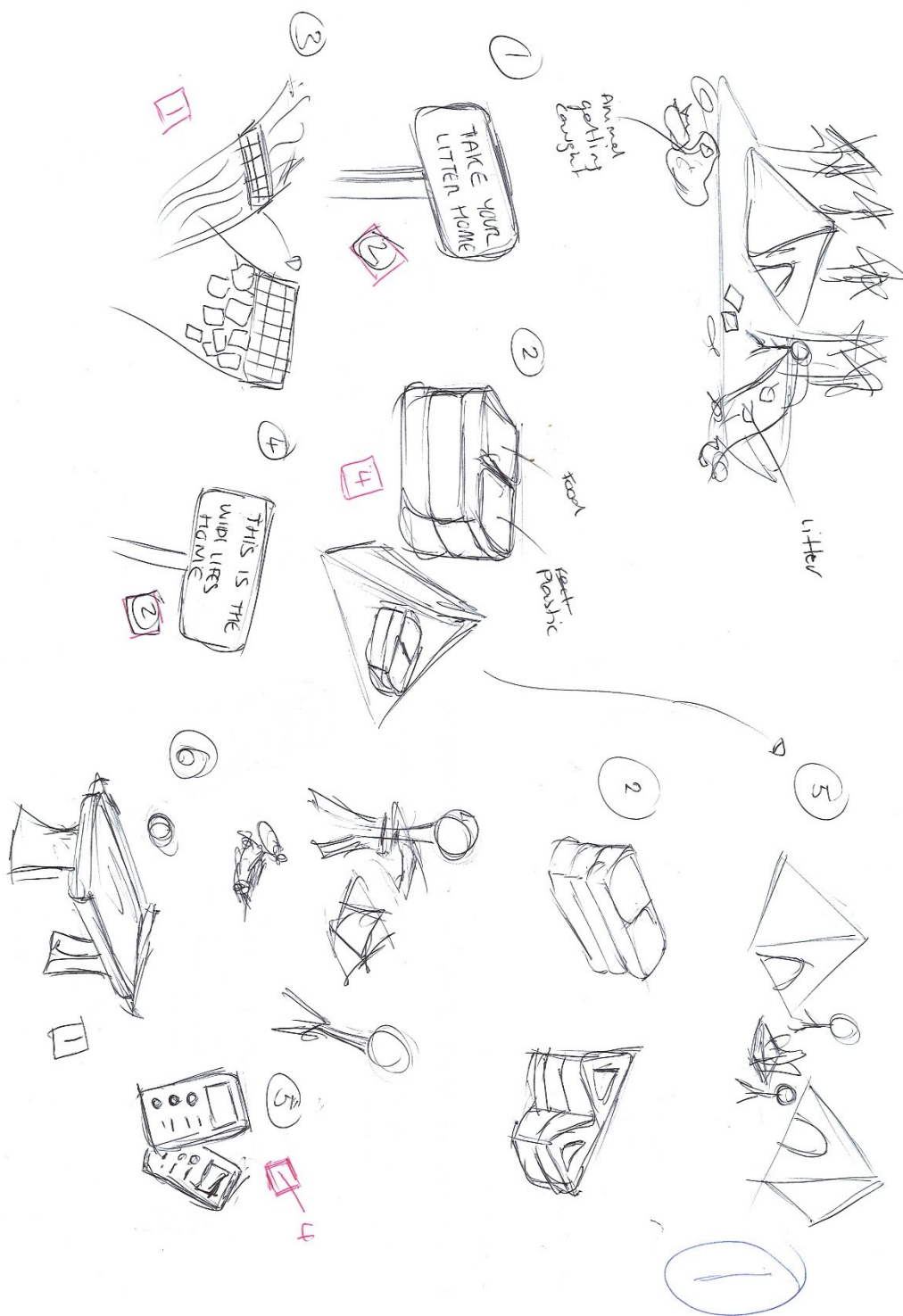
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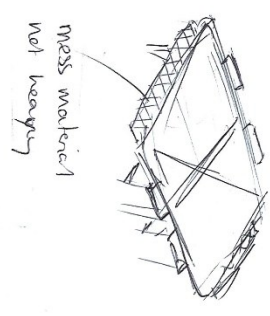
P10 Sketches:



P21 Sketches:



6



mesh material
not heavy

7



wildlife noise
detector



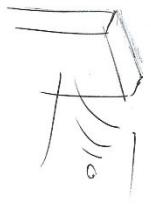
DEVELOPMENT

- 2 PORTABLE BIN FOR COMPUTER
- 5 DEVICE TO ALERT IF AN ANIMAL IS IN DANGER
- 7 DEVICE TO DETECT IF YOUR BLENDING TOO LOUP FOR WILDLIFE

5 + 7



device function
animal in danger
if computer says
too loud



also detects
if the area
you computer
is in good
condition

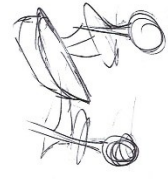


screen shows
level of noise
emergency
button
if they see
animal in
danger

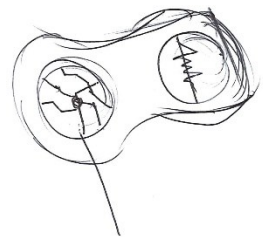
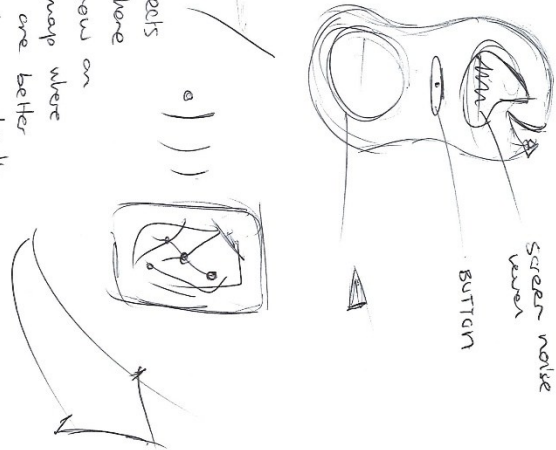
2 Portable bin



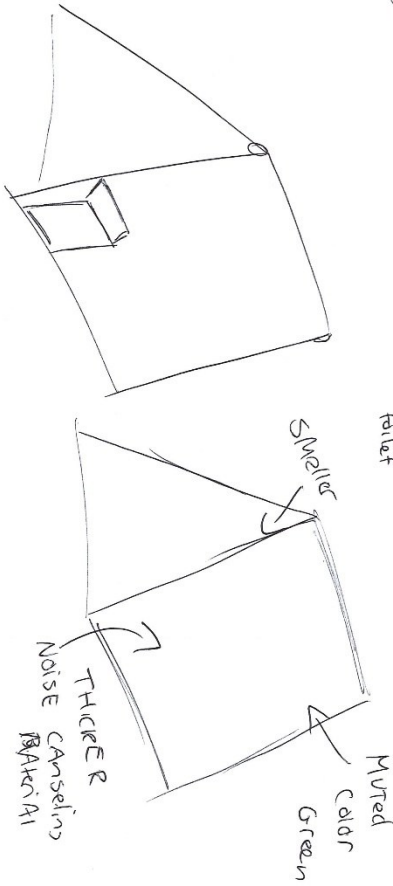
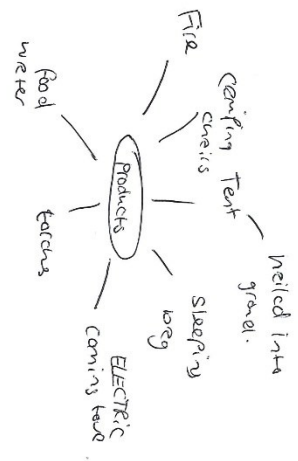
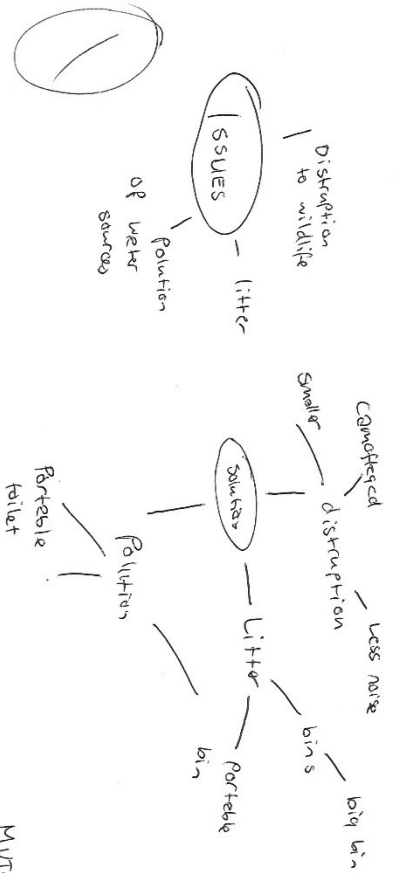
material
prevent
straws
small



connects
to phone
to show on
the map where
areas are better
so that you don't
disturb wildlife



P17 Sketches:



LITTER PROBLEM

DISRUPTION

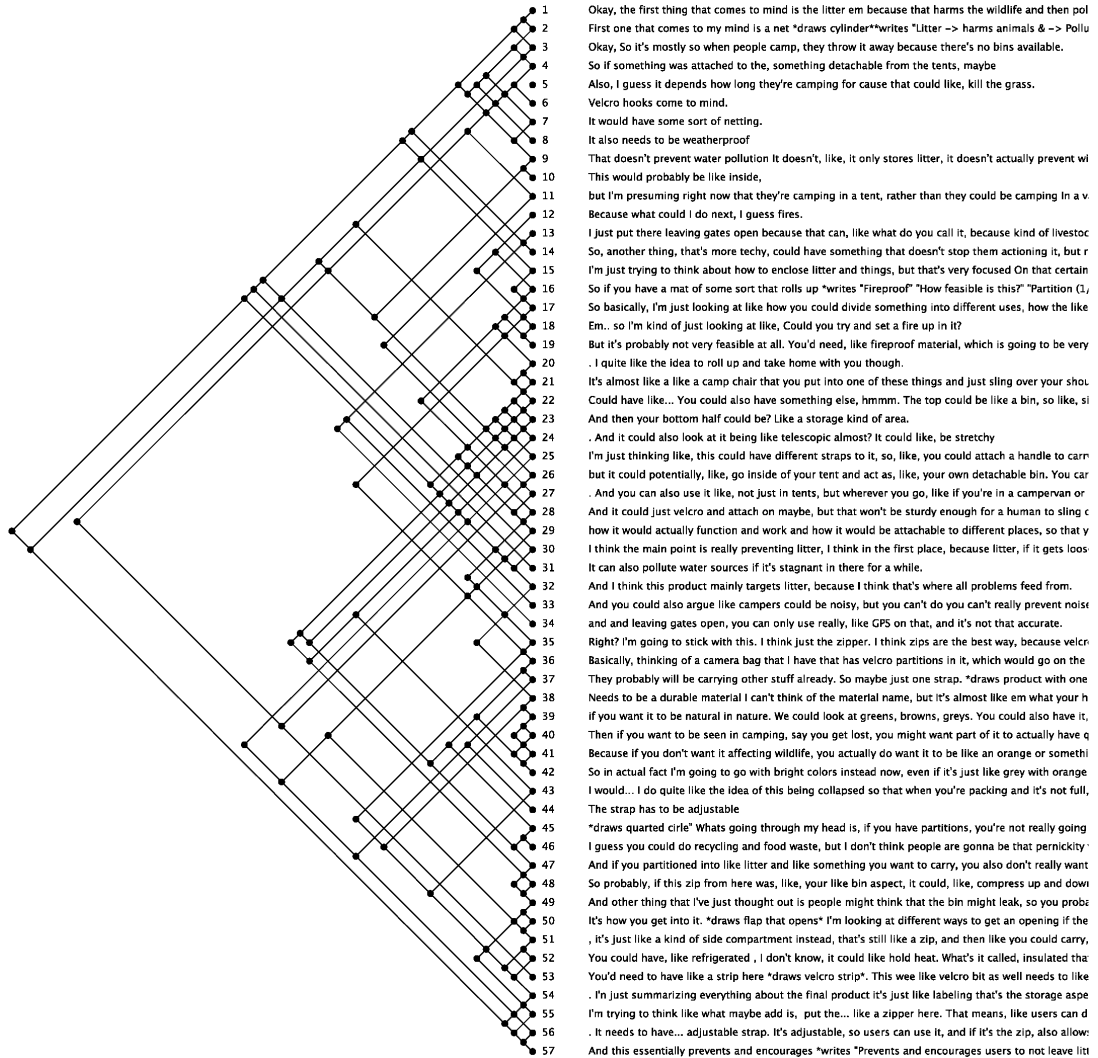
POLLUTION

17 7

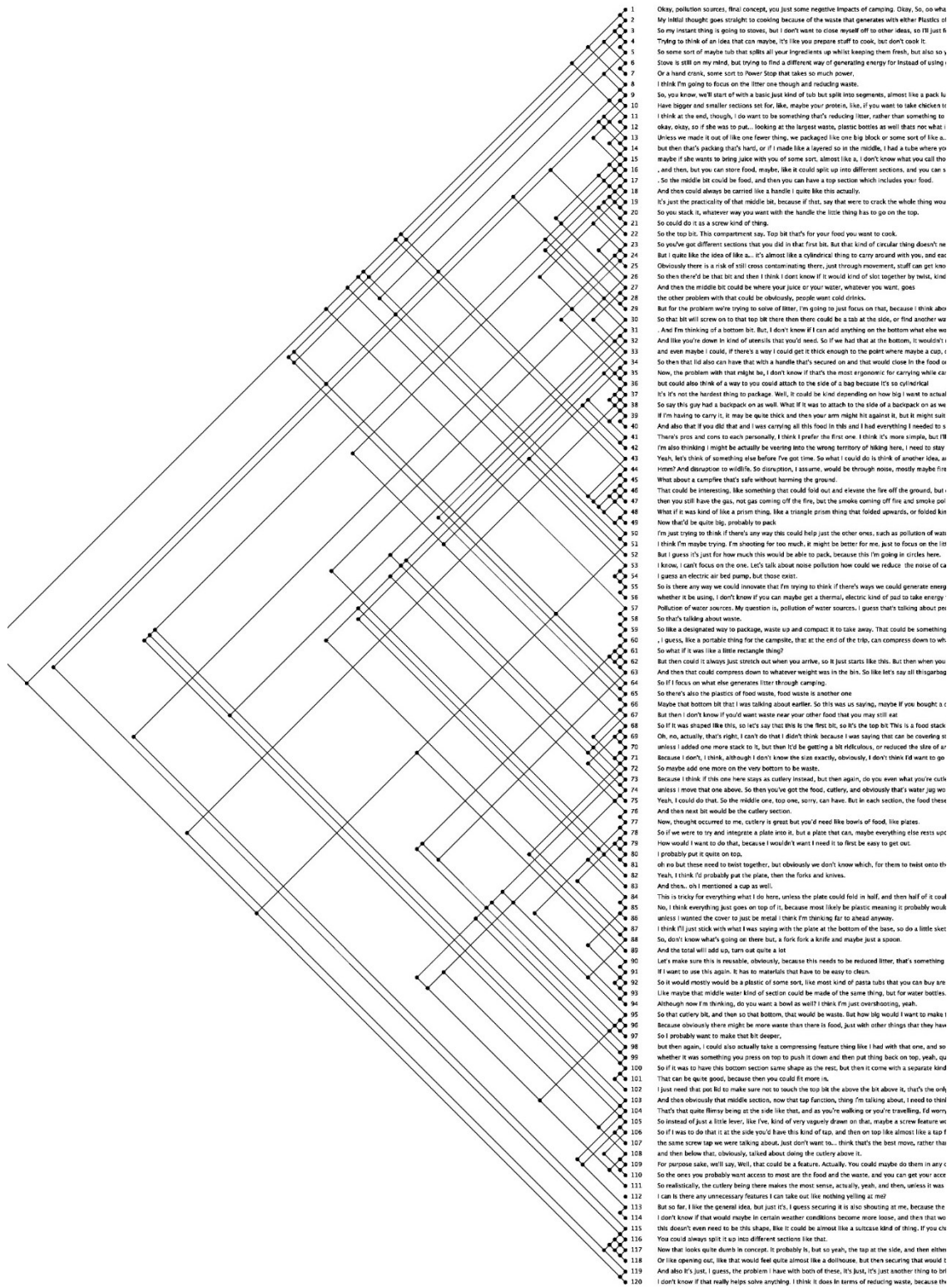
Appendix 10: Linkographs

All Linkographs were created on LINKODER.

P11 Linkograph:

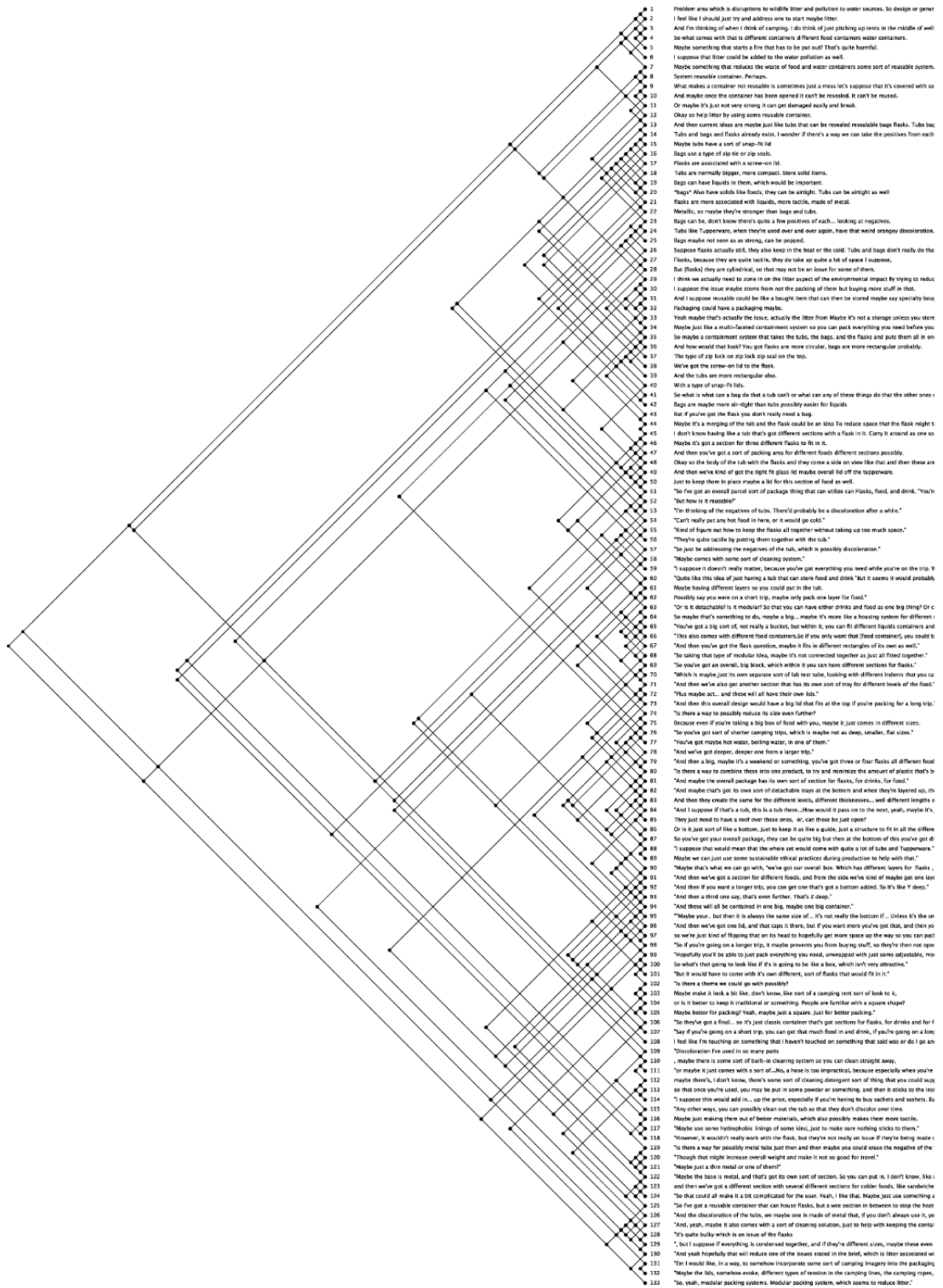


P24 Linkograph:

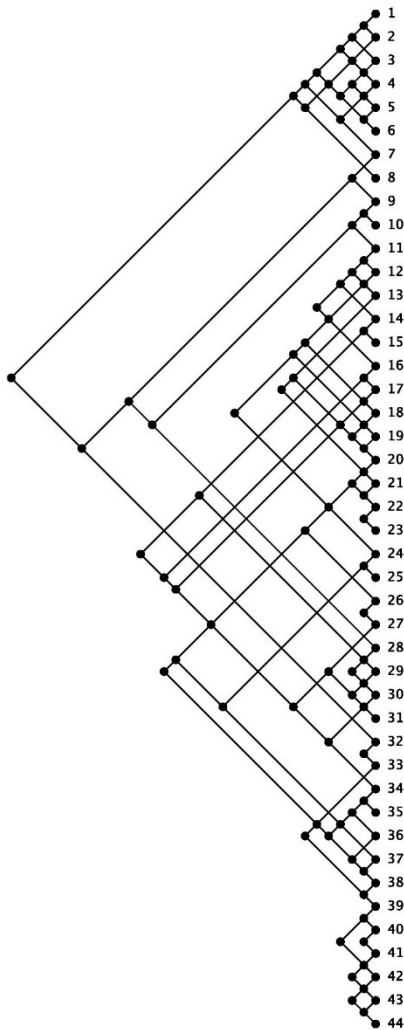


1 Okay, pollution sources, final concept, you just some negative impacts of camping. Okay, so, so who
2 my initial thought goes straight to cooking because of the waste that generates with either plastics of
3 so my next thing is going to assess, but I don't want to cross myself off at other ideas, so I'll just
4 Trying to think of an idea that can maybe, it's like you prepare stuff to cook, but don't cook it.
5 So some sort of maybe tub that sorts all your ingredients up whilst keeping them fresh, but also so
6 stove is still on my mind, but trying to find a different way of generating energy for instead of using
7 Or a hand crank, some sort to power. Stop that takes so much power.
8 I think I'm going to focus on the other one though and reading waste.
9 So, you know, we'll start with a basic just kind of tub but split into segments, almost like a pack
10 have bigger and smaller sections set for, like, maybe your protein, like, if you want to take chickens
11 I think at the end, though, I do want to be something that's reducing litter, rather than something
12 okay, okay, so if she was to pull... looking at the largest waste, plastic bottles as well (that's not what I
13 Unless we made it out of like one fewer thing, we packaged like one big block or some sort of like...
14 but then that's packing that's hard, or if I made like a layered so in the middle, I had a tube where you
15 maybe if she wants to bring juice with you of some sort, almost like a, I don't know what you call the
16 , and then, but you can store food, maybe, like it could split up into different sections, and you can
17 so the middle bit could be food, and then you can have a top section which includes your food.
18 And then could always be carried like a handle (quite like this actually).
19 It's just the practicality of that middle bit, because if that, say that were to crack the whole thing you
20 So you stack it, whatever way you want with the handle the little thing has to go on the top.
21 So could do it as a screw kind of thing.
22 So the top bit. This compartment say. Top bit that's for your food you want to cook.
23 So you've got different sections that you did in that first bit. But the kind of circular thing doesn't
24 But I quite like the idea of like a... it's almost like a cylindrical thing to carry around with you, and
25 Obviously there is a risk of still cross contaminating there, just through movement, stuff can get
26 So then there'd be that bit and then I think I don't know if it would kind of slot together by twist, kind
27 And then the middle bit could be where your juice or your water, whatever you want, goes
28 the other problem with that could be obviously, people want cold drinks.
29 But for the problem we're trying to solve of litter, I'm going to just focus on that, because I think
30 So that bit will screw on to that top bit there then there could be a tab at the side, or find another
31 And I'm thinking of a bottom bit. But, I don't know if I can do anything on the bottom what she
32 And like you're down in kind of areas that you'd need. So if we had that at the bottom, it wouldn't
33 and see how I could, if there's a way I could get it thick enough to the point where maybe a cup,
34 So then that lid also can have that with a handle that's secured on and that would close in the food or
35 Now, the problem with that might be, I don't know if that's the most ergonomic for carrying while car
36 but could also think of a way to you could attach to the side of a bag because it's so cylindrical
37 it's not the hardest thing to package. Well, it could be kind of depending on how big I want to actual
38 I say that you'd have a backpack on as well. What if we attach to the side of a backpack on as we
39 if I'm having to carry it, it may be quite thick and then your arm might hit against it, but it might suit
40 And also that if you did that and I was carrying all this food in this and I had everything I needed to
41 That's pros and cons to each personally, I think I prefer the first one. I think it's more simple, but I'll
42 I'm also thinking I might be actually be veering into the wrong territory of making here, I need to stay
43 Yeah, that's something that before I've got time. So what I could do is think of another idea, at
44 Here? And disruption to wildlife. So disruption, I assume, would be through noise, mostly maybe fire
45 What about a camper that's safe without harming the ground.
46 That could be interesting, like something that could fold out and elevate the fire off the ground, but
47 then you still have the gas, not gas coming off the fire, but the smoke coming off fire and smoke still
48 What if it was kind of like a prism thing, like a triangle prism thing that folded upwards, or folded
49 Now that'd be quite big, probably to pack.
50 I'm just trying to think if there's any way this could help just the other ones, such as pollution of water
51 I think I'm maybe trying, I'm shooting for too much, it might be better for me, just to focus on the
52 But I guess it's just for how much this would be able to pack, because this I'm going to circles here.
53 I know, I can't focus on the one. Let's talk about noise pollution how could we reduce the noise of ca
54 I guess an electric air bed pump, but those exist.
55 So is there any way we could innovate that I'm trying to think if there's ways we could generate energy
56 whether it be using, I don't know if you can maybe get a thermal, electric kind of pad to take energy
57 Pollution of water sources. My question is, pollution of water sources. I guess that's talking about pe
58 So that's talking about waste.
59 So like a designated way to package, waste up and compact it to take away. That could be something
60 , I guess, like a portable thing for the campsite, that at the end of the trip, can compress down to what
61 So what if it was like a little rectangle thing?
62 But then could it always just stretch out when you arrive, so it just stays like this. But then when you
63 And then could compress down to whatever weight you want in the bin. So like let's say of this thing
64 So if I focus on what she generates litter through camping.
65 So there's also the plastics of food waste, food waste is another one
66 Maybe that bottom bit that I was talking about earlier. So this was us saying, maybe if you bought a c
67 But then I don't know if you'd want waste near your other food that you may still eat
68 If it was shaped like this, so let's say that this is the first bit, so it's the top bit. This is a food stack
69 Oh, no, actually, that's right. I can't do that. I didn't think because I was saying that can be covering it
70 unless I added one more stack to it, but then I'd be getting a bit ridiculous, or reduced the size of ar
71 Because I don't, I think, although I don't know the size is exact, obviously, I don't think I'd want to go
72 So maybe add one more on the very bottom to be waste.
73 Because I think, if I sit one here, some as cutlery instead, but then again, do you even want your cutl
74 unless I move that one above. So then you've got the food, cutlery, and obviously that's water (ag w
75 Yeah, I could do that. So the middle one, top one, sorry, can have. But in each section, the food these
76 And then next bit would be the cutlery section.
77 Now, thought occurred to me, cutlery is great but you'd need like bowls of food, like plates.
78 So if we were to try and integrate a dish into it, but a plate that can, maybe even the rests up
79 How would I want to do that, because I wouldn't want I need to be first be easy to get out.
80 I probably put it quite on top.
81 oh no but these need to twist together, but obviously we don't know which, for them to twist onto th
82 Yeah, I think, I'd probably put the plate, then the forks and knives.
83 And then, oh I mentioned a cup as well.
84 This is tricky for everything what I do here, unless the plate could fold in half, and then half of it cou
85 No, I think everything just goes on top of it, because most likely be plastic meaning it probably woul
86 unless I wanted the cover to just be metal. I think I'm thinking far to ahead anyway.
87 I think I'll just stick with what I was saying with the plate at the bottom of the base, so do a little s
88 So, don't know what's going on there but, a fork fork a knife and maybe just a spoon.
89 And the total will add up, turn out quite a bit
90 Let's make sure this is reusable, obviously, because this needs to be reduced litter, that's something
91 if I want to use this again. It has to materials that have to be easy to clean.
92 So it would mostly would be a plastic of some sort, like most kind of pasta tubs that you can buy are
93 Like maybe that middle water kind of section could be made of the same thing, but for water bottles.
94 Although now I'm thinking, do you want a bowl as well? I think I'm just overthinking, yeah.
95 So that cutlery bit, and then so that bottom, that would be waste. But how big would I want to make
96 Because obviously there might be more waste than there is food, just with other things that they have
97 So I probably want to make the bit deeper.
98 But then again, I could also actually take a compressing feature thing like I had with that one, and so
99 whether it was something you press on top to push it down and then put thing back on top, yeah, so
100 So if it was to have this bottom section same shape as the rest, but then it come with a separate kind
101 That can be quite good, because then you could fit more in.
102 I just need that pot lid to make sure not to touch the top bit above the bit above it, that's the only
103 And then obviously that middle section, now that top function, they're talking about, I need to think
104 That's quite funny being at the side like that, and as you're walking or you're travelling, I'd worry
105 So instead of just a little lever, like I've, kind of very vaguely drawn on that, maybe a screw feature w
106 So if it was to do that it at the side you'd have this kind of tap, and then on top like almost like a tap f
107 the same screw tap we were talking about, just don't want to... think that's the best move, rather than
108 and then below that, obviously, talked about doing the cutlery above it.
109 For purposes sake, we'll say, well, that could be a feature. Actually, you could maybe do them in any c
110 So the ones you probably want access to most are the food and the waste, and you can get your acce
111 So realistically, the cutlery being there makes the most sense, actually, yeah, and then, unless it was
112 I can't think any unnecessary features I can take out like nothing yelling at me?
113 But so far like the general idea, but just... I guess assuming it is like showing at me, because the
114 I don't know if that would maybe in certain weather conditions become more loose, and then that this
115 this doesn't even need to be this shape, like it could be almost like a suitcase kind of thing, if you c
116 You could always split it up into different sections like that.
117 Now that looks quite dumb in concept. It probably is, but so yeah, the tap at the side, and then either
118 Or the opening, like that would feel quite almost like a delineate, but then securing that would
119 And also it's just, I guess, the problem I have with both of these, it's just, it's just another thing to b
120 I don't know if that really helps solve anything. I think it does in terms of reducing waste, because the

P09 Linkograph:



P10 Linkograph:



1 I guess with litter, it's mainly going to be all food related, stuff like that that causes that and pollution

2 Probably like keeping things clean, like a lot of people use those camping stoves and stuff so maybe

3 And wildlife might be campfires disrupting them, or maybe just the people being there,

4 But I think it seems like a lot of the environmental impact would be doing like, cooking food and stuff

5 Just going to draw like a campfire and see if that brings any ideas. I'm just doing some wee camping

6 Don't know if... I'm trying to think of something that can encompass it all in the one, but I don't know

7 or, something that people can cook food with, but will also, or it will have some storage or something

8 And then pollution of water, just trying to think how it would pollute water in the first place.

9 I guess it's like a some sort of stove that uses an environmentally friendly fuel... what about solar po

10 Things are powered by waves and stuff, but don't know if that would be any use, or if it's just a wee t

11 Maybe like a solar powered stove or something It would need time to charge up

12 So, I guess if it was something that could be stored on the outside of your backpack maybe, that cou

13 And then... yeah. I'm just trying to think how it would be, like what...who would power it if it was sol

14 So I know from ones that I've used in the past, still have, like the fuel sort of, there's like usually a we

15 And then that would need to be held in place somehow. Like some sort of stand for it.

16 Then kind of part of it would be solar powered so the kind of base part.

17 Maybe it could have a panel on either side. So even if it's off not in operation, if it's sunny at the time

18 Could maybe stick it on a backpack.

19 A lot of backpacks have kind of wee top compartment bit that lifts over itself maybe it could be place

20 This is just when you look at like a camping backpack it's got all the usual sort of pockets and things

21 And then, that would mean when someone was just walked around for the day that it could be gettin

22 Yeah, not sure if that would be uncomfortable it would depend what the material was.

23 I'd quite like that to be metal.

24 But maybe it could be... It would have to be angled at the right sort of angle so that it's getting the m

25 I suppose during the day the sun would be up in the air mostly. So just kind of coming down on the t

26 It shouldn't be too wide. It shouldn't be much what like it shouldn't be any wider than the shoulders,

27 It's like right here that goes to here until, the shoulder comes out like that. It's not the best drawing

28 It's just how you would use the solar energy to like heat, like food up.

29 I guess you get those hobs that don't have a flame or anything it's just like on the surface and then it

30 Then when it's not in use and it's all cooled down maybe the bowl could be placed over the top, but i

31 Right, I'll try and draw this a bit clearer. So how wide it would be compared to... so like a few inches c

32 And then there's also, just thinking about the litter, sort of aspect of it. So you would need it to like t

33 So maybe if it was like... had a bit underneath it where it's being carried to hold like a, bag with litter.

34 So you've got the kind of base bit with solar panels on either side, and the heating component in the

35 And then they'll start heating it up with like an on button.

36 It would probably have to be covered like for rain getting into that, and then when it's not in use. Yea

37 The solar panels are still visible for sunlight to reach. And then that could be then placed on someor

38 So that would be finishing right there. There's like a wee hood, which is there. You've got the regular

39 And then to pick up litter different sort of big sections on the bottom.

40 So they'll need to fold away into the product and stuff like that.

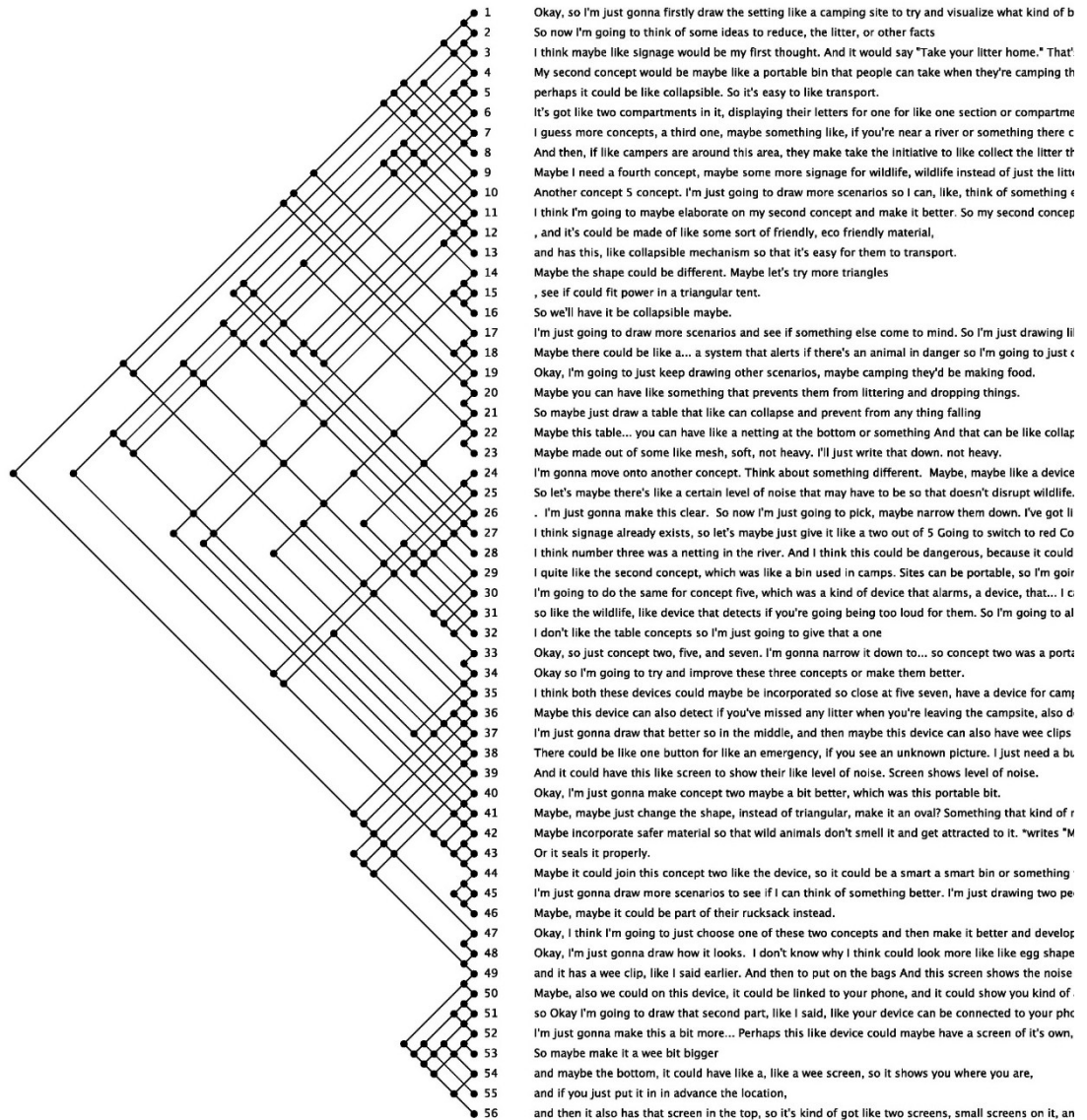
41 Then a wee slot for them. Then they could hang down. Should have probably drawn the hook first. M

42 Could be one of them at each side or then whether it comes with like reusable bags, to put litter in

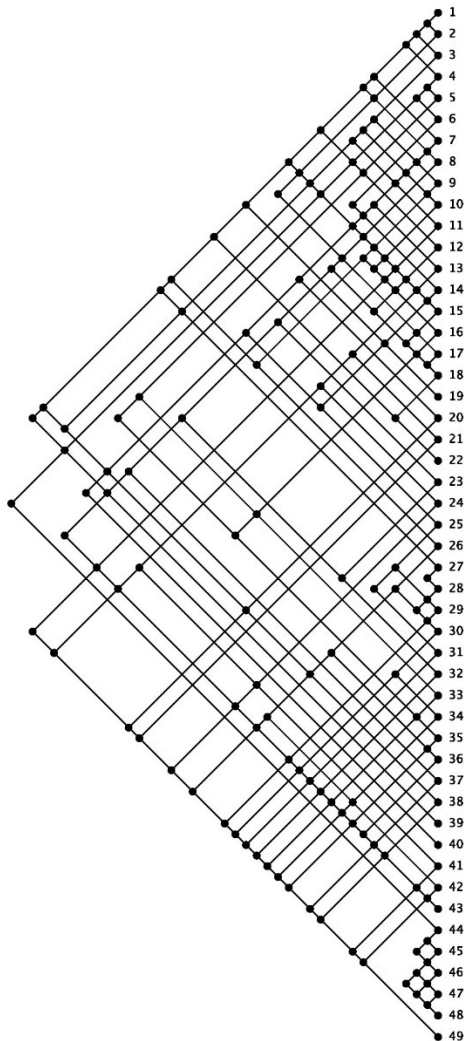
43 And then if that had either a strap or... in fact maybe instead of a hook it could be like one of those v

44 They can hold any rubbish that gets created. And then next time if someone goes past a bin they can

P21 Linkograph:



P17 Linkograph:



1 So I'll just start with a line graph now, that's the easiest way to get things down so One for issue. Get
2 I so to stop litter, you could have bins you could have the big bins somewhere or like a portable.
3 For destruction to wildlife, something that's quite camouflaged, less noise,
4 and then for pollution of water sources, wait how are they polluted.. am I allowed to ask? smaller I gu
5 I'm not sure, so portable toilet
6 maybe from food things?
7 And then products that are currently used for camping. Like a tent with like a sleeping bag and you c
8 So this one could be for the litter problem. So we could have some sort of bin attached to the tent.
9 And then.... There's the disruption one Could be a muted color of like Green,
10 like a thicker noise cancelling feature,
11 That's it then. And it's a bit smaller "the tent"
12 And then for the pollution one it could be like a separate bit of some sort of Portable Toilet or somet
13 so it's nailed into the ground, so it could be like weighted or something else to stop it from having Tr
14 like An electric camping stove.
15 . I might just combine some of the ones I've got right now into like a tent that reduces the three prob
16 "writes "smaller tent, muted green colour, thicker material "I'm just sketching the portable toilet on t
17 And also the bin, I'm not sure if that actually solves, oh, no well, that will definitely solve the litter iss
18 So everything's sketched on one thing now, but it's not a very creative solution. So I'm trying to think
19 I'm just gonna sketch the electric stove. Because that's bad for the environment,
20 and I don't think there's an issue with camping chairs.
21 So, I'm just gonna write that it'll be like weighted so the tent doesn't blow away.
22 So now I'm just trying to think of ways it could be, ways to fix the problems, maybe a bit better than
23 So the bin lid would like lock in place so it doesn't blow the rubbish out.
24 And the weights can be removed and packing.
25 And the stove can also be used as like a heater for outside. So they don't need to build a fire,
26 and then it might be the green color, but also look like leaves, so it blends in a bit more to not distur
27 I'm just trying to think how else the wildlife could be disturbed other than the noise and the... being !
28 . So they might also be, if the people are sitting outside, obviously, then that's they're still disturbing
29 So there might be, like a cover over where the stove is.
30 I'm just gonna resketch everything because I'm running out of space. So there's like a cover over the
31 And then they've got the heater, which doubles is the stove
32 then the bin can go in the area that they're going to use a bit more, and it's got a little cut in the top
33 And then still trying to think about the toilet thing, because that's a bit weird.
34 I and then that will be like a blackout material as well, so any light from inside doesn't shine out.
35 So I'm going to have the toilet separate, because might be a bit weird people going to the toilet right
36 It's got a wee cover that matches the same as tent as well.
37 The bin could have like separate compartments in it for recycling, for food waste and more general w
38 And the chairs as well will be the same color as the other stuff, so it doesn't stand out too much. The
39 the litter problem is solved more just the pollution of water sources that I'm not sure about, because
40 . And then you still need a sleeping bag and yeah sleeping bags would obviously just be inside the te
41 The weight, the weighted bits could be fastened in with like buttons to make sure that they don't con
42 And then the material needs to be quite heavy duty, So it doesn't rip and blow away, so a material thi
43 I'm just labeling the new drawing. And... I think I'm quite happy with the final thing. I don't think I ca
44 Oh I don't know if they have to like wash their clothes, maybe that can affect them more.
45 So they can also have, like, a little portible washing thing that it can you can fill up with water first, s
46 Maybe it's like handheld and they can spin it around the lever. And they can fill it up with water first
47 And then they... they could slip on that maybe the shape of it could be this angular
48 . You could have a light in it. An electric light or something.
49 I'm not really sure what else to add right now. And the seats can be weighted as well, so they don't bi