Design as a **catalyst** for **innovation** in **science**

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Dedication

For Osama and Rania

"I will sing the Lord's praise, for He has been good to me."

Psalm 13:6

Abstract

Science, as a broad field of study, is faced with the imperative to innovate, not just invent. However, innovation is often considered intangible or unattainable – a lofty, unrealistic goal. This is partly due to a cultural barrier where scientific research is perceived to be most valuable when it results in pure knowledge production. There are also significant systemic barriers that hinder attempts to translate scientific research into something more. As a result, there exists a phenomenon known as the "valley of death", which refers to the gap between new research knowledge and its potential translation into valuable solutions or market outcomes.

Addressing this gap has grown increasingly urgent, especially in the face of the upcoming "molecular age" that calls upon transdisciplinarity to tackle the complex challenges of our future. The scientific community has responded to the call, and there has been a growing shift away from discovery-level fundamental science towards research that seeks to address societal problems. However, the strategies and methodologies to achieve this transition remain unclear, and the aforementioned systemic barriers block innovation.

Design has been demonstrated in several other fields as a valuable approach to innovation and in more recent years, has been suggested as having the potential in supporting scientific projects. Embedded design practice has been proven to play a critical role in facilitating innovation and cultivating organisational transformation. Yet, this still needs to be thoroughly examined in the field of science. Current literature and practice in industry and academia have confirmed a need for cooperation between the fields of design and science. However, there needs to be more understanding of the practicalities in adopting design approaches in a scientific project.

This research seeks to address the literature gap for understanding the journey of design adoption experienced by a scientific team to determine the best approach for design practice in science. Thus, the overarching aim of the study is:
To investigate how design can be leveraged in scientific projects as a catalyst for innovation.

Through this journey of investigation, the following research questions are addressed:

RQ1: How is design perceived by scientists engaged in a scientific project?

RQ2: What opportunities and challenges are afforded by the application of design in a scientific project?

To achieve this aim and respond to the above research questions, a longitudinal case study approach was adopted, where the candidate was positioned within a scientific team over nine months, assuming the role of both embedded designer and case study researcher. Through the collection of qualitative data (such as interviews, observations, reflective journals, workshops, and surveys) and subsequent thematic analysis, this case study allowed for a thorough investigation of how design can play a critical role in catalysing innovation for science.

In addressing the first research question, this research uncovered that the journey towards design adoption is not a straightforward one. Design was met with initial scepticism, but it was revealed that through the process of experiencing design and seeing its value demonstrated first-hand, the scientific team grew to embrace design and perceive it in a positive light. Documenting the changing perceptions along this journey revealed key moments of tension and transition.

The journey explored in the first research question also invites the deeper exploration of the second research question, which sought to understand the opportunities and challenges afforded by design. These findings revealed the specific and unique value that design brings to science and invites future projects to capitalise on opportunities. Further, by considering not just opportunities but also challenges future practitioners can predict, mitigate, and proactively manage any hurdles in the design adoption journey.

This thesis synthesises the findings around the changing perceptions towards design, as well as the opportunities and challenges experienced along the way, to deliver key recommendations for design and science. These recommendations fall under five themes:

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- Embracing design as a mindset
- Drawing parallels and contrasts between design and science
- Recognising systemic challenges and barriers
- Adopting a team-centred approach
- Empowerment through experiential learning

These recommendations are intended to support three audiences – design practitioners working with scientists, scientists interested in adopting design, and researchers working at the intersection of design and science. Through the case study of one scientific team's journey of design adoption, this thesis provides implications for design and science, both in practice and research.

Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work, and that all the assistance received in preparing this thesis and sources have been acknowledged.

Carol Azzam Mackay

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Acknowledgements

To Martin,

Thank you for taking a chance on a science student who wanted to join your design class! Looking back now, more than five years later, that was the first step in a journey that has changed my life for the better. Thank you for your insightful feedback and for sharing your expertise. I have learnt so much from you.

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I am who I am, because of you. Your love and sacrifice have enabled me to dream big, and your unconditional support has been the wind beneath my wings. I am honoured to be your daughter, and this thesis is for you.

To Nathan,

Thank you for being my armour-bearer throughout the highs and lows of this journey. Your patience and gentleness have not gone unnoticed. I couldn't have done this without you.

Preface

This thesis, "Design as a catalyst for innovation in science", has been written to fulfil the requirements of the Doctor of Philosophy at The University of Sydney. I was engaged in researching and writing this thesis from March 2018 to December 2022.

I approached this research after completing a Bachelor of Science (Advanced), majoring in Chemistry. I have loved science for as long as I can remember. But as I learnt more at university, I found myself wondering about the drivers of scientific research, beyond the pursuit of knowledge. I also knew I wanted the opportunity to be both creative and analytical in my future career, and tackle complex real-world challenges.

What began as a design elective unit of study in my final year of a science degree, quickly turned into a new passion. To me, design and science both satisfied my curiosity to solve problems, be creative, and learn new things. And thus, the personal motivation for this doctoral candidature was born.

This thesis was completed by monograph, and there are no supporting publications at this stage. This was an intentional decision with many contributing factors, but the main reason was that I spent most of my candidature as a part-time student, balancing full-time work at the same time. I decided to focus on completing the research and thesis as efficiently as possible. I look forward to continuing work with my supervisors to develop publications after completing my PhD.

The experience of conducting this research and completing this thesis has been invaluable both personally and professionally, and I am thankful to have had this opportunity.

CHAPTER 1: INTRODUCTION

"The natural sciences are concerned with how things are… Design, on the other hand, is concerned with how things ought to be."
(Simon, 1969, p. 114)

"The best way to ensure a future of our liking is to do something about it."
(Björklund et al., 2017, p. 218)

1.1 Overview

This chapter aims to provide a contextual background for the research study and for this thesis as a whole. It also examines the significance of the study, with respect to the contributions to both design and science practice. An overarching aim is proposed, with two subsequent research questions and three research objectives, providing necessary signposts to the research questions. Finally, the scope of the study is summarised.

1.2 Background

In the face of technological booms and waves of research advancement, such as the upcoming (mid-2020s) "molecular age" (Linstone, 2011), there exists the imperative for innovation. This imperative is heightened in response to increasingly complex societal challenges to be addressed by scientific research outputs (Linton, 2009; Thong *et al.*, 2021). In the context of science, innovation has been defined as a process with "the ability to produce new ideas, and the ability to turn these ideas into something useful" (Nicolau, 2004, p. 454). Innovation enables the critical transfer of scientific research into tangible outputs, enhancing competition and differentiation (Baregheh, Rowley and Sambrook, 2009). And yet, there exist systemic constructs within the field of science, especially in academia, that frame innovation as an intangible or unattainable goal – a nicety, but not a certainty (Riol and Thuillier, 2015).

Moultrie (2015) describes this issue as a cultural one, where science is perceived to have innate value in and of itself, preventing cooperation or even consideration of a commercially-minded approach to research. The "valley of death" (Markham *et al.*, 2010; Merrifield, 1995) in science research translation refers to situations where research initiatives and outputs are not sufficiently resourced nor informed to translate into market outcomes. Responding to this challenge is reflected in the rise of startups, spin-offs, research centres of excellence, and industry-partnered research (Van Burg *et al.*, 2008). There has also been an effect on the financing of scientific research, where in recent years there has been a shift in focus from discovery-level fundamental science towards late-stage research with more obvious (or at least, imminent) applications (Moses *et al.*, 2015). This has led to the increasingly diverse disciplines working together, not only through parallel multidisciplinary practice but transdisciplinarity that blurs boundaries and creates an integrated approach to solving complex problems (Choi and Pak, 2006; Miyazaki and Islam, 2007; Mangematin and Walsh, 2012).

Design has proven to play a critical role in facilitating and promoting innovation in the spheres of business (Brown, 2009), management (Martin, 2009), and design itself (Verganti, 2009). Design has also been posited as having a role in supporting scientific research (Peralta and Moultrie, 2010; Mesa, Tan and Ranscombe, 2022). This research will explore how design can catalyse innovation in science, first by examining a scientific team on their journey of embracing design, unpacking the challenges and opportunities experienced along the way, and then providing recommendations for best practice.

1.3 Research context

To thoroughly investigate the role of design as a catalyst for innovation in science, I have chosen to draw on (and challenge) the historical values of design and science, explore the journey of design adoption by a scientific team, and ultimately evaluate the value brought by design to the field of science. The context of this research was through a case study, where I took the role of both doctoral researcher and embedded designer within a scientific team.

The disciplinary context of this study within science was physics, photonics, and smart sensing. This is due to the experience and practice of the scientific team involved in this research – the Jericho Smart Sensing Lab (JSSL) at the University of Sydney, in the Sydney Nanoscience Hub. The JSSL was tasked with a unique directive, bringing together a team of scientists, researchers, and engineers to deliver smart sensing solutions for the Royal Australian Air Force (RAAF). The intention of the JSSL was to integrate design with cutting-edge science in order to extract the maximum creative solutions for their end-users in RAAF. The project sponsor for this collaboration was Plan Jericho, a RAAF initiative aimed at ensuring strategic advantage and fifth-generation capability in the Air Force. The JSSL was established in May 2019, with my formal research involvement spanning November 2019 to July 2020. During this time, I joined the JSSL as the designer within the team, initiating design activities and inputs. Concurrently, I was also evaluating this engagement as a case study, conducting qualitative data collection and research. Activities conducted during the embedded practice had differing relevance to my roles as designer and researcher – as described in **Table 1.1**:

Table 1.1: Involvement in the JSSL as both embedded designer and in conducting case study research

Activity	Embedded designer	Case study researcher
Facilitating workshops	Facilitating the design innovation process through design methods; supporting development of innovative solutions	Observing how scientists adopt design, what was / was not received well
Attending weekly meetings	Keeping informed on current work and issues within the team, providing design support and advice	Collecting observations within the journal; improving understanding of the JSSL's response to design
Semi-structured interviews	Building rapport within the team, providing a space to reflect and honestly discuss their experience with design	Understanding the perspective of project leaders in JSSL towards design, including challenges and opportunities experienced

Surveys	Providing an opportunity for the team to reflect on their own experience	Collecting insights from the broader team context at key moments (e.g., at the conclusion of my engagement)

1.4 Research aim, objectives, and questions

This research is positioned in the unique and complex transdisciplinary space of science and design innovation. The overarching aim of this study is:

To investigate how design can be leveraged in scientific projects as a catalyst for innovation.

More specifically, this research will explore the interaction of design and science through the case study of design practice within a scientific project. In order to understand how design innovation is applied in science to facilitate innovation, this research seeks to:

- **Understand how to facilitate a design innovation engagement within a scientific project,**
- **Evaluate participant engagement with design in the discipline of science,**
- **Provide recommendations for design practice in science.**

To address the aim and objectives, two research questions are examined:

1. **How is design perceived by scientists engaged in a scientific project?**

   In order to eventually understand how design brings value to science, we must first understand how design in general is received. The case study involves the embedded practice of the researcher within the scientific team, facilitating and promoting design innovation activities. The embedded practice and rounded suite of qualitative data collection methods allow the researcher to identify both explicit and latent knowledge, to uncover deeper insights and nuanced perceptions. As these design activities and interventions are implemented, first-hand insights are collected to ultimately understand the dominant perceptions towards design at each stage of the project. Equipped with an understanding of

how design is perceived at each stage of the engagement, the next step is to holistically examine the data set to determine if there is an observed shift in these perceptions. This provides an overall understanding of the changing perceptions towards design.

2. **What opportunities and challenges are afforded by the application of design in a scientific project?**

   The complex transdisciplinary context of this research gives rise to a variety of opportunities and challenges. This question will involve revisiting the data set to identify the key features of design which have been perceived as opportunities. This involves deeper exploration of the changing perspectives towards design identified in the first research question, now searching for the exact moments and catalysts of change to identify to potential pivots, shifts, pain points, or breakthroughs. Understanding these key moments and the perceptions towards them will assist in identifying significant opportunities where design has been perceived to bring value to science. It will be equally significant to understand situations where the design engagement did not bring about opportunities or was not seen to bring value, as these emerge as either challenges, unique constraints to a design-science project, or potential areas for future exploration. Responding to this question will provide a unique evaluation of the design engagement, not solely grounded in theory, but a tailored recommendation based on the observed response of the scientific team.

These two questions contribute to understanding the overall research aim by observing the perceptions towards design and examining how these perceptions shift over time, then by identifying emergent opportunities and challenges throughout the engagement. Combining these two questions leads to a holistic understanding of how design can be leveraged in scientific projects as a catalyst for innovation, and inform the provision of recommendations for future practice.

1.5 Significance and contributions

This research focusses on the bridging of design and science as opposed to the individual disciplines themselves, allowing for a deeper understanding of how the work together. On an academic front, this provides an opportunity to both examine and challenge philosophical constructs of science and design in practice and gain a rich understanding of research approaches and methods in both fields. Additionally, the embedded role of the candidate facilitating and reflecting upon a design engagement within a scientific team is unique. This allows not only for the facilitation of design activities within the team but also a detailed reflection on the response of the team to design throughout the process, as it is being experienced.

Through examining a close engagement with a scientific team, this research will understand the nuances and challenges involved in adopting design, and what that journey looks like in a scientific context. This is a significant contribution to the current understanding of design innovation practice, as it allows future researchers to understand and anticipate the potentially complex and tumultuous path towards design acceptance and adoption within a team. This provides reassurance as well as supports proactive preparation in the face of potential barriers to adoption – "the way we've always done things" should indeed be challenged and questioned.

The study will also provide informed recommendations for design practice within the context of scientific innovation. The recommendations from the study elucidate areas where future practitioners can capitalise on the opportunities afforded by design. Finally, by also considering the challenges involved in adopting design, the recommendation is made more realistic as challenges can be predicted, mitigated, and managed proactively. This consideration of challenges adds nuance to the recommendation, ensuring a bespoke and balanced approach instead of "one size fits all".

This research is aligned with the Australian Government National Innovation and Science Agenda's (NISA) Global Innovation Strategy (Department of Industry,

Innovation and Science, 2018) as the translation of science into innovative projects is a national priority (although this is by no means a local dilemma). The key initiatives of the Global Innovation Strategy include facilitating "an innovative, open marketplace for Australian business and researchers" (Department of Industry, Innovation and Science, 2018). This research complements and advances this space as it will evaluate the potential for design to cultivate innovation, harnessing the unique capability of transdisciplinary collaboration. There is an increasing urgency in scientific contexts to differentiate *and* innovate, and it is this imperative upon which design has the potential to act to achieve research impact (Mesa *et al.*, 2020).

This research is positioned such that it will not only benefit the scientific industry itself, but also contribute to the field of design innovation through the development of new research knowledge. The transdisciplinary approach means that the resulting insights will not simply fill a niche problem, nor will they lack the ability for translation into other fields. Ideally, by providing strategies and tools to navigate complex relationships between design and science, this research will provide a useful case study for any research/industry collaborations where there is potential disciplinary friction. These insights will not (and by nature, cannot) exist in a vacuum, and by adding to the increasing body of design innovation knowledge, help advance the field of embedded design practice and provide opportunities for new research.

1.6 Scope

By spanning two disciplines, the overall research setting of this project is large, and has the potential to be overwhelming or misdirected. Hence the aim has not been to "fix" science research, rather to use findings from the implementation of design innovation to provide recommendations that *assist* scientists in facilitating innovation. This project provides a thorough evaluation of the journey towards design adoption with a scientific team, uncovering the challenges and opportunities along the way and informing future design and science practice.

There is great complexity in the project due to the transdisciplinary context, which provides both an opportunity and a limitation in terms of scope – the opportunity is in making detailed commentary on the challenges involved in complex research relationships, as well as providing a rich and varied data set from which to draw observations. However, the limitation in this is that the study must be discerning in data collection and selection, lest the scope extend far beyond that of a Doctoral candidature. A set of qualitative data collection methods have been selected to provide rich insights specific to the research questions, with the intentional choice to not include any scientific research data. Such data may indeed reveal potential quantitative insights about the effect of design within a scientific context but would have required a separate and extensive research protocol that would have detracted from the depth of the qualitative case study. Similarly, a decision was made to exclude input from end-user stakeholders in RAAF – while the study involved workshops where RAAF were engaged, the focus of the study was the response of the *scientific team* to design, not their end-users. Both scope constraints pose potential areas for further research, which are explained in more detail in **Chapter 5**.

Further, this study has intentionally avoided commentary and investigation around very specific needs and problems encountered by the scientific team. To do this would require not only a high level of involvement in the organisation (which at best, is an undue time commitment, and at worst, produces a conflict of interest) but also poses the risk of creating recommendations that are too niche. The intention of the study (which is reflected by the research questions and research design) is to elicit generalised learnings from a specific case study, such that the resulting implications and conclusions would provide value to scientific practice in general, beyond the specific case study context of smart sensing for RAAF.

Finally, the project will not consider radical recommendations on the organisational/employment structure of research teams – the tools will be constructed with the aim of being *utilised* by scientific groups, not disbanding or restructuring them.

1.7 Thesis outline

This thesis is presented in six chapters, progressing in the following manner:

- **Chapter 1: Introduction** examines the contextual background and significance of this research. The research aims, questions and objectives are outlined.

- **Chapter 2: Literature Review** summarises the relevant literature and research, specifically addressing (i) philosophies of scientific knowledge and the scientific method, (ii) the nature of scientific disciplines and multidisciplinarity, (iii) the call for design and design practice and (iv) the future of design and science for innovation. Consequently, this chapter identifies the key research gaps which this study seeks to fill.

- **Chapter 3: Research Design and Methodology** documents the research approach and design of this study. This includes the theoretical basis for the embedded case study approach and the various data collection methods employed, including semi-structured interviews, participant observation, surveys, reflective journaling, and focus groups. This chapter also outlines the qualitative thematic analysis protocol and methodology.

- **Chapter 4: Results and Findings** details the results and findings of the study with respect to the two research questions presented.

- **Chapter 5: Discussion** relates the findings of the study to the broader research and literature context, providing recommendations for practice. It also examines the limitations of the research and recommendations for future research.

- **Chapter 6: Conclusion** summarises the conclusions of the thesis and presents an overview of the findings. There is also a reflection on the entire research experience, from the perspective of the candidate as a designer and researcher.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter provides a literature context to the research in this thesis, by examining existing studies and theories of design and science, and then identifying the research gap to be filled. The chapter is divided into topics, first exploring the fields of science and design separately, then examining the synthesis of the two fields and the potential for multidisciplinary collaboration. Finally, there is a discussion of the potential for innovation through this synthesis, how this has been done in the literature, and what this means for innovation in science. These four areas are critical to the study of science innovation through design and provide a rich theoretical background to this study. Additionally, through this examination of the literature, the research gap will be highlighted, thus providing a literature context for this study.

2.2 The pursuit of knowledge

Before we explore the potential of design and science as a catalyst for innovation, it is important to recognise the frameworks and approaches within which science already operates. This section will provide an overview of the evolving philosophies of science, followed by exploring the nature of the scientific method, and what this means for research.

2.2.1 Philosophies of science

The pursuit of knowledge in science has long been studied in an attempt to understand both drivers and methodologies – extending beyond pure science into a broader understanding of human thinking (Klahr and Simon, 1999). Plato describes this as an "arch of knowledge" comprising the vast body of work and information within science (Sale and Thielke, 2018). Building further, Aristotle detailed a process of "ascending and descending the arch" (Oldroyd, 1986). In this model, ascending the arch refers to the process of induction where the observation of data leads to the development of theories and broader concepts while descending the arch is the converse deduction process where conclusions

can be drawn from an understanding of general concepts (Sale and Thielke, 2018; Chalmers, 1999).

Popper (1959) highlighted an issue with the early philosophical views of science, where greater emphasis was placed on discourse rather than actual scientific theory:

> "Some philosophers have made a virtue of talking to themselves; perhaps because they felt that there was nobody else worth talking to. I fear that the practice of philosophizing on this somewhat exalted plane may be a symptom of the decline of rational discussion." (Popper, 1959, p. Preface 20)

In response to this concern, Popper adds additional criteria to the construction of knowledge, suggesting that theory must be grounded in a broader historical and epistemological context. He insists that there is no completely "new" knowledge; rather, "the advance of knowledge consists, mainly, in the modification of earlier knowledge… the significance of the discovery will usually depend upon its power to modify our earlier theories" (Popper, 1962, p. 28). This paints the picture of a unified "body" of knowledge, where the body supports the growth of each part, and each part is a facet of the body.

Kuhn (1970), in his "Structure of Scientific Revolutions", posits a similar description of science as a "constellation of facts, theories, and methods" (Kuhn, 1970, p.1) and that new knowledge is never composed piecemeal – rather, through a process of historical reflection and reconstruction. It is this concept that led to Kuhn's idea of "scientific revolutions", a non-linear approach to the pursuit of knowledge, less about raw facts and more about evolving paradigms and mindsets (Kuhn, 1970). This marked a recognition that discourse around knowledge did not have to remain in the realm of philosophy – that there was a growing interest in understanding the pursuit of knowledge as a scientific endeavour in and of itself, with a direct impact on the way science was done. The purist approach fades in favour of a more open and collaborative model of science, where "an odd idea may be part of the next paradigm" (Spalding, 2010, p. 130) and the boundaries of what makes something "scientific" are challenged.

The changing philosophies of science are painted in a positive light by Levy (1985), as a sign of "health", not "chaos" in the field (p. 68). Multiple parallel approaches to discovery and research are suggested to indicate diversity in approach, and ultimately, diversity in the wide variety of issues science is able to tackle. There emerges a push away from the insular pursuit of knowledge, and a pull towards problem solving:

> "Whereas science was previously understood as steadily advancing in the certainty of our knowledge and control of the natural world, now science is seen as coping with many uncertainties … In response, new styles of scientific activity are being developed. The reductionist, analytical worldview which divides systems into ever smaller elements, studied by ever more esoteric specialism, is being replaced by a systemic, synthetic and humanistic approach." (Funtowicz and Ravetz, 1993, p. 739)

Similarly, as von Glasersfeld (2001, p. 2) describes, "the image of the scientist gradually unveiling the mysteries of a world that is and forever remains what it is, does not seem appropriate". These two arguments signify a cultural shift in science, rejecting the somewhat luxurious historical scientific approaches that gave greater veneration to the most "revolutionary" ideas, and demanding sociocultural impact. Science knowledge is reframed from knowledge of truth, to knowledge of means to attain a goal (von Glasersfeld, 2001). As the world grows increasingly interconnected, so too does the reach of science grow broader (Avenier, 2010).

2.2.2 The scientific method

The foundations of science as a process and method of study are grounded in the scientific method. Evolutions of science as a process of inquiry predate ancient Greek philosophers (Pozzo, 2004), however, the term "scientific method" came into greater use in the nineteenth century, in order to create a distinction between science and pseudoscience (Thurs, 2011). In a modern context, the scientific method has been defined in various ways. Bauer (1992, p. 19 *in* Driver, Peralta and Moultrie, 2011, p. 3) presents a detailed definition as follows:

> "Systematic controlled observation or experiment, whose results lead to hypothesis, which are found valid or invalid through further work, leading

to theories that are reliable because they were arrived at with open mindedness and continual critical scepticism."

Simon (1992, p. 8) poses a similar definition of scientific practice by describing the activities involved in the scientific method:

"Scientists discover and define problems, they find appropriate representations for problems, they design experimental procedures and strategies, and plan and execute experiments, they obtain data by observation, they formulate laws and theories to account for data, using mathematical and other forms of reasoning, they deduce consequences from their theories, they invent instruments for making observations, and they devise explanatory theories to give deeper accounts of descriptive laws."

A framework for the scientific method is pictured below in **Figure 2.1**, providing a visualisation of the aforementioned journey from problem discovery, to experimentation, observation, theory, reasoning, and conclusion.
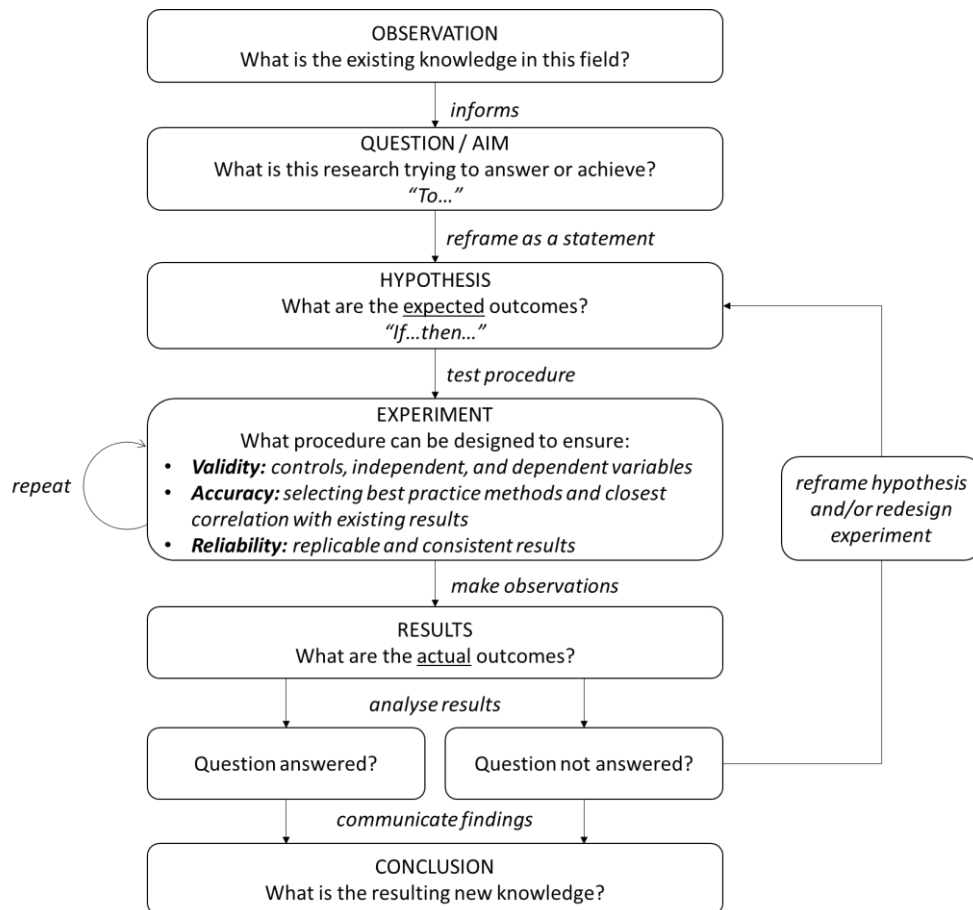
Figure 2.1: The process of the scientific method – adapted from (Voit, 2019).

This process centres on the presence of a falsifiable hypothesis, tested experimentally. The results of the experimentation provide either support or refutation of the hypothesis, triggering further iteration and another round of questioning (Voit, 2019). There are historically accepted boundaries to what can be questioned through the scientific method. Firstly, given the reliance on observation and analysis, the object of study must be observable and measurable (Spalding, 2010). Further, in order for a conclusion to be drawn, the hypothesis must be refutable by testing (Popper, 1959). Popper (1959, p.7) describes this process, demanding that "a hypothesis can only be empirically tested – and only after it has been advanced." The traditional scientific method approach necessitates the establishment of a theory, which is then rigorously tested and revealed through observation. This is framed in contrast to inductive reasoning, where hypotheses and theories emerge through and *after* the observation process (Sale and Thielke, 2018). The "elimination of psychologism" (Popper, 1959, p.7) implies that a strict understanding of the scientific method is very exclusively centred on this specific model of deductive testing of theories and that by definition science must exclude that which cannot be falsified through the above process.

The definitive nature of Popper's "Logic of Scientific Discovery" has come into question over the years, and increasingly so in the modern era. For example, Chalmers (1999) questions whether the falsifiability criterion is too broad, challenging the idea that *any* falsifiable claim is "scientific". Similarly, Kosso (2011) questions if a certain level of coherence and continuity is expected with respect to existing knowledge. Questions have also been raised as to the value of such strict discrete steps, as opposed to a more flexible critical thinking approach (Voit, 2019). Kosso (2011) argues that nuance is critical in a world where guesswork and certainty exist on a spectrum, and not as two discrete objective worlds. The scientific method is not dissimilar from everyday evidence-based reasoning and proof, although traditional science research places greater emphasis and intentionality on methodological rigour (Kosso, 2011).

This approach remains centred on key principles of scientific research, including validity (through classifying controlled, independent, and dependent variables), reliability (through replicates and iterative work) and accuracy (through specifying hypotheses and best practice methods) (Klahr and Simon, 1999; Maturana, 1988; Apud-Bell, Dasan, and Childs, 2018). These key features of the method are common with all scientific research activities, although the object of study, specific techniques, funding, and communication of results differ vastly. It is this process of questioning and testing that, in its rigour yet simplicity, has seen the establishment of both fundamental scientific laws and conceptual future technologies. The ultimate outcome of the scientific method is, quite literally, "re-search" – the "repeated search" for answers (Voit, 2019).

As the reach of science extends beyond the pursuit of absolutes, there emerge challenges and limitations in the scientific method. For example, Kulkurani and Simon (1988, p. 149) highlight the semantics around science experimentation, where the post-experiment confidence in a hypothesis is expressed through words such as "success", "failure", "failed-effort", "implied-success", and "implied-failure". The explicit and reductionist categorisation of results leaves little room for necessary nuance and creativity which is "inherently unexplainable" (Simon, 1992). There is a contrast between "curiosity-motivated" pure research and "mission-oriented" or "issue-driven" science in the modern age, and new approaches are needed to achieve this shift (Funtowicz and Ravetz, 1993). Addressing the uncertainty and complexity of modern scientific challenges demands more than the scientific method alone (Funtowicz and Ravetz, 1993).

Indeed, the scientific method provides a clear framework in both mindset and methodology for the exploration of truth and knowledge. As Kosso (2011, p. 3) explains:

> "Refusing the authority of evidence and logic, either in the form of believing without evidence or believing in spite of contrary evidence, is not just turning away from science; it is turning away from good sense."

However, despite the accepted value of the pursuit of knowledge, the scientific method has proven insufficient when we extend beyond knowledge and evaluate

and assess monetary, business, or translationary value – going beyond the "what" and "how", looking to the "why" of science (Linton, 2008; Kosso, 2011).

2.2.3 Summary

This section examined the changing philosophies of science, in terms of what science "means" and how this has evolved over time. This provides the foundation for a modern understanding of the perception and valuation of science, suggesting a call to consider science in a new light. The scientific method was also presented as the current operating picture for scientific research. However, the literature describes limitations in the scientific method, where pure scientific research is unable to mitigate the complexities and nuances of real-world challenges. There is the suggestion that the scientific method alone does not create enough space for the necessary creativity to tackle modern challenges, and therefore, there is a gap for alternative approaches to innovation.

2.3 The status quo of innovation in science

This section will examine the current state of innovation in science. First, there will be an exploration of the classifications of science and the evolution of disciplinary boundaries. This is followed by an examination of science innovation, including multidisciplinarity and collaboration in science.

2.3.1 Classification and disciplinary boundaries

An early exploration of scientific disciplines and their categorisation is in Peirce's (1903) "An Outline Classification of the Sciences". His preliminary claim is that all sciences can be labelled as a "science of discovery", "science of review", or "practical science" (Peirce, 1903). These groupings are split further several times, distinguishing fields such as mathematics, philosophy, history, and physical sciences. In this classification system, Pierce proposes that scientific activities are using the laws of physics to either create artefacts or explain them (Peirce, 1903; Vehkavaara, 2003). Looking towards a more traditional view of science, Pierce distinguishes "classificatory" physics (such as chemistry, biology – studying physical forms by scientific laws) and "descriptive" physics (such as geology, astronomy – describing individual objects to explain their phenomena).

But even these labels do not allow for the transience and fluidity we observe in science in the real world – Peirce, as quoted by Ambrosio (2016, p. 3) intended his theory to highlight the transitory nature of science classification, in the sense that it is "at best looking forward just a little." In this early assessment of the breadth in fields of scientific inquiry, there is already an admission that classification systems need to be updated, or at least exist as a reference point for further exploration and expansion.

Another classification system to be examined is the "Biglan Classification of Disciplines" (Biglan, 1973a). Biglan (1973a) presented the Biglan Classification of Disciplines, in an attempt to reconcile the disparity between "subject matter" and "academic departments" at universities (Biglan, 1973b, p. 195). This resulted in a classification of all "disciplines", or "academic subject areas" (Biglan, 1973a, p. 207), in a matrix of hard/soft, life/nonlife, and pure/applied (**Table 2.1**):

Table 2.1: Biglan's "Clustering of Academic Task Areas in Three Dimensions" – adapted from Biglan (1973a).

Task area	Hard		Soft	
	Nonlife system	Life system	Nonlife system	Life system
Pure	Astronomy Chemistry Geology Math Physics …	Botany Entomology Microbiology Physiology Zoology …	English Languages History Philosophy Communications …	Anthropology Political science Psychology Sociology …
Applied	Engineering Computer science …	Agriculture Medicine …	Accounting Finance Economics …	Education …

The motivation for this classification system was to categorise university departmental sectors and to understand the variety of research activities present in a tertiary education environment. However, this was later extrapolated into a commentary on scientific activities using the familiar descriptors in the matrix. "Hard" sciences are said to have a "single paradigm" (Biglan, 1973a), that is, their

research activities are generally met with consensus surrounding the body of theory from which they originate (Biglan, 1973b), as opposed to "soft" sciences where there is often a variety of theoretical foundations. The distinctions between "pure" / "applied" and "life" / "non-life" are more intuitive, with the former labels separating sciences with and without a focus on applications, and the latter on life systems (Biglan, 1973a).

A review of the Biglan Classification (Stoecker, 1993) considered perceptions of researchers from different points in the matrix, and issues such as funding, teaching, and research goals were identified. The research found that hard areas of study (traditional sciences) were driven more by funding sources and less by an overarching problem to solve (Stoecker, 1993). However, since the shift towards social and scientific innovation is imperative (Linton, 2008), Săvoiu (2014) concludes that aside from Biglan there must be a modern taxonomy of science, and one that does not discount the role of multidisciplinarity. Two models are proposed that, instead of mapping disciplines to single positions in a three-dimensional matrix, instead create genus-like "trees" where a single discipline can have several preceding/succeeding generations, as in **Figure 2.2**:
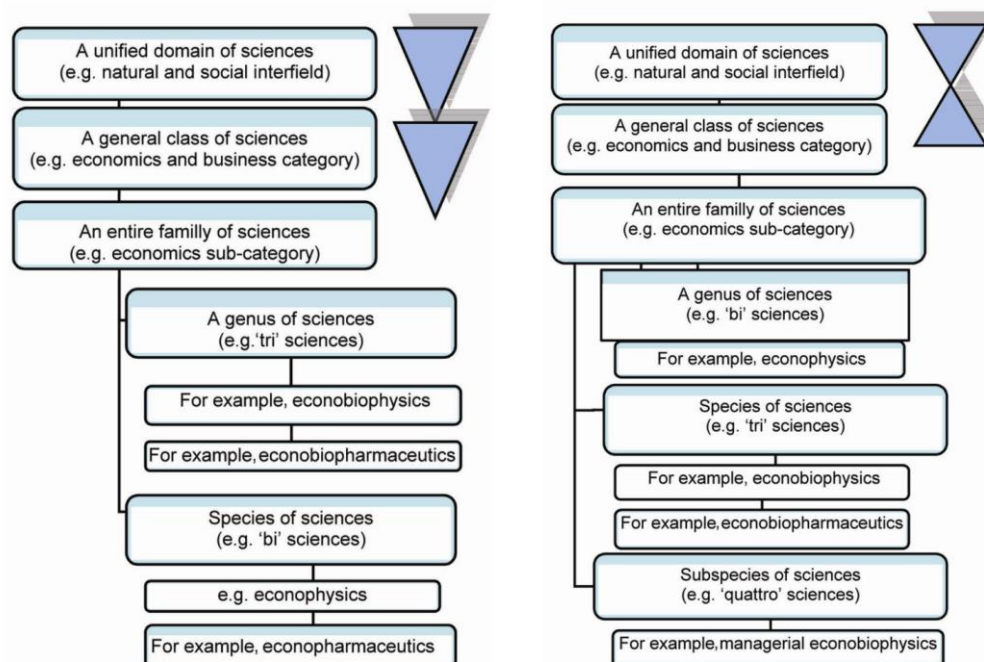
Figure 2.2: The "double funnel" and "mirror funnel" models for modern science taxonomy (Săvoiu, 2014).

Săvoiu's (2014) funnel models demonstrate how quickly we observe complexity in classifications once multidisciplinary enters the picture. Another example is in Stokes' (1997) *Pasteur's Quadrant*, where scientific research is positioned as a decision-making process, with basic and applied research resulting from the decision to either "extend the area of fundamental understanding", or direct toward "individual or group or societal need or use" (Stokes, 1997, p. 8). Stokes presents a similar matrix to the Biglan classification, with two questions posed around the "quest for fundamental understanding" and "considerations of use" to formulate the axes, resulting in three categories of research (with three seminal scientists as exemplars) – see **Table 2.2**:

Table 2.2: Stokes' quadrant model of scientific research – adapted from Stokes (1997)

		Considerations of use?	
		No	**Yes**
Quest for fundamental understanding?	**Yes**	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
	No	-	Pure applied research (Edison)

Stokes identifies the challenge of "fuzziness and overlap at the boundaries" (Stokes, 1997, p. 71), where issues of timeframes and evaluating what constitutes a "goal" or "use" introduce an element of subjectivity to the classification process. This "fuzziness" is increasingly poignant when we recognise the non-linearity of modern technology development (Phaal *et al.*, 2011; Stokes, 1997).

Atkins (2006) reflects on the evolution of scientific classifications – as science progresses and complexity increases, dichotomic classifications become inadequate and are replaced by trichotomic characteristics – but to what end? Similarly, in Săvoiu's model, there is greater depth *within* disciplines as we observe groups such as "tri" or "quattro" sciences. However, this combinatorial approach does not challenge boundaries *between* disciplines or allow for the

emergence of new fields altogether – the result is convergence on highly specialised fields, instead of divergence towards new possibilities. As society transitions away from the late-20th and early-21st century "information age", the imminent "molecular age" is expected to be marked by biotechnology, nanotechnology, and materials science (Linstone, 2011). These fields in their nature are divergent, bringing together chemistry, physics, engineering, and a myriad of expertise where "boundaries between previously distinctive disciplines such as mechanics and chemistry begin to blur, stimulating knowledge transfer and cross-fertilization" (Miyazaki and Islam, 2007, p. 662; de Vries, 1993). These fields are not only multidisciplinary (drawing from different disciplines but remaining within disciplinary boundaries), but transdisciplinary (transcending the boundaries to create an integrated operating picture) (Choi and Pak, 2006). Indeed, it is the very act of boundary crossing that leads to fruitful outcomes, which Troxler (2022, p. 69) describes as "creating power and direction from the commonalities and forming new ideas from the generative combination of the difference". The future of science demands new methods and approaches to embrace transdisciplinarity (Mangematin and Walsh, 2012), suggesting a space for further research.

2.3.2 Science innovation

Innovation in the context of science has been defined as a process that has "the ability to produce new ideas, and the ability to turn these ideas into something useful" (Nicolau, 2004, p. 454). This involves a transition from the "possible" to the "actual" – from "scientific discovery" to "technological innovation" (Stokes, 1997). However, this journey is non-linear – there is a symbiotic flow between science and technology, as well as a reverse flow as technology informs and directs new potential for scientific discovery (Stokes, 1997; Phaal *et al.*, 2011). This non-linearity is symptomatic of the increasingly complex demands placed on scientific research, where the imperative is to innovate, not just invent, thus delivering something of societal value (Owen, Macnaghten and Stilgoe, 2012). The result is a democratic view of science practice, where diversity, ethical considerations, and uncertainty become innately significant (Funtowicz and Ravetz, 1993; Owen, Macnaghten and Stilgoe, 2012). The realm of possibilities where science can act to deliver impact expands (Bartoloni *et al.*, 2022), and in

turn so does the demand for transdisciplinarity, as described by Àvila-Robinson and Sengoku (2017, p. 38):

> "The complexity of the problems and challenges faced by researchers and scientists is calling for solutions that cut across multiple and cognitively diverse disciplinary domains."

The problems of the future can no longer be solved by remaining in disciplinary silos – there is a demand for transdisciplinarity (McPhee, Bliemel, and van der Bijl-Brouwer, 2018). Choi and Pak (2006, p. 351) define transdisciplinarity as "transcending traditional boundaries" – where disciplines no longer work concurrently or even collaboratively, but are indeed intertwined in their search for an even richer perspective. It is in this very atmosphere of diversity where innovation is found, where multiple perspectives come together in creative tension (Mejía, Malina and Roldán, 2017; Jones, Chirino Chace and Wright, 2020). There is an urgent call to view the insular model of scientific research as a hurdle to overcome, not a crutch with which to grow comfortable (Markham *et al.*, 2010; Dean, Zhang and Xiao, 2022).

Despite this call, there still exists resistance to change among scientific communities. One reason is the inherent valuing of science for the pursuit of knowledge, as a noble pursuit in and of itself, to the exclusion of any initiatives with a clear end goal (Linton, 2008; Joore, Stompff and van den Eijnde, 2022). Linton (2008) describes that this is indeed a minority view – that, of course, the pursuit of knowledge is worthwhile, but that outcome-driven research has a much greater impact and interest. A similarly outdated "purist" approach is that the activities of science would be tainted by the introduction of transdisciplinary practice or anything outside the scientific method (Funtowicz and Ravetz, 1993).

Even though new scientific discoveries are usually at the front end of the new product development process, this marks the back end of the scientific research process, and ultimately the end of scientist interest and involvement (Markham *et al.*, 2010). However, these perspectives present a relatively reductionist view of the barriers to innovation – there are complex systemic factors to consider, grounded in significant uncertainty (Riol and Thuillier, 2015). It is not simply a matter of indifference or ignorance – to transition from research into product

development would mean leaving the security of the comparatively resource-laden research side, and stepping into all the risks and uncertainty of the commercialisation process (Markham *et al.*, 2010).

A similar issue around resourcing lies in the project management required to facilitate innovation in science (Yordanova *et al.*, 2019). Any innovative project management must remain sensitive to the nature of scientific projects, recognising the specific skills, culture, and structure of scientific teams (Riol and Thuillier, 2015). There also exists a challenge in integrating scientific methodologies with the necessary agility of an innovation project – flexibility is a luxury that is not always guaranteed in an academic context (Yordanova *et al.*, 2019). The structure of a team is a critical factor, where flexibility creates space for streamlined integration of innovation practice, and rigidity hinders it (Linton, 2009). However, the structure and constitution of a team can also be an opportunity to seize, where "the interaction between people and projects becomes a potential, although unpredictable, source of discovery and innovation" (Riol and Thuillier, 2015, p. 265). As science faces the undeniable call to confront ethical and societal challenges, the composition of scientific teams must also reflect this transition and embrace diversity in the perspectives invited to the table (Hepburn, 2022; Funtowicz and Ravetz, 1993).

Innovation thrives through knowledge sharing, which is not only a central activity of scientific research but also a key function of the universities and technology parks that house scientific teams (Díez-Vial and Montoro-Sánchez, 2016). The bringing together of different perspectives strengthens the translation of knowledge and the fostering of connections (Mejía, Malina and Roldán, 2017). Diversity can also lead to an improved understanding of a problem and different approaches to solving it (Rekonen, 2017). Increasingly, there exists a shift away from insularity towards relational collaboration (Díez-Vial and Montoro-Sánchez, 2016), where scientists "do not innovate in isolation, but depend on interactive learning between actors and institutions" (Bhattacharya, 2020, p. 348). In practice, this is observed through the establishment of centres of excellence, technology parks, incubators, and accelerators (Díez-Vial and Montoro-Sánchez, 2016; Bhattacharya, 2020). As Bhattacharya (2020, p. 348) continues to explain:

"These new institutional structures highlight the distinctive shift in innovation perspective influencing policy, from earlier one-dimensional directed science push / demand pull linear models, towards looking at innovation as a coupling and matching process that inescapably intertwines technological and economic dimensions."

Reflecting on the earlier commentary around disciplinary blurring and the symbiosis between science research and technological innovation, it is clear that intentionality in the dynamics of scientific teams acts as an enabler of innovation outcomes.

Returning to Nicolau's (2004, p. 454) definition of innovation, which centres on turning ideas into "something useful", a common metric of science innovation is the capacity for commercialisation (Mangematin and Walsh, 2012; Bhattacharya, 2020). Emergent fields of research (such as nanoscience) are, by design, conducive to commercial outcomes:

"Nanotechnology has been seen as critical to 21st century scientific advancement, technology development, product innovation and social innovation. The century's problems have been seen as convergent, and their solutions as likely to require emerging technologies that create new product paradigms at the interfaces with other technologies." (Mangematin and Walsh, 2012, p. 157).

This paradigm of scientific discovery is indicative of a concurrent pursuit of both social and technological innovation (Linton, 2009). This demonstrates an "increasing evidence of convergence" (Linstone, 2011) where science can no longer exist in a vacuum, rather, must confront societal challenges. However, as discussed earlier in this section, there are significant hurdles to innovation and layers of uncertainty – challenges which are not erased by the presence of collaboration and the blurring of disciplinary boundaries (Funtowicz and Ravetz, 1993).

2.3.3 Summary

This section highlighted how disciplinary classifications are growing increasingly intertwined in science, culminating in a demand for transdisciplinary collaboration. Transdisciplinary practice is suggested as an approach to tackle complex

problems and generate new directions for scientific research. The irrevocable call to innovation in science was also explored, which revealed many complexities involved. The imperative to innovate is undeniable, but the question remains of implementation in practice.

2.4 The call for design

Following the overview of philosophies in scientific research, a similar assessment of design method and theory must be made. This section introduces the call for design in response to the need for innovation in science. First, this section explores various theories of design, and then more specifically design innovation is highlighted as a demonstrated approach for organisational transformation and innovation. This will also include an evaluation of current embedded design practice.

2.4.1 Philosophies of design

Understanding the theoretical context of design involves exploring how the definitions of design have evolved over time, from design through to design innovation, and further, recognising the overarching characteristics of design. Design has been defined in multiple ways throughout the literature – three seminal examples are listed below. Archer (1976, p. 15) focuses on the humanity and creativity of design, defining it as "the field of human experience, skill, understanding and imagination that is concerned with the conception and realisation of new things". Simon (1969, p. 111) points to another fact of design as the act of "changing existing situations into preferred ones" – here, design is seen as the vehicle through which the world becomes a better place. Design can be defined as a rigorous and logical process, with enabling methods and activities, where "Design activities can be seen as the reasoning from a set of needs, requirements and intentions to a new bit of reality, consisting of a (physical) structure and an intended use." (Dorst, 2003, p. 2).

In a more literal definition, Gasparski (1993, p. 168) describes the Latin origins of the word "design", as "*designo* = 'to define', 'to point out', 'to mark', 'to form', and *dissigno* = 'to unseal', 'to manage'" – exemplifying the myriad of activities and

methods that are involved in design. For this reason, design projects employ a balance of methodological approaches, with creativity arising at areas of friction between the evolving problem and proposed solutions (Cross, 2004, 2018a). This creativity is made possible through divergent thought, as described by Lawson (1993, p. 364):

> "The good designer seems to be one who is not unduly concerned too early in the process about any lack of resolution. There is thus no rush to get thoughts to converge. Such a designer is capable of generating new and alternative lines of thought without allowing this to throw the process off the rails as it were."

Such an exploratory mindset is well suited to the adoption of design methods, which bring clarity and focus to complex projects without restraining creativity (Cross, 2018a). Design thinking as a methodology uniquely centres on exploration, starting by "identifying the right question to ask" (Bjorklund, 2019, p. 21) and "what the real issues are" (Norman, 2013, p. 218). With each step forward in the design process, designers reflect and evaluate their decisions against the criteria of coherence in reasoning, according to specifications, and problem-solving value (Dorst and Dijkhuis, 1995, p. 271).

Uniquely "wicked" problems (Rittel and Webber, 1973) are characteristic of design projects, where there is a lack of complete clarity regarding the problem at hand, and information is discovered through the process of discovery itself that requires a novel approach (Lawson, 1993). Simon (1973) presents a similar definition of "ill-structured problems" in design, in comparison to the traditional "well-structured problems" of science, where the hypothesis is a well-formed prediction of outcomes based on the existing knowledge space. In design, the hypothesis is an evolving series of idea generations, used to explore an ill-formed solution that teaches us about the problem itself (Simon, 1973; Lawson, 1993). Design problems are those where the full breadth of information is not always available to the designer, and indeed, may never be (Cross, 1982). This results in an ideation process that is fluid and non-linear, demanding rapid and cyclic iteration to ensure no one step of the process dominates, and that the design can adapt with respect to new results and knowledge (Lawson, 1993; Dorst, 2006; Wrigley, 2017).

By this very nature, a design process is innately creative, where problem definition and problem framing are critical foci when there is little structure (Cross, 1982). Dorst and Cross (2001) elaborate to insist that even with this problem definition, the design process does not proceed linearly nor does the problem stagnate. Rather, both the problem and the ideas for solutions are iterated, revisited, analysed and synthesised throughout the design process, stating that "defining and framing the design problem is therefore a key aspect of creativity" (Dorst and Cross, 2001, p. 431). The path is not from problem to solution, but rather a "co-evolution" of "two notional design 'spaces' – problem space and solution space" (Dorst and Cross, 2001, p. 434). This leads to a threefold nature of design problems: determined (defined by specific needs and briefs), underdetermined (where problems and solutions evolve from the very process of designing), and undetermined (where there exists creative freedom for the designer) (Dorst, 2003). Very often the design problem is only loosely defined, and in itself evolves and transforms through the design project and through the formulation of ideas and bridges to solutions (Cross, 2018a). This complements the "material culture" as described by Cross, where designers are positioned to both "read" and "write" – creativity is the device through which they both understand *and* produce (Cross, 1982, p. 225).

Another key value of design is in the capturing of new knowledge and consistent reframing of possibilities in close creation with users (Giacomin, 2014). Sanders and Stappers (2007) describe the transition from user-centred design, towards co-design where users are brought along the design journey. This kind of participatory design allows for "rapid realisation of social meanings and attitudes" by engaging users early and regularly (Behrendorff, Bucolo, and Miller, 2011) to achieve mutual goals and create new things together (Björklund *et al.*, 2017). There exists an art to designing wherein the methodology reveals insights around user needs and experiences that go beyond what may be explicitly expressed by the user (Giacomin, 2014). An invitation is posed to the designer to "consider every problem from the viewpoint of the end-user and to repeatedly test his/her assumptions with real users in actual situations along the way." (Ward, Runcie and Morris, 2009, p. 81). By co-creating with the end-user, the designer removes

themselves from the "expert" position, transitioning the user from "subject" to "partner" (Sanders and Stappers, 2007, p. 5). Design thinking centres and values the human experience of the problem, with empathy as the driver of radically innovative solutions (Efeoglu *et al.*, 2013; Björklund *et al.*, 2021). This innovation process requires the creation of "bridges between products, services, people and information", fostered through collaboration, facilitation, and mediation (Björklund *et al.*, 2021, p. 21).

In the current innovation environment, design innovation has been described by Wrigley (2017, p. 236) as drawing together three key components: "(i) user needs (also called human-centred design), (ii) technology (the core intellectual property) and (iii) a business model (strategic value offering)." In recent literature, there is also a growing demand for "life-centred design" or "responsible innovation", where "it is crucial to take into account not only feasibility, viability and desirability but also the responsibility that comes with designing new products" (Borthwick, Tomitsch and Gaughwin, 2022, p. 6). It is argued that design must remain mindful of environmental and ethical considerations with just as much weight as user needs, technology, and business – as visualised in **Figure 2.3**:
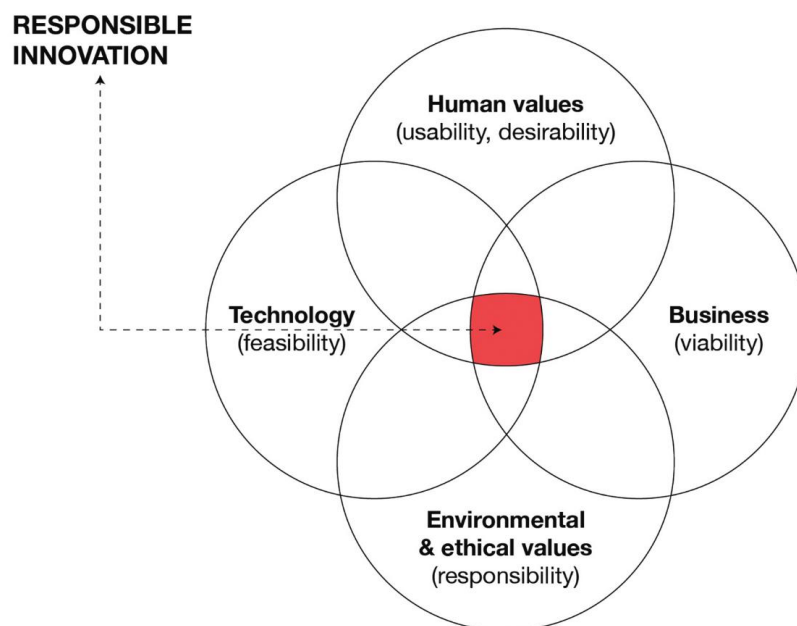
Figure 2.3: Responsible innovation at the intersection of desirability, viability, feasibility, and responsibility - from Borthwick, Tomitsch and Gaughwin (2022).

The relationship between design and innovation has been explored by a variety of fields such as design itself (Wrigley, 2017; Verganti, 2009), business (Brown, 2008), and management (Martin, 2009). The suitability of design as an approach for science innovation is due to its position as a future oriented activity, with the designer situated between the world as it is, and the space that it could be (Margolin, 2007; Krippendorff, 2006; Seymour, 2008). Designers empathise with the future in the design process through creating visions of the future. This future is made visible through the application of designers' creative and intellectual capabilities (Evans, 2011). The iterative nature of pivoting between concepts or abstract positions and concrete knowledge illustrates the convergent and divergent thinking of the creative process to design innovative opportunities (Banathy, 1996). Although there exists a myriad of diverse processes by which to adopt design, there are also hallmark characteristics, indicative of three key focus areas – understanding user needs, generating ideas, and testing those ideas (Liedtka, 2015). Björklund (2019, p. 27) supports these characteristics in their reflection on the value of process models:

> "Whichever process model you choose, it should be considered as a guideline and a source for shared vocabulary that smooths collaboration, rather than a depiction of reality. In practice, the design process is 'messy', with feedback loops between different phases and some customization for each problem."

This highlights the distinction between design theory and design practice, wherein practice demands a concrete understanding of design principles but also agility in their application (Randhawa *et al.*, 2021). The next section of the literature review will go on to explore the "reality" of "messy" design in practice, and specifically, the unique role of embedded design practitioners.

2.4.2 Design innovation in practice

Design thinking provides value to organisations not only in uncovering new possibilities and opportunities, but in its potential for cultural transformation by instilling a mindset of experimentation, innovation, and collaboration (Maula *et al.*, 2019; Bucolo, Wrigley and Matthews, 2012; Brown, 2008). However, given the radically innovative and disruptive nature of design, the process of integrating

design in an organisation is not without its challenges (van der Marel and Mäkelä, 2019). This is especially evident in organisations with a traditionally technical focus, where there is difficulty in breaking free from established ways of working (Riol and Thuillier, 2015; Mosely, Wright and Wrigley, 2018). Scientific research teams often fall into this category, where there is a struggle to consolidate the potentially conflicting goals of innovation and knowledge creation (Riol and Thuillier, 2015). Thus, there emerges a role for designers to act as "change agents" (van der Marel and Mäkelä, 2019), facilitating more open discussion and mutual understanding within a project (Rekonen and Vanhakartano, 2019). Early facilitation and design engagement prevents the risk of a team solely focussing on developing requirements, at the risk of those requirements proving faulty (Norman, 2013, p. 234).

Hatchuel (2002) posits that design is not only the output of teamwork; it is the very essence of *how* a team works. The skills and principles involved in design innovation are just as relevant to the design of products and projects as they are to the design of teams and businesses (Ward, Runcie and Morris, 2009; Mejía *et al.*, 2018). This fosters greater team success, where design invites and celebrates the diversity of "perspectives, talents, and experiences" (Liedtka, 2014, p. 44). The very practice of design inevitably impacts the culture of the team adopting it (Maaula *et al.*, 2019). In this way, design offers teams a sense of "true north", where there exists "agreement on what really matters" to "cut through the clutter [and] achieve focus" (Liedtka, 2014, p. 44). Diverse and multidisciplinary teams are unified as design establishes a sense of common ground and mutual respect (Norman, 2013). This essentially begins a self-fulfilling cycle, wherein design facilitates collaboration, but collaboration also fosters greater understanding, visibility, adoption, and appreciation of design (Björklund *et al.*, 2021; Norman, 2013; Björklund, 2019).

The adoption of a radical organisational change such as design must be accompanied by parallel cultural transformation to ensure the change maintains relevance within the organisation (Doherty *et al.*, 2015). The Danish Design Centre (2001) established a framework for understanding the adoption and

perception of design in an organisation in their "Design Ladder" (Kretzschmar, 2003) (**Figure 2.4**):

Figure 2.4: The Danish Design Ladder – from Kretzchmar (2003).

Doherty et al. (2015) describe this model as the progression from "No Design", where design is negligible or non-existent in an organisation, to "Design as Styling" where design plays a traditionally form-focussed role, to "Design as Process" where design is used as a methodology, and finally "Design as Strategy" where the transformational and strategic value of design is realised. By adopting more design innovation practices and programs, an organisation naturally climbs the Design Ladder, where lived and hands-on experience leads to a greater understanding of the value of design (Bucolo and Matthews, 2011a; Björklund, Hannukainen and Manninen, 2019). The journey of design acceptance must be a flexible one, where adaptability "softens the edges" of challenges, preventing barriers to adoption (Randhawa *et al.*, 2021). Adopting design practice reveals communication challenges in interdisciplinary teams, which if not correctly managed, can lead to a negative perception of design (Mosely, Wright and Wrigley, 2018; Rekonen, 2017). These conflicts can grow emotionally-charged, where discomfort with ambiguity evolves into discontentment (Rekonen, 2017). To prevent this, there must be careful management of team culture alongside project management, such that the potential of interdisciplinary teams can be maximised (Doherty *et al.,* 2015; Rekonen, 2017).

Björklund *et al.* (2021, p. 12) present a description of four key contributions of design in terms of the value provided to an organisation (**Figure 2.5**):

THE KEY ROLES OF DESIGN
IN ORGANIZATIONS

Design as a way to explore & experiment

Creating new ways of working & problem-solving

Design as strategic positioning & direction

Driving competitive advantage & new opportunities as an organization

DESIGN

Facilitating & creating connections & collaboration

Embracing & enabling the user perspective

Design as the glue for collaboration & basis of a shared understanding

Design as an advocate of customer-centricity

Figure 2.5: Key roles and values of design – from Björklund et al. (2021).

Here Björklund *et al.* (2021) describe the multi-faceted role of design in an organisation and how it infiltrates operational, cultural, and external elements of team function. Although the appreciation of design is not limited to professional designers, the complex role of design is effectively facilitated by an embedded designer, where the designer's impact extends beyond the minutiae of a project and into its context, influencing and transforming the work environment (Dorst, 2008; Maula *et al.*, 2019). This necessitates certain characteristics of an embedded designer, including empathy, curiosity, tolerance, optimism, and experimentalism (Efeoglu *et al.*, 2013), equipping the designer to tackle the concrete problem at hand alongside the overarching challenge of "building design capability from within" (Dorst and Dijkhuis, 1995; Price, Wrigley and Matthews, 2018).

Design innovation necessitates embedding the principles and practices of design thinking within an organisation, with the aim of facilitating strategic cultural transformation (Bucolo and Matthews, 2011a; Wrigley, 2016). By centring the human experience, design can establish positive strategic impact within an innovation ecosystem (van der Bijl-Brouwer and Dorst, 2017). Beckman and Barry (2007, p. 29) describe the design innovation process as a movement between "concrete and abstract worlds", using "analysis and synthesis to generate new products, services, business models, and other designs" (**Figure 2.6**). Reflective practice is emphasised as a key driver and complement to the process, enabling the conversion of observations and experiences into frameworks and insights (Beckman and Barry, 2009, p. 153).
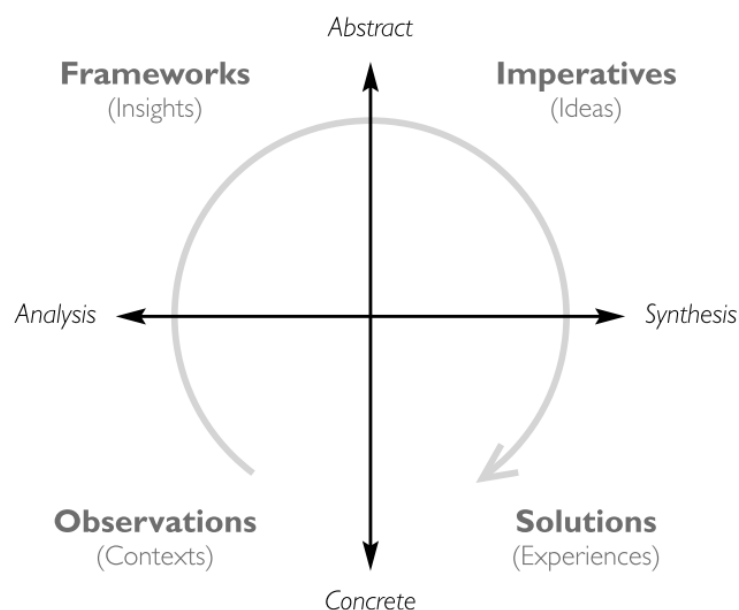
Figure 2.6: Beckman and Barry's Innovation Process – from Beckman and Barry (2007).

When embedded within an organisation, design must permeate "operational and strategic activities" to develop a holistic and sustainable model of practice (Bucolo and Matthews, 2011a, p. 247; Björklund *et al.*, 2021; Luo, 2015). The act of designing cannot be separated from the organisation itself, as the everyday operations of an organisation indicate existing and legacy design perspectives (Junginger, 2015). The positioning of design is therefore no longer a new

intrusion, rather, an intrinsic activity that is worth optimising to maximise value –
as Junginger (2015, p. 216) describes, "if we are doing it anyways, how can
we do it better?" Junginger (2015) posits that such design conversations are the
vehicle by which practitioners can enable organisations to reflect upon legacy
perspectives, and ultimately streamline engagement with new design practices.

There must also be a balance between internal and external perspectives, to
ensure applicability in contexts with complex stakeholder relationships (Bucolo
and Matthews, 2011b; Buckley *et al.*, 2012). Therefore, Wrigley (2016) posits that
in order to see the value of design truly demonstrated and to have its impact
infiltrate within an organisation, there must exist the role of "Design Innovation
Catalysts", who "translate and facilitate design observation, insight, meaning, and
strategy for all facts of the organization" (Wrigley, 2016, p. 151). The Design
Innovation Catalyst (DIC) Framework (**Figure 2.7**) by Wrigley (2016) describes
two axes of "Learning-Teaching" and "Academia-Industry" as key dimensions for
understanding and improving an organisation, where the "Learning-Teaching"
axis involves a continual reflective practice on the knowledge imparted, and the
"Academia-Industry" axis balances the production of new knowledge while also
delivering towards real-world scenarios.
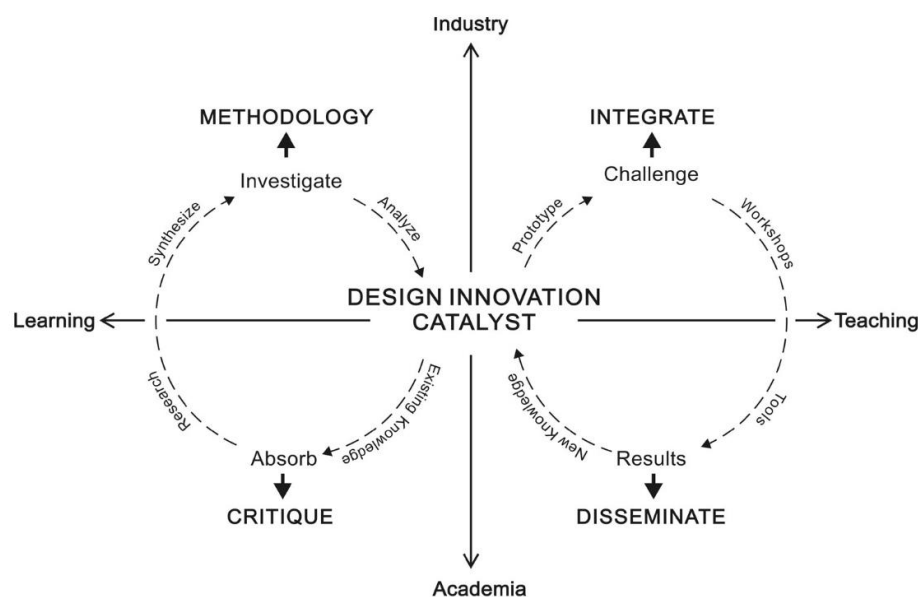
Figure 2.7: Design Innovation Catalyst Framework – from Wrigley (2016).

Within the DIC framework, there exist three stages with ten sub-stages (**Figure 2.8**), intended to be applied in a non-linear process to facilitate organisational transformation (Wrigley, 2016, 2017). The process is also flexible based on the organisational context, although there exist common principles and systems of behaviour (Wrigley, 2017).
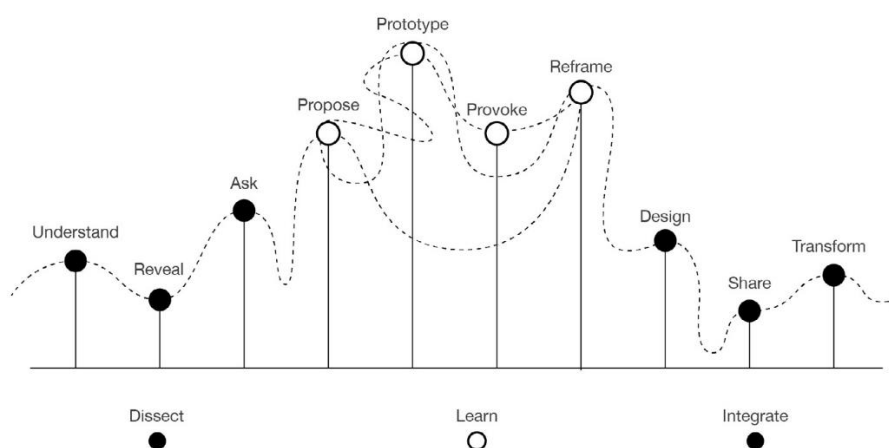
Figure 2.8: Design-led Innovation Approach – from Wrigley (2016).

By intention, a DIC establishes a prolonged relationship with the organisation, leading transformation and design learning from within (Price, Matthews and Wrigley, 2018). The DIC provides value by deepening the understanding of the customer, enabling translation between academia and industry, and streamlining cultural complexities (Wrigley, 2016, 2017). This requires the establishment of trust within the organisation, balancing sensitivity and resilience, to ensure the *transformation* is not perceived as *disruption* (Price, Wrigley and Matthews, 2018). The DIC model has been implemented in many sectors (Wrigley, 2017), including transport (Price and Wrigley, 2016), healthcare (Nusem, Wrigley and Matthews, 2017), infrastructure (Stevenson, Wrigley, and Matthews, 2016), manufacturing (Doherty *et al.*, 2015), mining (Townson *et al.*, 2014) and education (Mosely, Wright and Wrigley, 2018). However, the model has not yet been implemented in the field of science and scientific research. Considering the positioning of the DIC at the intersection of industry and academia (Wrigley, 2016), there exists an opportunity to explore the role of the DIC in a scientific academic context, where there is the intention to translate research into industry

outcomes. Returning to Junginger's (2015) discussion of design conversations, such an embedded designer role could facilitate organisational change not only through discrete stages of design practice, but through a consistent and permeating dialogue that infiltrates the way the team works and thinks (Björklund *et al.*, 2021).

2.4.3 Summary

This section presented the philosophical foundations of design, presenting design innovation as a rigorous theoretical and practical approach to innovation. Unique value is presented by design in tackling wicked problems, engaging end-users, and fostering creativity. There is also an opportunity for design as a way of both working and thinking, as it permeates all elements of a team. This suggests the suitability of design in a scientific context, which the next section will continue to explore.

2.5 The future of design and science

Given the science and design context provided by the previous sections of literature review, it follows to now consider the intersection of the two fields. This section describes historical and current theories of design and science, as well as some methods which have emerged. It then proceeds to explain what these insights mean for design and science innovation in practice. This will support the revelation of a research gap and opportunity for research.

2.5.1 Dimensions of design and science

There has been extensive discussion throughout the literature regarding the interplay of design and science, in terms of origins, distinctions, and similarities. Therefore, in order to best understand the way design and science work together and provide informed recommendations, we must initially consider the philosophical conversation (Bahari, 2010). Cross (1993, p. 16) posits that new design methods emerged in the 1950s and 1960s as a "scientific" response to the "novel and pressing problems of the 2nd World War". This resulted in attempts to compare and contrast design and science, for example, Skolimowski (1966, *in* de

Vries, 1993 p. 4) poses science as the "investigation of the natural" while design is the "creation of the artificial". Gregory (1967, *in* Cross, 1982, p. 224) states:

"The scientific method is a pattern of problem-solving behaviour employed in finding out the nature of what exists, whereas the design method is a pattern of behaviour employed in inventing things of value which do not yet exist. Science is analytic; design is constructive."

Similarly, Simon (1969, p. 114) describes how "the natural sciences are concerned with how things are… Design, on the other hand, is concerned with how things ought to be." Finally, this is also explored by Willem (1990, p. 45) who states that "it is only through design that science is made visible". These four examples signify the 20th Century perspective on design and science, where science is perceived as focussing on producing knowledge about the current state of the world, while design focusses on creative application of that knowledge for a future state of the world.

However, these early distinctions frame science in a solely positivist and methodological light – which Glynn (1985) and Cross (1993) argue is an oversimplified and reductionist view of modern science that centres more on problem-solving in a complex challenge context. As Cross (1993, p. 19) goes on to explain:

"The simple dichotomies expressed in the 1960s are being replaced by a more complex recognition of the web of interdependencies between knowledge, action and reflection".

Schön (1983) further details the reflective practice of a scientist, with each phenomenological observation leading to further experimentation, questioning, and indeed, reflection. Levy (1985) insists that this shifting understanding of science should not be a source of confusion (or Cross, Naughton and Walker's (1981) "epistemological chaos"), but rather a sign of healthy progress in response to societal development. Despite the evolving perception of science, there still exist pockets of hesitation when it comes to embracing innovation (Linton, 2008). Cross, Naughton and Walker (1981, p.1) suggest that hesitation to deviate from the pure scientific method is less about the innate value of the method, and more about the way science is valued as a whole, for its "rationality, neutrality, and universalism". The pursuit of "understanding" without an agenda for "solutions"

still holds weight in the scientific community, as it supports the universal concern for "truth" (Cross, 1982; Cross, Naughton and Walker, 1981). There also exist principles in science (such as the treatment of controlled variables) that are agnostic to the goal of the research, and solely exist to ensure rigour and quality (Apud-Bell, Dasan and Childs, 2018). The imperative then becomes a matter of understanding the interplay of design and science in a modern context in a cooperative sense rather than competitive, such that the value of both fields can be exploited.

In this spirit, Willem (1990, p. 45) suggests that design and science are intertwined – where "it is only through design that science is made visible". Here, design is seen as a "lens" into the world of science: that "science knowledge is part of the fabric with which designer's design" (Willem, 1990, p. 44). Science is described as the knowledge foundation of design, with design providing the necessary creativity that perceives and meets a need. There is an elegance to creativity that requires expertise in both "mastery and immersion" (Ogunleye, 2016, p. 6; Cross, 2018b) – depth of knowledge is a pre-requisite for well-informed creativity. However, what distinguishes creativity from simply producing knowledge is novelty and usefulness (Pringle *et al.*, 2016), which indicates a transition from *information* to *innovation* (Nicolau, 2004). Farrell and Hooker (2013, 2015) suggest that this creative pursuit of novelty and usefulness exists in modern science, where science is no longer reserved for "tame" problems (Rittel and Webber, 1973). They insist that the "wicked/tame distinction" is a "continuum upon which all problems can be based, scientific and design alike" (Farrell and Hooker, 2013, p. 701).

Galle and Kroes (2014) present a complementary view to Farrell and Hooker (2013), suggesting that while design and science can indeed co-exist and address similarly wicked problems, there is value in understanding their distinctly unique activities. Most obviously, science facilitates "breakthrough, path-breaking, and significant innovations" by providing cutting-edge knowledge input for the design process (Luo, 2015, p.11). Hatchuel and Weil (2003) introduce C-K Theory as a potential language for processing knowledge in design, by describing design as a series of actions between two spaces – "concept" (C – abstract

ideas) and "knowledge" (K – facts and information). C-K Theory has been proposed as a potentially valuable modelling system for design for science, due to its mathematically logical notation lowering the barrier to acceptance for scientists and has been used for retrospective modelling of design and science projects (Mabogunje, Sonalkar and Leifer, 2016; Azzam, Straker and Wrigley, 2018). Buchanan (1993, p. 270) describes the interplay of design and science knowledge further:

> "All knowledge is relevant to the designer and, in turn, the scientist must be cognizant of the possible uses of scientific knowledge in the practical world… To bring science to design is to force the recognition of diverse values and beliefs in the scientific enterprise; to bring design to science is to force a recognition that knowledge is required for effective design thinking."

Design invites scientific research to move beyond engineering applications for science, towards understanding societal needs (Mabogunje, Sonalkar and Leifer, 2016) and provoking complex problems (Hooker, 2018).

Addressing the "continuum" of "wicked/tame" problems that may be confronted by design and science (Farrell and Hooker, 2013) requires shifting modes of thought – where more creative and ill-defined problems demand a greater degree of shifting (Pringle *et al.*, 2016). Pringle *et al.* (2016, p. 221) present two modes of thinking as necessary for creativity: "associative" and "analytic", each characterised by "defocussed" and "focussed" attention respectively, where:

> "Shifting from analytic to associative thinking may enable one to overcome being 'stuck in a rut' while shifts from associative to analytic thinking enable the evaluation of previously generated novel insights."

This poses a challenge within traditional scientific domains where traditionally analytic methods may be deeply entrenched, making the shift to associative thinking more difficult, but all the more imperative (Pringle *et al.*, 2016). The invitation to design requires constant divergence and convergence, enabled by flexibility in modes of thought (Brunswicker, Wrigley and Bucolo, 2013). This also involves adopting "playful, exploratory, iterative and divergent methods", following the pattern of the Double Diamond and exploring new possibilities (Shneiderman, 2019, p. 1841). Embracing design invites scientists to suspend belief even if

there is incomplete information, opening up space for creativity and originality (Apud-Bell, Dasan and Childs, 2018; Shneiderman, 2019).

Both design and science rely on the formation and testing of hypotheses, drawing meaning from a process of experimentation (Laakso, 2017), as Glynn (1985, p. 122) describes:

> "Whereas science moves from observations of particular facts to the theoretical hypotheses of universal laws and theories, design moves from knowledge of such universal laws and theories to practical innovation of individual concrete alternatives."

Forming a hypothesis in design is centred on imagination of new scenarios and futures, providing value to science by not only identifying ideas with purpose and impact, but creating space to experiment with them (Levy, 1985; Rust, 2004). By inviting user-centricity and consideration of societal impact, design allows research to be more effectively integrated into society (Bartoloni *et al.*, 2022; Wouters, 2022). Design is able to stimulate the revelation of tacit knowledge, which can assist in establishing common ground between scientists and potential end-users of their science, alleviating one of the most critical risks to research and development (Mäkinen, Hannukainen, and Hyysalo, 2017; Rust, 2004). Design is a response to the undeniable call for science that "changes the world" through "projective and poetic activity" (Hernández-Ramírez, 2018, p. 51). The next and final section of literature will consider the remaining question within this call – namely, understanding how the integration of design and science unfolds in practice.

2.5.2 Design and science in practice

Scientific research is commonly (albeit not exclusively) carried out in the pursuit of new knowledge (Linton, 2008; Chandra and Patwardhan, 2010). However, knowledge *invention* is not enough to foster *innovation* that leaves the laboratory and enters the market (Luo, 2015). Research carried out based on "academic curiosity" often faces challenges in commercialisation and business development (Chandra and Patwardhan, 2010). There is the additional systemic challenge of success measures in science, where publications and patents are highly valued but can lead to risk-aversion when introducing new and creative approaches such

as design (Gonera and Pabst, 2019). Markham (2002, p. 31) describes the "Valley of Death" as "the gap between the technical invention or market recognition of an idea, and the efforts to commercialize it" - see **Figure 2.9**:
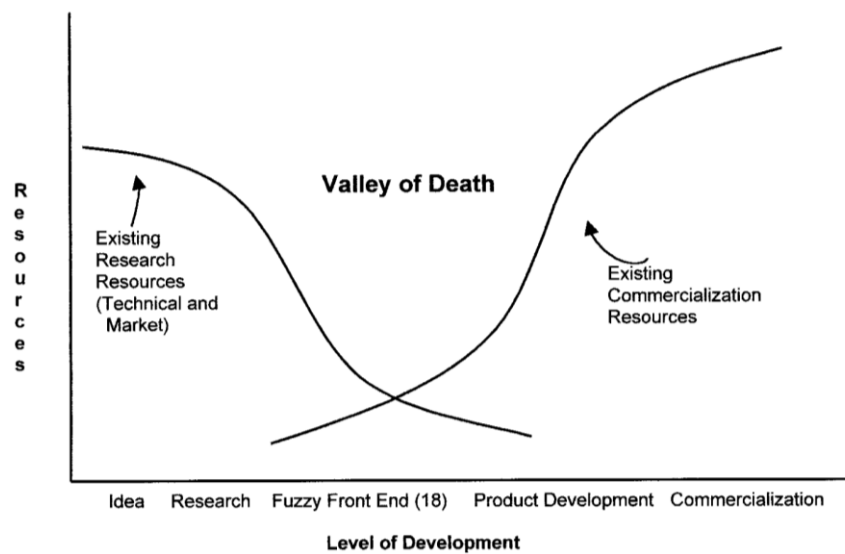
Figure 2.9: The Valley of Death – from Markham (2002).

Resources exist on both sides of the valley, but conflicting value systems, objectives, and reward structures deepen the divide (Markham, 2002). In order for new scientific developments to reach the market, there indeed must be novelty in the research, but also deep consideration of the current market and potential business model (Chandra and Patwardhan, 2010). This reveals a critical challenge for innovation, which Randhawa *et al.* (2021, p. 668) refer to as the "transition to ambidextrous innovation… balancing explorative and exploitative innovation while managing competing objectives". This challenge is exacerbated in a scientific field, where the exploratory pursuit of knowledge may potentially steer away from identified societal challenges. (Simpson and Powell, 1999). These challenges are increasingly complex, demanding a high level of technical innovation, but also new and unexpected solutions with a clear understanding of the market and end-user (Randhawa *et al.*, 2021). This is a multifaceted process, but design has been proposed as a critical actor within the context of scientific research to enable increasing the commercial output of research findings by demonstrating feasibility and viability (Mesa *et al.*, 2019; Mesa, Tan and Ranscombe, 2022).

There is a two-sided challenge in terms of the suitability of a scientific project for design engagement. Especially in terms of new developments, there must be a certain level of technology readiness and established research capability before design can provide meaningful value (Mankins, 1995; Peralta, Driver and Moultrie, 2010). Conversely, a design project requires the potential for "unexpected expansion" and new directions – something which is challenging in science after significant research development has been done (Hatchuel, 2002, p. 265). Finding a balance between these two states is a potential hurdle for identifying scientific projects suitable for design input (Mangematin and Walsh, 2012; Peralta, Driver and Moultrie, 2010). Another challenge is the perceived risk of losing scientific rigour in the creation of design artefacts – that involving design would detract from the "purity" of the science (Simon, 1969; Linton, 2008). This raises the issue of shifting mindsets to accept and embrace design, recognising the value it can provide (Mosely, Wright and Wrigley, 2018). Driver, Peralta and Moultrie (2010, 2011) describe their experience of exposing scientists to design work and evaluating their perceptions towards it. They conclude that most initial perceptions subscribe to classic design principles such as "functionality, aesthetics and useability" but not creativity or innovation (Driver, Peralta and Moultrie, 2010, p. 7; 2011). They also reflect on their observations of scepticism – since the scientific team had little previous design experience, they struggled to recognise the value brought by design (Driver, Peralta and Moultrie, 2010).

In positioning design as a catalyst for innovation in science, we must consider the interpersonal impact of bringing together different modes of practice. As Björklund *et al.* (2017, p. 15) describe:

> "You will be hard-pressed to find anyone opposed to development and improvement in principle. It may, however, be equally hard to find people who agree on how we might go about pursuing these goals."

Calling diverse perspectives to the table for design practice is a high-risk endeavour due to the added complexity of transdisciplinarity, but the value brought to science is greater than if design was never involved at all (Mejía, Malina and Roldán, 2017; de Leon *et al.*, 2018; Bartoloni *et al.*, 2022). Passera (2017) reports on the critical nature of establishing common ground in a diverse team to moderate conversation and ensure all parties share consistent goals.

Communication has been identified as a challenge in embedded design practice, especially when designers introduce terminology and language that may be unfamiliar to non-expert designers (Mosely, Wright and Wrigley, 2018). Introducing new roles and team members also proves challenging, as the team navigates role clarity and trust building (Peralta, Driver and Moultrie, 2010). Surprisingly, these team dynamics can play an even larger role in a project than the actual technical challenges at hand (Lee, 2020). Kosso (2011, p. 40) goes so far as to suggest that the scientific method itself is less a "method" and more "a feature of a group of scientists, and it's the social interaction that holds it together… the whole method is an activity of the whole group." Design facilitates the transition from the outdated "solitary genius" model of scientific research towards balancing "technology push" and "market pull" dynamics (Giacomin, 2014; Simpson and Powell, 1999), creating a collaborative atmosphere of practice that nurtures innovation (Lee, 2020).

Lawson (1993, p. 362) describes design projects as "vehicles through which they explore their chosen intellectual territory". In the scientific "intellectual territory", design facilitates knowledge transactions between different perspectives, enabling true transdisciplinary practice, as opposed to participants working in parallel but segregated multidisciplinarity (Kocsis et al., 2017; Mejía et al., 2018). Specifically, design brings significant value through its ability to demonstrate and visualise scientific artefacts through prototypes (Moultrie, 2015; Mesa, Tan and Ranscombe, 2022). Design has the potential to act in this interface role between research and commercial outcomes, bringing a "lens of realism to the technology under development" by demonstrating capability beyond the laboratory environment (Mesa, Tan and Ranscombe, 2022, p. 2349; Moultrie, 2015). Design is proposed as a boundary object, transforming knowledge and spanning disciplines (Johnson et al., 2017a). The role of design as a boundary object introduces concepts such as the STAM (Science, Technology, Application, Market) Model (Phaal et al., 2011), where scientific research evolves through "phases of industrial emergence", spanning research development to market outcome. Mesa et al. (2019) describe a potential integration of a design product development process (PDP) with the STAM model in **Figure 2.10**. This process describes how design plays an initial supportive role, allowing the emergence of

key scientific phenomena, but takes a greater role in the "S-T transition" through to the "Nurture phase". In this model, design supports technology development by demonstrating feasibility, understanding user needs, generating concepts, defining systems and product plans, testing, and evaluating the user experience (Mesa *et al.*, 2019).
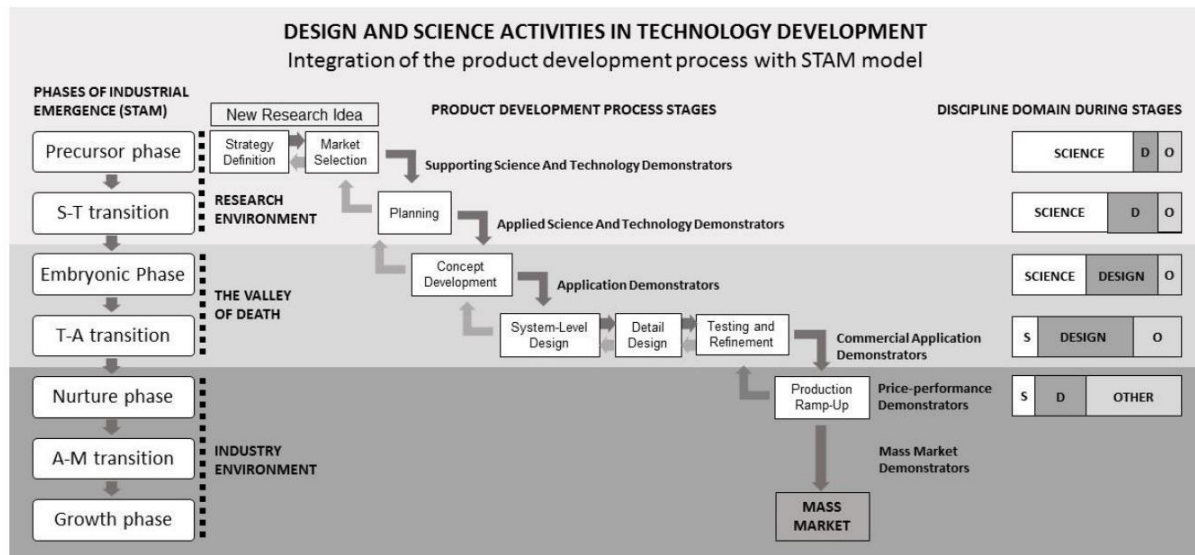
Figure 2.10: Suggested integration of design (PDP) and science (STAM) for technology development - from Mesa et al. (2019).

There is a significant call for design innovation capability in addressing future societal challenges (Hepburn, 2022; Thong *et al.*, 2021). This demands the implementation of mediation between design and science, in the form of a methodological and logic-based approach that can combine the rigour of science with the creativity of design (Shai *et al.*, 2013). However, previous examples of design and science practice have not been able to overcome the hurdle of sceptical perceptions towards design, due to the relegation of "design" and "science" activities as parallel, but not integrated (Driver, Peralta and Moultrie, 2010) – ironically, instead of challenging the stereotype of a scientific "lone genius", the designer steps into that role themselves, enacting a design process behind closed doors and only revealing the outcomes at the end of the process. Kolko (2010, p. 15) describes the significant risk of design as a "private exercise", wherein the design insights are unable to be understood as valuable simply because they are not visible. There is also a risk of breaching trust in projects where values between different disciplines are not intentionally made clear

(Mejía, Malina and Roldán, 2017). Mesa *et al.* (2020, p. 1118), however, explain a converse challenge, where it is unrealistic to expect both research excellence *and* design, marketing, and business excellence from a scientist – rather, a collaborative sharing of expertise is more appropriate.

The question then becomes a matter of balancing these two challenges – how could design remain visible for scientists, while also respecting the need for focussed research practice? Design radically transforms the end-user experience, but also the experience of the one designing (Hepburn, 2022; Dorst and Dijkhuis, 1995; Cautela *et al.*, 2017). There is an opportunity to present this experience not just to "designers by trade", but to the scientists with whom they work, in the spirit of true transdisciplinarity (Choi and Pak, 2006). Peralta, Driver and Moultrie (2010) suggest the potential for design and science projects where the designer works within and alongside the scientific team as a team member instead of as a design provider external to the team. The designer adopts a delicately balanced role of guiding participants, while also empowering them to design for themselves (van der Lugt, 2022). Design engagement must permeate all stages of the scientific development process but do so by *collaboration*, not *consultation* (Leon *et al.*, 2018). This prevents the previously discussed issues of mistrust (Kolko, 2010; Mejía, Malina and Roldán, 2017) by creating space for trust to be built. There must also be modified leadership models that centre on "procedural leadership", equipping the entire team with design confidence, as opposed to hierarchal modes of operation (Mejía, Malina and Roldán, 2017, p. 684; (Randhawa *et al.*, 2021). Design methods can be adopted in a "disciplinary-agnostic" approach to invite input from all team members, with the team working closely in constant communication (Mejía, Malina and Roldán, 2017; Diamond, 2018). Instead of the designer as the sole expert, they act to translate design learnings and empower the team from within (Norman, 2010; Wrigley, 2016; Price, Wrigley and Matthews, 2018).

2.5.3 Summary

This section detailed the philosophies of design and science, including the ongoing conversation around the similarities and differences between the two fields. The unique value that design can bring to science is highlighted as a key

opportunity. This section also examined what has already been tried in previous design and science projects, with a gap emerging for close examination of a design and science project. This gap will be detailed further in the following **Section 2.6**.

2.6 Research gap

This chapter established a foundation for understanding science and design in practice – first by reviewing the philosophies and approaches involved in each field alone, then by considering the future of science with design as a catalyst for innovation. In this final section, the research gap that emerges from this literature foundation is revealed.

A timely opportunity exists in the face of the upcoming "molecular age" (Linstone, 2011 – see Section 2.3.1). There is the imperative for scientific *innovation*, where previously *invention* sufficed. It is this imperative upon which design has significant potential to act. The literature gap for this thesis is positioned within this imperative. Section 2.2 explored the evolving philosophies of science, and the effect this had on the scientific method. This led to Section 2.3, which mapped the ever-shifting disciplinary boundaries within science, and how this is indicative of increased complexity in societal challenges, followed by an evaluation of the status quo in science innovation. The call for design was explored in Section 2.4, which detailed the nature of design innovation and how it operates in practice. Finally, Section 2.5 examined design and science together – both in philosophy and practice, which culminates and reveals the gaps in the previous literature, namely:

- The role of a Design Innovation Catalyst (Wrigley, 2016 - see Section 2.4.2) is demonstrated to provide valuable design capability to an organisation, but this has not yet been tested in a scientific context.
- Design in general is suggested to provide value to scientific research. However, there has not been an attempt to understand the journey of scientists as they experience design for themselves, and the revelation of what value such an engagement could provide.

- The perception of design by scientists is reported as generally sceptical, but this has been reported from an external designer perspective (Driver, Peralta, and Moultrie, 2010). The current body of work has not examined the perceptions towards design from a scientific team that is actively undergoing a design process themselves, nor is there consideration of the potentially evolving perceptions towards design as a result of that experience.

Theses gaps in the literature suggest potential for a practitioner role within scientific teams, where a Design Innovation Catalyst (Wrigley, 2016) goes beyond embedded design, and transitions to equipping the team to design for themselves. In this approach, the embedded designer empowers the scientific team with design skills, insights, and tools to make the design process visible. The designer provides guidance on design activities but enables the team to design for themselves instead of holding sole responsibility. The team is able to continue scientific research and development, learning design alongside this and applying it to their own work. This approach is hypothesised to transform the scientific understanding and valuing of design through collaborative practice and first-hand experience, where design is effectively applied in science to catalyse innovation.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Overview

The following chapter outlines the methodological approach for this study in response to the proposed research questions. This research is in the form of a qualitative case study (Yin, 1981) where the candidate takes the role of a "Design Innovation Catalyst" (Wrigley, 2016) within a scientific team. This chapter first describes the research approach, then explains the selected data collection and analysis methodologies. Finally, there is a statement regarding the ethics approval for this study.

This research has revealed a significant gap in the current body of knowledge concerning design and science practice. Specifically, there is an opportunity to investigate the role of design and journey of its adoption within a scientific team, in terms of the value brought to and perceived by scientists. This gap informs the overarching aim of the study and research questions, summarised in **Table 3.1**.

Table 3.1: Research gap, aim, questions, and objectives

Research Gap	Exploring the adoption of design within a scientific team, to understand the value brought to and perceived by scientists.	
Research Aim	To investigate how design can be leveraged in scientific projects as a catalyst for innovation.	
Research Questions	How is design perceived by scientists engaged in a scientific project?	What opportunities and challenges are afforded by the application of design in a scientific project?
Research Objectives	• Facilitate a design innovation engagement within a scientific project, • Evaluate the engagement through a scientific perspective, • Provide a recommendation of design practice for innovation in science.	

3.2 Research approach

A case study approach was selected for this study due to its rigorous and innately scientific nature (Horner *et al.*, 2005). This section will elaborate on the research approach and justify the selection of specific modes of study, data collection, and analysis.

3.2.1 Case study approach

This research adopts Yin's (2009, p. 49) definition of a longitudinal single case study:

> *"The longitudinal case: studying the same single case at two or more different points of time. The theory of interest would likely specify how certain conditions change over time, and the desired time intervals would presumably reflect the anticipated stages at which the changes should reveal themselves."*

This study fits the longitudinal definition as change-over-time is a critical variable in assessing the design engagement within the scientific team. Further, the time intervals used to divide the project were selected intentionally to measure critical insights occurring at pivotal points in the design intervention.

Klahr and Simon (1999) describe multiple approaches to studying scientific projects, including historical accounts, laboratory studies, ongoing observations, and sociological approaches. A case study approach accommodates this wide variety of research methods, resulting in a more rounded examination of scientific practice as opposed to purely studying the technological outputs of a project. Further, a case study approach is defined by Yin (1981, p. 98) as necessary when "an empirical inquiry must examine a contemporary phenomenon in its real-life context, especially when the boundaries between phenomenon and context are not clearly evident". This research is considered suitable for an embedded analysis case study approach as the activities involved in the design engagement are closely intertwined with the everyday operations of the scientific team (Creswell, 2007). This real-life and real-time context is also critical in developing a rich understanding of the drivers behind the participants' responses to design.

Hence this study adopts a phenomenological theoretical context, as it derives meaning from the "lived experience" of several participants (Creswell, 2007, p. 57).

Yin (1981) continues to describe the case study as an optimal approach for studying knowledge utilisation which again proves relevant to this study, as it involves examining the response to new design knowledge. By using a case study approach to study knowledge utilisation, it allows a researcher to "recommend and design appropriate policy interventions" (Yin, 1981, p.100), which again proves valuable as it also enables rich insights for identifying emergent design opportunities, as well as future recommendations and implications of this research. The provision of appropriate interventions and design activities was conducted in discussion with and under the supervision of experienced design practitioners. This also included consistent engagement with reflective notes (described in **Section 3.3.3**) as a process of validation and evaluation.

Further, this case study positions the researcher as embedded in a scientific team over a period of nine months, in order to provoke design interventions, evaluate the response of the team, and assess what meanings can be concluded regarding the interaction of design and science. This embedded practice involved attending weekly meetings with the JSSL, facilitating workshops, and providing ad-hoc design support in project work during the week (approximately 1-4 touchpoints per week). The study adopts a social constructivist worldview, in that that act of participant interaction itself derives meaning, as participants build shared understanding and contribute their own perspectives (Creswell, 2007). Through the approach, the continual interaction between the researcher and the research object (in this case, the scientific team) is critical, as the quality of the data collected (e.g. the honesty of interview participants, the interpretation of focus group results, etc.) relies heavily on mutual understanding (Aaltio and Heilmann, 2010).

3.2.2 Case study as a Design Innovation Catalyst

The use of case studies is ubiquitous in design research, as they provide the means to explore phenomena in depth, especially in circumstances where not all outcomes can be controlled (as would be the case in, for example, a quantitative experiment) or where the outcome is predominantly descriptive rather than causal (Blatter, 2008). Further, the nature of data collection for design projects (and indeed, this study itself) lends itself to case studies, as they allow exploration of a variety of data sources with a rich depth of insights (Yin, 1981; Blatter, 2008). Case studies have been used for various aims in design, for example: to evaluate the efficacy of a design program (Ward, Runcie and Morris, 2009), describe the utilisation of design (Dewberry and Sherwin, 2002); outline the details of a design process (Haines-Gadd *et al.*, 2015); and compare different design approaches and perspectives (Kostrzewski, 2018). Case studies are also suitable to facilitate the observation, reflection, and documentation process that are essential to design research (Rowe, 1991). Hence, this study of design within a scientific team has adopted a case study approach, as it enables depth and rigour of study and meaningful descriptive outcomes, while still accommodating the complexities and subtleties of a complex multidisciplinary research collaboration (Rowe, 1991; Blatter, 2008).

More specifically, the embedded position of the researcher takes the form of a Design Innovation Catalyst (Wrigley, 2016), a "role spanning both business and design knowledge domains" (Wrigley, 2016, p. 149). By definition, a Design Innovation Catalyst (DIC) bridges multidisciplinary gaps by translating insights across domains (Wrigley, 2016). Wrigley (2013) describes the role of the DIC:

> *"The 'Design Innovation Catalyst' translates and facilitates design observation, insight, meaning and strategy, into all facets of the organisation. In this role, the design continually instigates, challenges and disrupts innovation internally and externally from a position <u>within</u> the company."*

This positioning of the DIC has occurred in fields such as manufacturing (Pozzey, Bucolo and Wrigley, 2012), aged care (Nusem, Wrigley and Matthews, 2017), energy (Bryant, Straker and Wrigley, 2018), aviation (Price, Wrigley and Matthews, 2017), education (Wright, 2018), agriculture (Behrendorff, Bucolo and

Miller, 2011), etc., however, it is yet to be adopted in a scientific context. Nevertheless, the approach and methodology of the DIC remain consistent across these domains, where the DIC is responsible for facilitating design engagement, and is thus a suitable model for describing the embedded practice in this study.

Given the "valley of death" in scientific research between the research domain and product development domain (Markham, 2002), mediation that bridges these two domains is necessary in order for scientific research to engage with users and develop tangible solutions that create value for stakeholders. Moultrie (2015) describes the potential for design to be positioned at the interface between two fields, supporting technology transfer. Such a translator role is necessary to facilitate the complex nature of scientific problems that seek to engage end-users and deliver tangible outcomes. Dorst (2008) describes the multi-faceted role played by a designer, that goes beyond design and towards transforming the environment around them. The candidate, therefore, sought to position themselves as a Design Innovation Catalyst – not only acting as a "design interface", but also facilitating a design intervention through active engagement with both the scientific and end-user domains.

3.2.3 Summary of case study approach

In summary, the case study approach for this study is justified due to its:

- Innate scientific rigour as a process (Horner *et al.*, 2005)
- Ability to facilitate a longitudinal study of change within a single case (Yin, 2009)
- Suitability for study of a phenomenon within its own context (Yin, 1981)
- Ability to deeply investigate knowledge utilisation to provide recommendations and assess future implications (Yin, 1981)
- Provision of high-quality data through enabling embedded practice (Aaltio and Heilmann, 2010)

A unique dual role is played by the candidate, wherein they are an embedded designer *facilitating* design practice through the DIC role, but additionally a case study researcher, *evaluating* design practice through the role of a PhD candidate.

This involves adopting both design methods (to instigate design interventions and activities), and also qualitative data collection methods (to facilitate a case study).

3.3 Data collection methods

This section describes the methodological approach and specific methods of data collection and analysis employed and provides an explanation and justification for how these were implemented.

The data collected from this research is qualitative, which is uncommon in scientific projects but not an entirely foreign concept. Indeed, it has been argued that "qualitative research generates meaning through a systematic approach to induction and deduction, and thus is essential to the scientific method in the pursuit of knowledge" (Sale and Thielke, 2018, p. 129). Additionally, the qualitative research process can be scientific itself, through the establishment and testing of assumptions (or hypotheses), experimentation and validation to challenge accepted "truths" and develop new ideas (Kuhn, 1970; Spalding, 2010).

The ability to draw on multiple qualitative data collection methods is a strength of the case study approach, as triangulation provides rigour and can "overcome or counterbalance the deficiencies and biases that flow from single methodologies" (Evers and van Staa, 2010, p. 749). This process is described by Yin (1981, p. 110) as having great relevance to scientific inquiry in both exploratory and confirmatory phases of research. The selection of qualitative methods is intended to elucidate the varying and complex levels of knowledge that can be learned in an embedded longitudinal case study (Visser *et al.*, 2005), as seen in **Figure 3.1**. Interviews are a source of explicit knowledge and openly shared opinions from participants, however, tacit knowledge from participants does not generally emerge in an interview context (Visser *et al.,* 2005, p, 122). This is where methods such as observations or focus group sessions are greatly valuable – we not only learn the visible insights of how participants act or behave, but also latent needs revealed through engagement with workshop sessions.
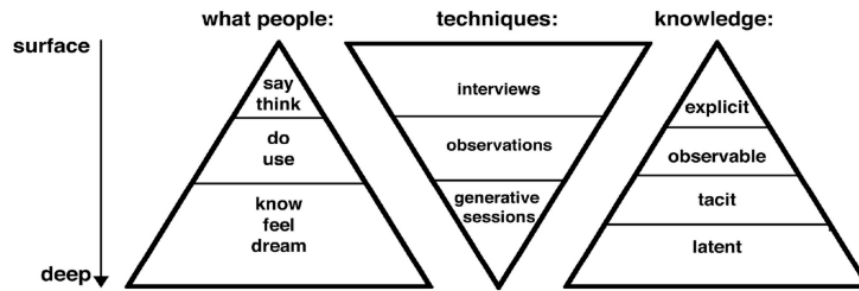
Figure 3.1: Levels of insight accessed by various qualitative data collection techniques - from Vissier et al. (2005).

In this study, these three key methods are used to ascertain this wide scope of knowledge that can be learned about the participants' experience: interviews, observation, and workshops (supplemented by surveys and reflective journaling). In this way, a detailed understanding of the perceptions towards design can be established.

The data collection methods used in this study, along with their purposes are summarised below in **Table 3.2.** The following sections elaborate further on the use of each method, including a breakdown of workshops and focus groups in **Section 3.3.5**.

Table 3.2: Data collection methods

Method	**Usage**	**Quantity**	**Participants**	**Purpose**
Semi-structured interviews	Before and after workshops; at conclusion of project	26 interviews, 30 min each	4 project leaders*, 1 project coordinator	Uncovering specific insights and reflections on key design engagements
Participant observation	Ongoing; during weekly team meetings and workshops	160 pages (LHS of Journal)**	JSSL team (18 participants)	Recording latent insights and observable phenomena regarding the engagement of design
Reflective journaling	Ongoing; during weekly team meetings and workshops	160 pages (LHS and RHS of Journal)**	Candidate; JSSL team (18 participants)	Facilitating the recording of field notes and allowing for a continual reflective practice for the candidate

Surveys	Preceding prototyping workshop; at the conclusion of project	Prototyping survey: 4 questions, 15 responses. Concluding survey: 22 questions, 17 responses	JSSL team (18 participants)	Understanding broader perspectives towards design from a large sample size (entire participant group)
Workshops / focus groups	Key design interventions	6 workshops / focus groups	JSSL team (18 participants); representatives from RAAF and DST	High-intensity design engagements, allowing for observations and deep-dives into perspectives on design

* **Note 1:** interviews were conducted with the team leaders of the individual scientific projects, as well as the overall project coordinator. At the start of the engagement there were four projects, and thus four project team leaders participating in interviews. However, after the first two sets of interviews, one project was cancelled, and thus only three project team leader and one project coordinator took part in interviews from that point forward.

** **Note 2:** the same physical notebook was used for reflective journaling and field notes / observations. This was structured as the left-hand-side of the notebook used for observations, and then the right-hand-side used for reflections either during a workshop or after the fact. The sum total of these two records is 160 pages.

While the JSSL as a whole was collectively striving to deliver smart sensing solutions to the Royal Australian Air Force (RAAF), there were four sub-projects operating within the JSSL, with many team members working across multiple projects. These are referred to as Projects A, B, C and D in this study. Each project was developing a specific smart sensing solution to an identified challenge from RAAF. There were eighteen participants in the JSSL team, all with varying levels and nature of involvement – a summary of which can be found below (**Table 3.3**). Most JSSL participants had disciplinary backgrounds ranging from physics, photonics, and smart sensing. The majority of data collection occurred between participants with high levels of involvement in the JSSL project since they naturally participated more in workshops and group discussions. For example, participants who joined the team short-term or late in the project did not contribute as much data as those who were involved from the start. Similarly, PhD students who had their own research projects aside from the JSSL did not contribute as much data as, for example, the Project Leads (P1-P5) whose main

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work was centred on the JSSL. The Project Leads and Project Manager were also selected for interviews due to their deeper involvement and knowledge of the projects, which is reflected in a higher density of quotes from these participants.

Table 3.3: Participants in the research study

	Position	Level of involvement	Nature of involvement
P1	Senior Project Manager	High	Managerial
P2	Project A Lead	High	Project lead
P3	Project B / D Lead	High	Project lead
P4	Project C Lead	High	Project lead
P5	Technical development, ex-lead of Project D	Medium	Technical & previously project lead
P6	Director	High	Managerial
P7	Electronics Engineer	Low	Technical
P8	Researcher	Low	Technical
P9	Consultant	Low	Short-term, technical
P10	PhD student	Low	Student
P11	PhD student	Low	Student
P12	PhD student	Low	Student
P13	Software Engineer	Medium	Short term but high involvement
P14	Hardware Engineer	Low	Short term, technical
P15	ML / Data Engineer	Medium	Short term but high involvement
P16	Process Development Engineer	Low	Short term, technical
P17	Electronics Engineer	Low	Short term, technical
P18	Software Engineer	Low	Very short term (joined towards end of data collection), technical

3.3.1 Semi structured interviews

Semi-structured interviews were used to gather nuanced and specific insights from strategic samplings of the team. Hong and Nam (2010) report that the use of

interviews in concept design and design phases allows for rich feedback for the researcher, as well as inviting the participants to reflect on their own decision-making process. A semi-structured approach was selected to ensure that key topics were addressed, while also making room for follow-on questions, and inviting further discussion on concepts that emerged during the interview to "fully understand [the participants'] unique experiences" (Barlow, 2010, p. 496).

Interviews were conducted with key team leaders in the JSSL who were responsible for coordinating specific scientific projects, and one participant who was the overall project coordinator for the JSSL (see the appendices for the interview protocol). These interviews were performed before and after key workshops in the engagement, as these were identified to be critical pivot points in their design process. This meant it was significant to process the participants' expectations regarding the outcome and purpose of the workshop, and then following this, their reflections on its outcomes and their learnings.

Semi-structured interviews were also used at the conclusion of the study with the same group of team leaders / participants. This was intended to supplement the concluding survey data to allow for any additional participant insights on the overall process that may not have been captured in a structured survey. Due to the significant input from project / team leaders into the research data, the content and quotes from these individuals (Participants 1-4) are more recurrent than from some other participants.

3.3.2 Participant observation

Participant observation was used in this study to gain insights into the way the JSSL team operates in their day-to-day work environments, through team meetings and activities (Di Domenico and Phillips, 2010). It was important to collect data directly from the team in a more comfortable context, as by definition, the design workshops were an unfamiliar operating environment for a traditionally science-focussed team, and the observations allowed for data on the natural modes of operation of the team and the meanings they prescribe to their own work (McKechnie, 2008, p. 598). Additionally, participant observation ensured that the researcher was able to truly see the world from the participants'

perspective through close collaboration, and elucidated unspoken detail that might not emerge in an interview or survey (Bryman, 1984).

Field notes (Brodsky, 2008) were used to record details of observations or verbal comments from the team, along with a reflective journal (more detail of this method is in **Section 3.3.3**). It is important to acknowledge the role that the researcher plays themselves in the observation process, especially in this instance where the candidate was embedded within the team. This falls under Gold's (1958) classification of a participant-as-observer, where during the observation sessions, weekly team meetings, and workshops, the researcher was themselves engaging with the participants in a clearly defined role. Field notes were recorded on the left-hand side page of a notebook as "observations", with the right-hand side reserved for reflective journaling (see the following **Section 3.3.3**). Each entry noted the date and time of the activity, any other participants/attendees present, and the overall aim of the activity. Specific quotations were also labelled with a timestamp to ensure that the flow of data was accurately recounted during the researcher's reflective process.

3.3.3 Reflective journaling

Schon (1984) describes design as a reflective practice and hence, a reflective journal was kept by the researcher as a method of collecting incidental data (for example, insights during a weekly team meeting with the participants) as well as reflecting on their own process of research and analysis. Valkenburg and Dorst (1998) emphasise the value of reflective practice in the study of teams throughout the course of a project, as a method for identifying key moments of interest, insights, and transitions. As a researcher, reflexivity allows for continual evaluation and assessment of the research process, as well as challenging potential assumptions that have emerged throughout the process (Dowling, 2008; Bergoray and Banister, 2010). Acknowledging the natural and inseparable involvement of the researcher in their own research is a means of ensuring validity in the research process and providing context to the observations and insights collected over a long period of time (Bergoray and Banister, 2010, p. 789).

Each reflective journalling session included introductory content, such as the date, participants, and aim of the session. The reflective journal notebook was simultaneously used to note down in situ observations, quotations, actions, and other comments that occurred while they were engaging with participants, as described in the previous section. This content formed what was labelled as the "observations" column of the journal. The right-hand side of each page was reserved for reflections and the insights to which each observation had led, labelled as the "insights" column. At times these reflections occurred simultaneously with the observations, and at other times the researcher spent time reflecting after the fact. Such an approach was chosen as suitable for a design project where, as Beckman and Barry (2009, p. 154) describe, "observations or experiences in the concrete world are converted to frameworks or insights through a process of reflection." This practice allowed back-and-forth movement within the design and research spaces, continually challenging and refining knowledge about their research through both "reflection-in-action" and "reflection-on-action" approaches (Griffiths and Tann, 1992, p.78; Jaskiewicz, 2022). "Reflection-in-action" was used during the activities, often to note down any quick thoughts or insights in the moment. The journals were then revisited after each activity, and "reflection-on-action" was conducted, where at a slower and more detailed pace the overarching insights following each research activity could be ascertained. Dorst and Dijkhuis (1995) describe the value of this reflective approach in a design project, as it enables informed decision-making for the next appropriate action in the design process. Please refer to the appendices for a sample of the reflective journal.

3.3.4 Surveys

Surveys were used at two points in the study to gain more general insights from the overall group of participants – first to understand perceptions towards design prototyping (in contrast to sensor packaging and prototyping), and then a concluding survey to evaluate their experience of adopting design at the conclusion of the study (see the appendices for copies of the survey forms). The surveys used short, open-ended question items to allow for detailed creative responses, suitable for qualitative analysis (Boynton and Greenhalgh, 2004). Additionally, the use of open-ended questions allowed for reflection by both the

participants and the researchers regarding how the participants engage with their circumstances and their interpretation of them, as opposed to leading responses towards a predetermined hypothesis (Chasteauneuf, 2010).

The aim of the surveys was to gauge what the case study team's perceptions were towards design in response to frequent engagement with design through the presence of the candidate as a DIC and also the various workshop activities. The surveys were distributed to the entire JSSL team, which included leadership staff, postdoctoral researchers, academics / research fellows, PhD students, and engineers. The choice to distribute the survey to the entire team was intended to compare further how perceptions towards and understanding of design varied between different roles in the project, along with any overall changes from the start to the end of the collaboration.

3.3.5 Workshop activities

A series of workshop activities were conducted with the JSSL team throughout the research collaboration. The aim of the workshops was to create a collaborative atmosphere where the team could collectively engage with design methods. End-users from RAAF and DST were invited to Workshops 2, 5, and 6 (see **Table 3.4**) as participants and co-creators. Therefore, these workshop events also formed the only contexts wherein the entire JSSL team could engage directly with their end-users and stakeholders. These workshops provided a context for rapid and concentrated ideation, making the most of the relatively infrequent engagement of the team with their end-users and stakeholders (Heck *et al.*, 2018). Note that some of the workshop events were not entirely reserved for design activities, in that the researcher's involvement and design intervention was through one or more activities within the workshop event but not the entire workshop schedule.

The use of focus groups is suitable for a design research project as it accommodates the exploratory and open-ended nature of qualitative research questions and provides insights into "experiences, opinions, ideas, and motivations for behaviour" (Bruesberg and McDonagh-Philp, 2002, p. 28). In the context of this study, the workshops themselves allowed the scientific team

exposure to various design tools and brainstorming approaches, however, they also provided a focus group context where the qualitative insights were elucidated.

Morgan (2008, p. 354) reports that it is of paramount importance to design focus group questions that promote active discussion between participants and the researcher. This was facilitated further through the "participant-as-observer" approach (Gold, 1958), where the researcher was able to collect immediate and incidental data during the workshops. This participant-as-observer approach is well suited to longitudinal research to observe subtle changes over time and provide deeper understanding, especially when combined with direct data collection methods (Gold, 1958; McKechnie, 2008). Adopting this approach through focus groups meant that the data collection did not solely rely on direct comments and observations, but the researcher was enabled to ask incidental prompting questions or invite the participants to think aloud (Ericsson and Simon, 1998) whenever there was potential for deeper insights.

An outline of the workshops is presented in **Table 3.4**, followed by a summary explanation of each workshop, including the design methods employed and their aims in terms of the design process.

Table 3.4: Outline of workshops

Timeline (month)	Workshop	Participants*	Design Methods Used	Purpose	Outcomes
Nov-2019	1. Understanding personas and scenarios (2 hours + follow up activities in participants' own time)	JSSL team (15 participants)	User profiles (LeRouge *et al.*, 2013) Scenarios (Carroll, 2000) Personas (Heck *et al.*, 2018)	Building understanding and familiarity with design methods; learning the importance of user perspective	Developed four personas for each project, conducted user research; built empathy with end-user perspective
Nov-2019	2. Ideation and collaboration workshop (2 days)	JSSL team (15 participants), representatives from RAAF and DST (15 participants)	User profiles (LeRouge *et al.*, 2013) Scenarios (Carroll, 2000) Personas (Heck *et al.*, 2018) Brainstorming (Andrzejewski et al., 2018)	Uncovering user needs through co-design; ideation and development of solutions	Developed solutions within the four projects; received feedback and input from end-users

Feb-2020	3. Journey reflections (3x 30 min sessions)	JSSL team (17 participants)	Brainstorming (Andrzejewski et al., 2018) Reflective practice (Schon, 1984; Valkenburg and Dorst, 1998)	Reflecting on the design engagement in terms of highlights, setbacks, and goals for the future	Discussed moments of significance in the journey so far; identified team goals; fostered a sense of team unity
Apr-2020	4. Understanding prototyping (2 hours)	JSSL team (18 participants)	Brainstorming (Andrzejewski et al., 2018) Low-fidelity prototyping (Camburn *et al.*, 2017)	Learning about prototyping from a design perspective; exploring design terminology and language; preparing for prototyping solutions	Challenged existing understanding of prototyping to include a design perspective; started plans for prototyping approach
May-2020	5. Problem reframing (3x 30 min sessions)	JSSL team (18 participants split across three sessions), representatives from RAAF (2 participants)	Reframing (Lawson and Dorst, 2009) Co-design (Adikari, Keighran and Sarbazhosseini, 2016)	Challenging the problem definition; reaching common ground with end-users; consolidating stakeholder vision with team capability	Reframed the problem definitions; engaged with end-users
Jun-2020	6. Demonstration and feedback workshop (2 hours)	JSSL team (18 participants), representatives from RAAF and DST (10 participants)	Pitching (Parkinson and Warwick, 2017) Feedback Grid (IBM Corporation, 2018)	Pitching solutions and early prototypes for end-user input; engaging and responding to user feedback	Demonstrated solutions and prototypes

* End-user and stakeholder representatives from RAAF and DST were at times in attendance at the workshops but were not participants of the research data collection.

Workshop 1: Understanding personas and scenarios

The first workshop activity was designed to assist the JSSL in understanding the importance of user engagement early in the design process. This was centred on the idea of preparing and using personas as a valuable tool in ideation workshops (Rittiner *et al.*, 2016; Heck *et al.*, 2018). Personas can be used in both the idea generation and idea evaluation phases of the design process, and can evolve into members of the design team itself (Rittiner *et al.*, 2016). This is of great value in a design team where users are not easily accessible (such as in

the context of JSSL engaging with users in the military), as a persona captures "the user's mental model comprising of their expectations, prior experience and anticipated behaviour… not just their demographics, but also how they think, feel and behave" (LeRouge *et al.*, 2013). In a workshop context where most participants are from a non-design background, personas ensure the design process is informed and user needs are frequently communicated (Heck *et al.*, 2018). Given the unfamiliar design context, this activity was designed to elucidate the significance of deeply understanding end-user needs, through engaging with different personas. The JSSL team was presented with one example design brief, but split into four groups, each aiming to brainstorm a solution that meets the needs of one of two given personas. The groups then reported back to each other and compared the differences in solutions between the two given personas in a focus group format (Bruseberg and McDonagh-Philp, 2002). This was followed by a group brainstorming session (Andrzejewski *et al.*, 2018), discussing the importance of understanding the nuances of end-user needs.

This fundamental understanding was followed by an activity where the JSSL project teams were equipped to create personas of their own, in preparation for Workshop 2. The team leaders in the JSSL prepared user profiles (LeRouge *et al.*, 2013) and scenarios (Carroll, 2000) based on each project. This activity was facilitated by the DIC but primarily assigned to the team leaders, to provide ownership of the task and deeper reflection of their own users' experiences (Boylorn, 2008). These documents were edited and validated by representatives from the RAAF, for accuracy in terms of terminology, military ranks, and consensus with current Defence technologies. These profiles and scenarios were then made into personas, which were to be used in the next workshop stage.

Workshop 2: Ideation and collaboration workshop
Now equipped with some understanding about engaging with users, this workshop marked the first time that the JSSL was able to present their work in progress to their stakeholders in RAAF and DST for feedback and to facilitate the ideation process. This workshop relied heavily on the use of personas to enable communication and common ground between the end-users and the JSSL team (LeRouge *et al.,* 2013). On the day, the entire group split into mixed teams

(approximately 6-8 participants each), centred on each JSSL project. The teams were equipped with posters of their project's persona photograph and background information, including a short scenario. They were also assigned a series of prompting questions to assist in understanding (i) how the persona interacts with the technology, (ii) what problems / issues the persona experiences, (iii) what questions the persona might have, and (iv) how the technology / sensor solution could meet their needs. The groups were also instructed to use the personas as a starting point and not the "be-all and end-all", and all participants were invited to critique, challenge, and edit the personas throughout the brainstorming session. At the conclusion of the workshop, each team reported back to the entire group, sharing their findings and learnings about the user experience.

Workshop 3: Journey reflections

This activity was intended to invite the JSSL team to reflect on their journey so far, to assist in team cohesion and design understanding – being a multidisciplinary team, a reflective approach was necessary to consolidate team vision and understand areas of tension or complexity (Valkenburg and Dorst, 1998). Schön (1984) describes the reflective practice of a designer, inviting a "conversation with the situation" that allows for problem framing, moving towards a solution, and then ultimately evaluating those movements (Valkenburg and Dorst, 1998, p. 251). Hence for the JSSL, this workshop involved training the team to adopt reflective practice by evaluating the highlights, setbacks, and goals for the future. The workshop also involved preparing a timeline of the key activities and milestones within the first year of the JSSL.

Workshop 4: Understanding prototyping

This workshop marked the start of the prototyping journey within JSSL and was intended to help establish common ground and terminology across the multidisciplinary team, amongst which each member had a different prior understanding of prototyping. This workshop was centred on brainstorming and using mind-maps (Andrzejewski *et al.*, 2018) to discuss what prototyping means to each team member, followed by an introduction to low-fidelity prototyping in a design context to frame the following weeks and months of iterative development.

The key distinction in using low-fidelity prototypes as opposed to fully-fledged technologies is in accommodating testing and feedback, inviting forward progress, learning from failure, and free expression without fixating on early ideas (Camburn *et al.*, 2017).

Workshop 5: Problem reframing

At this point in the JSSL journey, the team was invited to revisit their original projects and abstract their problem statements to align with broader vision from their RAAF end-users. This involved problem reframing to challenge and provoke assumptions. The value in reframing lies in creative interpretations of the problem, that in turn assist in unique solution development (Lawson and Dorst, 2009). This involved the individual project teams adopting a co-design approach (Adikari, Keighran and Sarbazhosseini, 2016) where the existing problem set was reframed in response to end-user input. This workshop took the form of three smaller sessions, one with each project team, accompanied by two RAAF representatives, where the problem reframe was discussed with respect to the specifics of each project.

Workshop 6: Demonstration and feedback workshop

The final activity was a demonstration session where the JSSL was once again invited to present their progress back to their stakeholders in RAAF and DST. In preparation for this, the team was invited to prepare pitches (Parkinson and Warwick, 2017), to create a platform for storytelling and sharing of insights between the knowledge holders (JSSL) and the end-user (RAAF). This also helped to establish a bridge between the high-level technical detail of JSSL's scientific developments, and the nuances of the niche end-user experience in RAAF. Pitch preparation sessions were done within each individual project team to provide specific guidance and feedback. Then on the day of the demonstration workshop and pitches, the project teams were provided with a slightly modified Feedback Grid tool (IBM Corporation, 2018) to assist in sorting verbal feedback into categories of "on the right track", "changes to explore", "questions" and "new ideas" and then clustering these insights to identify patterns, themes, and action steps.

A timeline of the project is outlined in **Figure 3.2**, which describes the research data collection in parallel to the workshop / project activities undertaken as part of the embedded design practice. This visualisation reflects the iterative and flexible movement between design (project) and research spaces, where design and research actions stimulate each other while pursuing unique goals (Jaskiewicz, 2022).
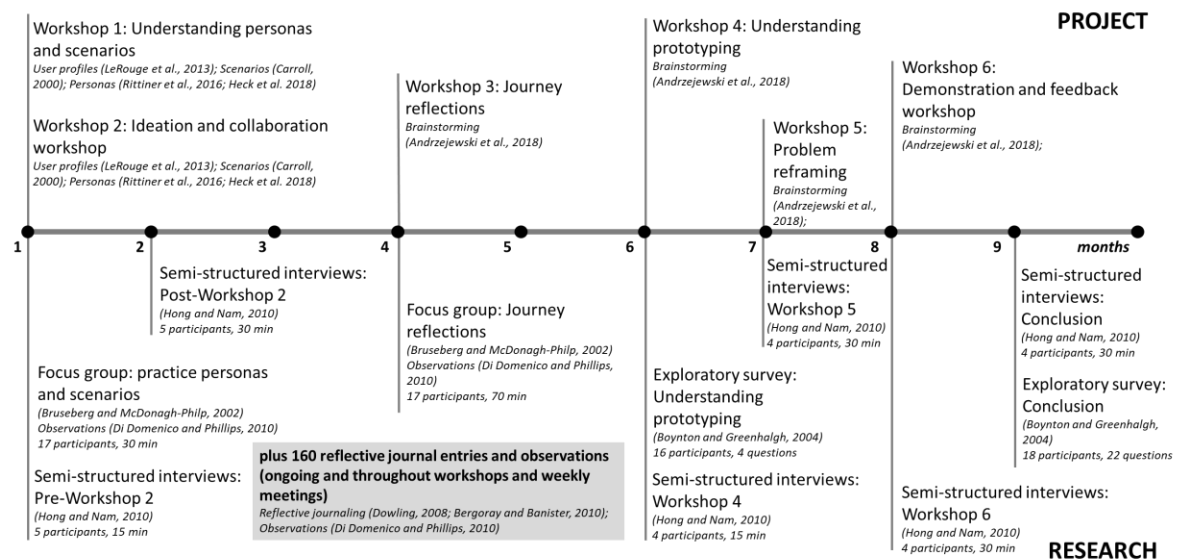
Figure 3.2: Timeline of research data and embedded design practice.

3.4 Analysis

Given the nascent state of prior research in the field of design and science, a qualitative and exploratory approach to data collection and analysis was required (Edmondson and McManus, 2007), enabled by a grounded theory approach (Glaser and Strauss, 1967) to "discover or construct theory from data, systematically obtained and analysed" (Chun Tie, Birks and Francis, 2019, p.1). More specifically, this study adopts a qualitative thematic analysis process, centred on the triangulation of qualitative data collection methods, the process of coding and sorting data, and the generation of key themes (Aronson, 1994; Connolly, 2003; Braun and Clarke, 2006). This emergent theory was compared to existing literature to determine the contribution to new knowledge (Eisenhardt, 1989).

The five methods of semi-structured interviews, participant observation, reflective journaling, surveys, and focus groups were selected to allow for methods of triangulation (Kimchi, Polivka and Sabol Stevenson, 1991), which can "overcome or counterbalance the deficiencies and biases that flow from single methodologies", allowing for the convergence of lines of inquiry and key insights (Evers and van Staa, 2010; Yin, 1981). The data collected from each of these methods was transcribed (in the case of interviews, surveys, or focus group recordings) or scanned (in the case of reflective journal or field note entries) and compiled using the NVivo qualitative data analysis software (see appendices for screen captures of the NVivo program for examples of the coding process and coding scheme). Data emerging from the methods were coded simultaneously and with the same coding scheme, as the data collection methods were designed to uncover latent and explicit insights for the same evaluation of the one design intervention. This was necessary to ensure an accurate assessment of the design intervention and correctly identify the changing perceptions, challenges, and opportunities throughout the engagement through a wholistic approach and with balanced consideration for the different nature of insights each data type contributes. Thematic analysis has been found to be suitable for studying design projects in order to retain these rich contextual insights (Johnson *et al.*, 2017b).

The thematic analysis and coding process followed Braun and Clarke's (2006) approach, and using the "NVivo 12 Plus" computer-assisted qualitative data analysis software (CAQDAS). The analysis process adopted the following 4 steps:

1. **Developing familiarity with the data**
   Collating data and immersing within it as the researcher through careful "reading and re-reading" (Braun and Clarke, 2006, p.87). For interviews and focus groups, this involved listening to and transcribing the recordings and then reading and re-reading the transcripts. For the reflective journal and observational field notes, this involved scanning hand-written notes, and then reading and revising the content. Finally, surveys were collated, any hand-written responses were transcribed, and all responses were read and reviewed. During the reading and revision process, this stage included

taking notes of any surface-level insights or loosely structured ideas, in preparation for the generation of initial codes.

2. **Sorting data and generating initial codes**

Once the researcher was familiar with the entire data set, then began the data structuring process, followed by the production of initial codes. Given the nature of data collection, the data was already sorted chronologically but needed to be placed in logical groups. This led to the formation of seven phases of the project. Note that the phases were not explicitly used to structure the design engagement – they were an artefact of the data analysis and sorting process. Each phase was centred on one main focus group or workshop and the surrounding (prior/post) meetings and interviews, with the exception of one final "wrap up" phase to collate concluding insights.

Codes are defined as "the most basic segment, or element, of the raw data or information that can be assessed in a meaningful way regarding the phenomenon" (Boyatzis, 1998, p. 63). At this stage it was important to ensure "full and equal attention to each data item" (Braun and Clarke, 2006, p.89) to identify semantic content, often sorting through the data iteratively and repeatedly.

Given the interconnected nature of the research questions, all data types were examined in parallel, identifying both perceptions towards design and emergent design opportunities and challenges. Further, it was important to code all data concurrently, as the aspect of change over time is a critical element of the research. As each data file was examined, text (or in the case of reflective journal scans, areas of text / diagrams) were selected and assigned initial codes in terms of the potential perceptions towards design that were being expressed by the participants. Additionally, the same data was also examined to highlight and code any instances of design being utilised by the scientific team, and/or any indications of the perceived opportunities / challenges brought by design. The researcher also took note of any additional thought-provoking observations or key

quotes, especially those which were highly demonstrative of the perceptions towards design or an expression of the perceived value of design.

3. **Searching for and defining themes**

Once all data had been initially coded, this phase involved broadening the perspective of the researcher, sorting and organising the initial codes by considering how they might combine into overall themes. The organisation of codes was done with respect to the research questions. Firstly, all codes relating to the perceptions towards design expressed by the participants were grouped into the theme of "perceptions towards design". Similarly, the opportunities brought about by design were grouped together.

This stage also focussed on the refinement of the emergent themes, where the complete data set is examined for themes that need to be combined, collapsed, or broken down further. This process involved looking at the quantity of data within the codes and examining the emerging patterns and similarities between themes. This led to the re-grouping of codes around the opportunities and challenges afforded by design, each exploring one key area, for example, "strategic thinking", "user engagement", and so on.

4. **Reviewing and refining themes**

Once confident with the emergent themes, this next stage involved the "define and refine" process (Braun and Clarke, 2006, p. 92) to ensure cohesion across the entire data set and clarity in the true meaning behind each code and theme. This also involved careful consideration of the research questions to ensure consistency in language and relevance. This involved renaming codes to be as explicit as possible in terms of their meaning and relevance to the research questions. Further, following the sorting process from Step 3, it was found that some codes were essentially doubled up, while others were too broad and required more nuanced detail. The codes were thus re-examined, expanding any that

were too broad into more specific codes, and condensing codes that were either too narrow, had too few data points or were sharing the same meaning as another code.

3.5 Ethics approval

The nature of this project involved the candidate being embedded in a scientific research team, collecting data through observations, semi-structured interviews, surveys, workshop / focus group discussions, as well as commentary and insights through a reflective journal. The protocol of this study was assessed and approved by the University of Sydney Human Research Ethics Committee (Protocol Number 2019/858) and the Department of Defence and Veterans' Affairs Human Research Ethics Committee (Protocol Number 185-19). The research practice involved in this study complies with the conditions of ethics approval. Please find in the appendices the relevant approval documents from both Committees.

CHAPTER 4: RESULTS AND FINDINGS

4.1 Overview

Following the description of the research design and methodology in **Chapter 3**, this chapter will uncover the results and findings of the study. First, introductory context is provided in terms of the participants and timeline. This will be followed by the results of Research Question 1, in order to understand the changing perceptions towards design over time. Results for Research Question 2 follow accordingly, exploring the opportunities and challenges afforded by design.

4.2 RQ1: Changing perceptions towards design over time

The response to RQ1 explores the changes in perceptions towards design throughout a project by a scientific team:

How is design perceived by scientists engaged in a scientific project?

This includes documentation of the dominant two perceptions towards design at each phase of the project, accompanied by exemplar quotes from research participants that support these observations. Responding to RQ1 will thus create a foundation for RQ2, which looks deeper into the cause of these changes in perceptions to uncover the opportunities and challenges offered by a design engagement for science.

The perceptions towards design (which emerged from the thematic analysis described in **Section 3.4**), along with their definitions within the context of this study and example quotes, are summarised in **Table 4.1** below:

Table 4.1: Perceptions towards design – definitions and exemplar quotes

Perception	Definition	Examples
Scepticism	A reserved and doubtful perspective, showing cynicism and a clearly negative opinion	"Low-fi prototype, I mean... sure, they're all, little... they're all methods. They're not anything new, they've been around for ages. People have been doing that for years!" (P2) "I don't think such collaboration would achieve anything." (P14)

Uncertainty	Hesitation; lack of confidence and/or clarity	"The squiggly line in terms of the design process, the 'what ifs', the 'how' – it's very difficult." (P5) "I think it's still not very clear at the moment. I just don't know if design innovation could help in this space, or it could be the facilitator or the bridge." (P4)
Pride	High satisfaction in one's own understanding, skill, or achievements	"Anything less than world-leading would not be something we sign up to." (P6) "We were pushing very very hard to get that demo working! I think it's just a great opportunity for the whole team to show their great efforts and show what we can do." (P3)
Optimism	Showing hope and confidence for the future; a tentatively positive outlook	"I'm looking forward to seeing how design can help." (P11) You need to try sometimes. Physics is there, science is there, but you need to be creative and also put a bit of, I guess, love into what you are doing. (P1) This is seeing things differently, which allows us to see the problem differently. It's a completely different way of thinking about deep tech. (P6)
Desire to learn	An eagerness and anticipation to uncover and understand more; curiosity	"It has been a journey of learning as well, a learning experience for us. It's new, and there's a lot of questions, but in general the approach that we have been taking - going step by step, learning, introducing new concepts, things like that - has been very useful." (P1) "Let's try and get more feedback whenever we can, whenever we get another opportunity." (P2)
Excitement	Embracing and deeply valuing something; clear appreciation and positive opinions; looking forward to the future	"It gave me a totally different way of thinking than just solving scientific problems. Sometimes design thinking is as important as scientific research, especially when end-users are involved." (P8) "This has been a wonderful collaboration of design and science – it *really* works." (P6) "We need to integrate the end-user's feedback on this. That's why [design] is so vital. Design innovation is involved in making sure this is useful." (P6)

As described in **Chapter 3**, the data was sorted into seven phases that span the entire project timeline. The phases were roughly divided around key shifts and/or moments in the JSSL, for example, a change in focus, or a major workshop. In the event of a workshop, the phase will include some time before and after the workshop as context. **Table 4.2** below provides an "at-a-glance" summary of the dominant perceptions towards design at each phase of the project, with the following sections unpacking these results in detail.

Table 4.2: Dominant perceptions towards design during the seven phases of the JSSL project

		1: Understanding personas and scenarios	2: Ideation and collaboration workshop	3: Journey reflections	4: Understanding prototyping	5: Problem reframing	6: Demonstration and feedback workshop	7: Wrap-up
Phase								
Timeline		Nov 2019	Nov 2019 - Jan 2020	Jan - Feb 2020	Feb - Apr 2020	Apr - May 2020	May - Jun 2020	Jul 2020
Month		1	1-2	3-4	4-6	6-7	7-8	9
Perceptions towards design	Scepticism	▓						
	Uncertainty	▓		▓		▓		
	Pride		▓	▓				
	Optimism		▓		▓	▓	▓	
	Desire to learn				▓		▓	▓
	Excitement							▓

4.2.1 Phase 1: Understanding personas and scenarios

SCEPTICISM

This phase was intended as an introduction to the design strategies of user profiles, scenarios, and personas, as well as practice of group brainstorming and co-creation. A practice personas activity using a non-scientific example case study was assigned to the team so they could firstly become familiar with using these design tools, and secondly understand the importance of understanding your end-users, all in the lead up to an end-user collaboration workshop (**Phase 2**) where actual personas, profiles and scenarios would be created in relation to their own scientific projects. This was the first time the majority of the team had encountered these design methods, and at first interaction the two most dominant perceptions during this phase were uncertainty and scepticism towards design. This sceptical response reflected the team's initial hesitation to shift from traditional scientific thinking to embracing creative tools, as evidenced by quotes which challenge the validity of the design methods such as, "I feel like I'm bootstrapping, I'm using the same data to come up with new results" (P2). The validity of an experiment or tool is an integral part of the scientific method, however the traditional metrics of scientific validity are not immediately evident in an unfamiliar design approach where the information is predominantly qualitative. Further, at the end of the focus group, there was a significant amount of hesitation and unease regarding engaging with personas during the upcoming collaboration workshop, as not only would the personas be unfamiliar, but the nature of the workshop and co-creating with end-users was unfamiliar, as evidenced by questions and speculations about how the workshop itself would operate, such as, "So… we're going to have this persona… they're going to be sitting there virtually… but what's going to happen? I don't have that clarity" (P1).

UNCERTAINTY

After building some level of familiarity with personas and design in general, the team began to prepare for the ideation and collaboration workshop (Phase 2). There was observed a continued level of uncertainty about design, although there was an emerging element of intrigue and optimism as the team grew curious as to what they would experience in the workshop. For example, P2 expresses, "it

was uncomfortable for us to send [the personas] out" (P2) – the discomfort of design led to some uncertainty. There was also a more practical sense of uncertainty as to the "how" of adopting design, for example, "I think the idea of having a virtual person joining the breakout sessions is going to work very well, if the team leaders manage to embrace it as it is… to bring the unknown knowledge, perhaps." (P1) Here P1 described their willingness to use design to deepen end-user understanding, however, they are still unsure of the exact value that would be brought by such an activity. This sentiment was echoed by other team leaders, with P3 expressing that "ideally, we get more clarity, I guess? On the exact needs, the specifications... um... and maybe establish, sort of a… ongoing collaboration" (P3) – there was a lot of uncertainty around what value the workshop would bring, but an underlying optimism for the future clarity and collaboration to be achieved between the scientific team and their end-users. The dominant sense of uncertainty however was often attributed once again to the struggle in deviating from traditional scientific thinking – as mentioned in the quote from P1, the value of the workshop was thought to be contingent on the ability of the team to embrace design. This sentiment was further reiterated by P2 "I think that's the hardest bit about academics, being quite stubborn about what we've developed." (P2) – this mindset proves challenging in a context where end-user feedback is of critical importance.

4.2.2   Phase 2: Ideation and collaboration workshop
PRIDE

Following the collaboration workshop, there was a significant sense of pride within the team, both relating to a sense of showcasing and demonstration, but also as an outlook on the reception of design. For example, P6 during the workshop stated that "anything less than world-leading would not be something we sign up to," (P6) which elucidates the dominant two perspectives in this post-workshop phase of pride and optimism. Now, after the value of design has been somewhat demonstrated through a workshop, the teams are proud of their involvement and evolving understanding and are also still optimistic about the future value that design will bring in being a "world-leading" project. P6 later reiterates this dual perception: "[our end-users] definitely agree with [our science], we just need it to be working on problems that matter." (P6) which shows an

interesting shift away from the unease noticed in previous phases – now, design is not seen as a threat or challenge to the science itself, rather a means to ensure the science is applied to "problems that matter" and creates tangible value for the end-users. P3 seconds this sentiment, stating, "our experiment didn't change, but the problem it is solving has changed." (P3) and "It was a learning experience and emphasises the importance to really understand the needs of the end-user to make sure all efforts, energy, personnel, and money are directed in the right direction." (P3) This drive to bring value to users also reiterates the perceptions of both pride and optimism, where user engagement is now seen as a significant achievement instead of just technical development: "It went very well! I think the biggest achievement would be that we had the users actually in the room, so they provided us with lots of specifications they are looking for." (P4)

OPTIMISM

Further, P2 reflected that the workshop was "super worth it" – implying a "cost" as such, wherein investing in design had perceived risks and was met with a lot of initial uncertainty, but the outcome of engaging so closely with users through design brought more value than expected. This shift in thinking was attributed by P1 to an increased clarity about design through exposure to it in the workshop: "I think initially it was confusing, not very confusing but it was unfamiliar, right? After we clarified the idea behind it, I think it became very clear." (P1) This transition from confusion to cautious optimism was of course not immediate for the entire team, as some traditional perspectives were still quite prominent with some team members. For example, feedback from P5 included "I do find there are challenges within the group dynamic in terms of co-design where people who have come from an engineering or 'science-y' background are trying to do planning on a very linear scale, and that is very hard to break away from" (P5) and "It was very difficult to go back and talk about our persona… area we sort of then tended towards the technical rather than the actual application… well, we tried to come back to it, but it wasn't a natural fit for us." (P5) – here we see some of the tensions between the way science and design cooperate, and the counter-cultural challenge of shifting from linear thinking and technical focus to an iterative user-driven design process.

4.2.3 Phase 3: Journey reflections

UNCERTAINTY

Shortly following **Phase 2: Collaboration workshop**, one of the projects was discontinued by the project sponsors, which led to team reshuffling and cancelled lines of work. The response of the team to this sort of disruption was interesting to observe, and more specifically, it was important to note how this would impact their perceptions of design, if at all. Unsurprisingly, in **Phase 3: Journey reflections** we observe a shift back in the direction of uncertainty towards design.

There was observed tension between a vague understanding of the need for design versus the tangible execution of a design process, made especially evident in discussions around understanding user needs, for example: "Of course, we can elicit the needs from [our end-users], but how can we actually polish those needs and also constantly check in if we are actually doing the right thing? I think it's still not very clear at the moment. I just don't know if design innovation could help in this space, or it could be the facilitator or the bridge." (P4) This tension of understanding "why" but not quite "how" contributes to the persistence of uncertainty towards design.

This uncertainty is not paired with scepticism (as was the case in **Phase 1**), rather a genuine frustration. For example, P3 explains that the team is interested in design when they express, "I think generally people were very open to it and just curious what it is. Because we didn't know much about it so we just said, okay let's see what this is, how can it help, and how can it link in," (P3) while P6 describes the uncertainty of not yet knowing the full potential of design: "I think I still feel like I haven't seen the full breadth of what design means and what the team means by design innovation. There's more to it... maybe there's not? I don't know." (P6) In these quotes, this frustration is elucidated – a design intervention in the scientific process has now made clear the importance of end-user feedback and constant engagement, however the disconnect between this understanding and the actual ability to engage with users has left the team uncertain.

PRIDE

This phase also involved a timeline reflection activity, where the team was invited to a focus group where each stage of the project was discussed so far, unpacking the highlights, setbacks, and goals for the future. One exchange between P3, P5 and P6 during this focus group provides an example of the second dominant perception of pride, demonstrated by a general resistance towards the chaos of design:

> "I always had in mind this picture *[waves hands erratically]*" (P6)
>
> "*[laughs]* spaghetti!" (P3)
>
> "The squiggly line in terms of the design process, the "what ifs", it's very difficult." (P5)

We observe that the team has chosen the light-hearted context of the focus group to express a deeper frustration – that the intentional ambiguity we recognise as often framing the start of a design process doesn't appear to be intentional or even useful when, first, you are accustomed to the structure of a scientific process, and second, you are still in the middle of the "spaghetti".

While in the previous phase, there was some appreciation of design's value, the actual process of design still remained to be proven to the team. This lack of clarity led to a resurgence in prideful and resistant perspectives towards design, especially in light of the setback of cancelled lines of work – arguably putting design at fault. P2 expresses their hesitation towards what they called "making guesses," explaining:

> "I *tried* to think about the end-user perspective but I'm not the end-user, so there's a limit to the knowledge, and the knowledge is only as much what feedback [end-user representative] has given me. So, to go beyond that I think I'm making guesses, and I don't want to do that." (P2)

There were also risk-averse perspectives, as team members do not want a repeat of the cancelled project, with P13 concerned they might "waste time coding a design [the end-users] are not happy with" (P13) and P1 referring to feedback as "protecting us" (P1).

4.2.4 Phase 4: Understanding prototyping

DESIRE TO LEARN

Phase 4: Understanding prototyping saw a transition in focus from solely focussing on evolving an understanding of the problem and potentially relevant technologies, to developing and demonstrating solutions. This required another learning-centred activity on prototyping to establish a common ground and unified understanding of terminology. From a sensor science perspective, "prototyping" refers to the packaging of a sensor, while the intent of this phase was to expand the team's understanding towards a user-focussed approach of co-creation, low-fidelity prototyping, and field testing. However, compared to **Phase 1** where learning a new design technique was met with scepticism, here at **Phase 4** the initial perception of the team is a desire to learn, paired with optimism about design. At this phase, design has been proven to provide value through the collaboration workshop (**Phase 2**), and the team was eager to learn more about design to alleviate the uncertainties of **Phase 3**.

The desire to learn about design was motivated by establishing common ground between the scientists and the designer, as well as to broaden the team's understanding of what is involved in prototyping. Terminology was a recurring discussion during this workshop, for example P6 exploring the evolving language around end-users: "We used to call it 'customer' but designers now say 'end-user'." (P6). Even within the team, there were differences in terminology depending on their disciplinary backgrounds, for example, in this conversation between P6 and P13:

> "We used to call that a 'research prototype' – a kind of box you could ship to someone in the lab, demonstrate functionality, but it wasn't the specs of the final product." (P6)
>
> "And that's interesting, because in software we call that a 'proof of concept' prototype." (P13)

This workshop proved the real value of communication in establishing common ground – not only between the scientific team and their end-users, but also between the scientists and designers, and further within the scientific team itself. The underlying optimism towards design during this phase also saw quick adoption of design language, for example, "Our aim is to make a low-fidelity

prototype – thanks to yesterday's workshop for that name!" (P13) – the team was ready to learn and broaden their perspectives. This inclusion of design terminology was not merely semantic, rather a shift in language also saw a shift in perspective, for example, in this conversation between P3 and P2 following some end-user feedback suggesting an adjustment to the technology:

"This sounds like more than complexity, but actually a pivot." (P3)

"Well it comes down to what problem are you trying to solve?" (P2)

In this exchange we see the significance of broadening perspectives – P3 now knows the relevant language to communicate what responding to end-user feedback now looks like and is comfortable exploring pivots to their project. Similarly, P2 has also developed their understanding of design, and instead of shifting the conversation towards technical specifics, they broaden the question to ensure the discussion remains relevant and problem-focussed.

This growing sense of team cohesion also contributed to the desire to learn more about design – as opposed to the perceptions in **Phase 3**, design was no longer seen as an intrusion to the science, rather, a complement to help deliver value to the end-user. P1 reflects on this process of learning and growing in the prototyping workshop: "I was a participant, learning and listening! Understanding what was going on and all the changes." (P1), and then further, reiterates the value of broadening perspectives:

"We will gain a lot of expertise that we don't have! Like the design and innovation team and [end-users] are going to plug in so nicely with what we are doing and it will actually target to deliver the outcomes that they want, and I guess that's the whole point!" (P1).

OPTIMISM

This phase elucidated the value of transdisciplinary collaboration – where the value brought by two fields such as design and science coming together could be greater than the sum of the individual domains. This was also the stage where the scientific team grew in optimism, as they began to see the similarities between design and science, the validity of design approaches, and the way in which the two fields could truly cooperate. P3 reflects on how the iterative nature of the design process is in fact familiar,

> "So, we're actually used to that - to try something, have an idea, it doesn't work, you adjust, you try again, you adjust, until it actually works. So, it's almost, like, part of our daily life as a scientist!" (P3)

and

> "I think we always have to pivot around - even if you're just doing research for the sake of research, we're sort of pivoting all the time because there's always different things and different problems you need to solve. You can go down one direction and something comes up, you slightly adjust for something you didn't see coming. I think that's just the nature of doing cutting-edge research, trying to do something really new and novel." (P3)

This reiterates the increasingly optimistic perspective on design – pivoting, iterating, responding to problems, all now seen as a natural part of the scientific process and not an inconvenience triggered by design intervention. P1 extends this thought, commenting that science itself necessitates creativity:

> "Doing research, doing science, you need to learn what's going on and you won't succeed the first time. You need to try sometimes. Physics is there, science is there, but you need to be creative and also put a bit of, I guess, love into what you are doing." (P1)

The optimistic perspective towards design was especially evident in terms of future vision, where new opportunities and avenues of work illuminated through design were welcomed. P4 reflects on this, commenting, "I think [design] is very inspirational… it brought different angles of thinking as well as more work." (P4) and "The JSSL team is basically getting into this new framework or new architecture of doing innovation and innovative work… I don't think mistakes are 100% wrong, it's more like a test, more like a trial." (P4) The novelty of design was perceived to be "inspirational", and there was a growing comfort with the idea of "mistakes" as part of the process, and pivoting, a natural transition.

4.2.5 Phase 5: Problem reframing
OPTIMISM

Phase 5: Problem reframing involved considering new broader problem sets assigned from the end-users, to provide big-picture context and vision to the individual scientific projects. The involvement of design through facilitating

brainstorming sessions was critical at this stage, as these reframed problems required significant pivoting and a shift in focus for the scientific team. Considering the negative response to a design pivot after **Phase 2**, there was a risk that this would happen again, and that design would be seen as an interruption to the science. However, in **Phase 5**, this was not the case. The dominant perception in this phase was, for the first time, optimism about design – the team was looking forward to seeing how design could facilitate this reframe and ensure a positive transition. The team attributed this optimism to having understood the significance of design in ensuring an end-user focus, and that this focus is essential in delivering a valuable outcome, as explained by P6, "We need to integrate the end-user's feedback on this. That's why [design] is so vital. Design innovation is involved in making sure this is useful." (P6) Design is now seen as a "vital" part of the scientific process. P1 similarly reflects that during this phase, they were able to observe how design, science, and the end-user co-operate:

> "[Reframing the problem] is a perfect way to link us, the scientists, with them, the users, that are also very intelligent people and need to use what we do in a very easy and efficient way. This is exactly what you guys are trying to do with the [reframed problems] - trying to find out all the links and loops and what's behind bringing both of us together." (P1)

As was the case in **Phase 4**, the real power of transdisciplinary collaboration for knowledge sharing and brainstorming was taking shape in the scientific team and leading to an optimistic perspective on design.

This transdisciplinary focus also sees a shift in the team's perceptions of their own value offering – it is no longer just about cutting-edge science, but actually about bringing that science into tangible outcomes for their end-users. P4 explains this concept, "The most important thing for the end-user is not how fancy it is, but how we deliver the information." (P4) This is a notable shift from the traditional approach to scientific development which places a significant emphasis on technical novelty. Here P4 demonstrates that the team now recognises that, while there is great expertise and scientific breakthroughs at play here, the real novelty and true value is not in showmanship, but in the right

information going to the right people. Similarly, a shift away from performative work and one-sided demonstrations was explained by P3:

> "The [problem reframing] exercise was good in that sense where we got feedback but it was also good that we could show a little bit about how we think, how we tackle these projects, and what kind of solutions we potentially have on the table, and feed that back towards RAAF." (P3)

Here we see that, instead of solely focussing on the science, the team is embracing the back-and-forth of co-design, sharing their own skills but also learning insights and feedback from their end-users. This demonstrates once again the optimistic approach to design – where co-design sessions and collaborative brainstorming were not perceived to be a threat to the science, rather something to embrace.

UNCERTAINTY

Phase 5 also still saw some underlying perceptions of uncertainty – while the dominant feelings towards design were optimistic, there was still a desire for clarity, and the familiarity of a systematic traditional scientific approach. P1 reflects on this confusion:

> "I think it was very confusing in the beginning but I think the fact that we have a lot of minds and people looking at it helped us nail it quite easily. So, at the end it's that approach we took to understand it helped us work with it quite nicely." (P1)

Here, P1 attributes the alleviation of confusion to the collaborative approach of the team, understanding that communication and constant engagement with both design and their end-users was vital to reaching clarity. P2 provides a different perspective, contrasting this project with traditional academic research: "Being ambitious is always the trickiest part about academic research contracts. But this is one where there's an end-user inside. So, I think getting that balance is the hard bit." (P2) There is a sense of uncertainty in how to navigate a high-end scientific project while also remaining flexible enough to respond to end-user feedback. P2 continues, expressing confusion around the problem reframe and why there is so much uncertainty in the project, saying, "You know, it's funny, after *one whole year*, still not exactly sure what the problem is! But we're starting to get a good idea." (P2) – this demonstrates the underlying sense of uncertainty

about design as there is a lot of frustration about the non-linear design process, however still an overarching sense of optimism, as P2 feels that clarity is slowly but surely being reached. P3 attributes this tension between scientific research within an end-user-driven project to the very nature of doing something novel:

> "I think there's always uncertainty, especially in research, because we can never really predict the outcomes. If you can already precisely predict the outcome, then it's probably not a big scientific breakthrough! (chuckles) Not something very novel because then you know already what's going to happen. But there's always that level of uncertainty in all the projects, but I think it's not beyond any other project. There's always the thought of "can we actually make it work?" but I think at this stage we're quite optimistic that we can find the solutions in the given time frame." (P3)

and

> "I guess there was always a bit of uncertainty about the deliverables, desired outcomes, what milestones we need to hit. I think that's much more defined now, so I'm optimistic. Yeah, I'm optimistic. Clarity is always good! Clarity helps. If there are clear milestones, we can hit them." (P3)

Here the team is described as embracing the uncertainty as a natural part of the scientific process (and in fact, innate to the design process as well), acknowledging that finding the right solutions and desired outcomes for the end-user are more important than having complete control over the process.

4.2.6   Phase 6: Demonstration and feedback workshop
OPTIMISM

Phase 6: Demonstration workshop was an opportunity for the team to present their progress so far, demonstrate scientific prototypes, and receive feedback from their end-users. In the lead-up to this workshop, design pitching sessions were used to assist the teams in communicating their work in an accessible and meaningful way that would result in the most helpful user feedback. The project teams were also encouraged to develop their own prompting questions to facilitate feedback sessions with their users and uncover more insights. In this phase, the dominant perception was once again optimism, as the teams were looking forward to collaborating with their end-users. Further, in contrast to **Phase 5** where the second-most-dominant perception was uncertainty, now we

see a greater desire to learn – not only were the teams optimistic about end-user engagement, but they put great value on not just showcasing their own work, but learning and receiving feedback.

The optimistic approach to design was revealed through a shift in understanding of the team towards problem exploration and prototyping, instead of just scientific development. P4 explains, "Previously I thought it's more about the tech, but now I know if we put the problems and demonstration in the centre, we can get feedback from [our end-users] throughout." (P4) and "I think there are a lot of questions to ask [our end-users] – if we deliver something they can't use, what's the point!" (P4) P4 quite emphatically stresses the ultimate goal of getting consistent end-user feedback, which reflects the team's general optimism towards co-design. The focus is no longer on developing the most impressive technologies, rather, solving real problems for the end-user – otherwise, "what's the point!" P6 expresses a similar sentiment, asserting that the focus of the entire collaboration of science and design is in order to deeply understand end-user needs: "The whole point of [science] and design and engaging [end-users] is understanding how their needs might change." (P6)

This phase also saw an increased understanding of the power of communication and collaboration. The team was very optimistic about collaborating with design and working closely with their end-users to broaden their perspectives and target their projects from every angle: "How critical it is to have a diverse team to solve such a complicated problem!" (P3) Once again, the way to tackle the problem is no longer attributed to flashy technology or impressive science, rather, diverse perspectives and consistent collaboration. P1 reiterates the importance of communication in facilitating this collaboration: "We need to target all different types of audiences – technical or not." (P1) This showed the team's optimism towards design, specifically the pitching exercises to assist with their demonstration workshop presentations, as the ability to communicate well with people of different expertise backgrounds proved vital in deeply engaging with end-users.

DESIRE TO LEARN

This heavy importance placed on the end-user's perspective also reiterates the secondary perception of desiring to learn – understanding and receiving feedback is now seen as critical to this project, above anything else. In contrast to **Phase 5**, where a lack of clarity about the process led to feelings of uncertainty, now the team is embracing the fact that "needs might change", because they are optimistic that through design engagement they can understand and respond to these changes appropriately. This optimism towards design fed into their desire to learn about how design can assist in balancing both scientific demonstrations and the processing of end-user feedback. For example, P6 explains, "[the users] will want us to pivot, and we need the agility to do that, but we also need to build our capability." (P6) – the team is eager to learn the best way to consistently improve their technical capabilities, while also being flexible and responsive to feedback.

Following the demonstration workshop, the teams were invited to process their end-user feedback and the outcomes from their prompting questions. The team expressed that they were increasingly comfortable with embracing design tools and approaches, for example, P4 stressed that "the first thing we need to talk about is the problem statement" (P4) to centre their demonstration, as opposed to focussing on scientific developments. This showed the team's real understanding of what is important to the end-user, and that they cannot focus on technology without grounding the science within a problem space. Further, the team also adopted creative ways to communicate, even outside of the prompting from the design team. For example, P3 used sketches to aid in context-setting for new audience members, stating, "I think a picture says more than a thousand words." (P3) This reinforces the positive perception of design within the team, and their own initiative to embrace design strategies.

The team's initiative and optimistic perspective were also clearly evident in their desire to progress and delve deeper into the next stages of the design process, especially in terms of prototyping and field testing. One of the framing questions for this phase from P2 was, "We can have [the science] but it needs to be useful – how do we get meaningful information?" (P2), to which they continued, "I want

to get to the field, a more real-life environment, so I can get a sense of the limitations." (P2) This demonstrated an eagerness to deeply understand end-users, and a true acceptance of design strategies such as field testing in order to achieve this deeper understanding. P3 expressed similar sentiments, stating,

> "There's actually a push to bring it into the field, do the first tests, get some data, get some input from that, get some feedback. I think that will be an important step. And then we go back to the drawing board to see how we can adjust to real world situations - what do we need to change, what works well in the field, what doesn't work well, what needs to be adjusted." (P3)

This not only reiterates the team's willingness to undergo field testing, but also a complete shift in mindset towards project development – they have fully embraced the iterative and creative brainstorming approach of a design process, recognising its value in an end-user driven project over a traditionally linear academic process.

It is important to note that field testing itself is not usually undertaken in a scientific process at this early stage, however, the team chose to no longer rely on traditional approaches. For example, P2 expressed that, now they have learnt about the value design can bring, they are experiencing frustration over the way academic science traditionally operates: "Academics should be able to do this already, it's just a matter of do they care about that or not, and unfortunately most of them don't care, they only care about talking about themselves!" (P2) This shows that the cooperation of design and science has complex reception issues that require a real shift in traditional thinking. In contrast to the "design spaghetti" conversation in **Phase 3**, P2 again describes the design process: "It felt like this *(moves hands in squiggly motion)* but it really gave us direction." (P2) This shows an acceptance of the unknown – it was not that the ambiguity which is often characteristic of design was suddenly clear, rather, the purpose of embracing that ambiguity and finding deeper insights was finally understood, and clarity in direction was a result. P6 also reiterates this point in reference to the entire project, "This should be about capability, not research excellence – we should be focussed on [our end-users]." (P6) – research excellence has no value if it is not delivering capability to the end-user. P6 continues to attribute this shift in

traditional thinking to design, expressing an extremely positive perception: "This has been a wonderful collaboration of design and science – it REALLY works." (P6) Design has been accepted by the team, who attribute value to its ability to support the delivery of capability to the end-user.

4.2.7 Phase 7: Wrap-up
DESIRE TO LEARN

The final stage was **Phase 7: Wrap up** where the main focus was reflecting on the overall journey of design and science in collaboration. The two most dominant perceptions of design at this stage were the desire to learn more, and, for the first time, excitement about design. This is distinct from the previous instances of optimism or positivity – this phase saw the team not only embrace design and expect value, but also actively look forward to engaging more with design and seeking out more opportunities to implement design in their future work. The teams reflected on their learning experience so far and the broadening of their perspectives towards design, for example, P2 describes their experience with engaging with design methods: "Even though in my head I may understand, actually writing it down and doing those exercises is what makes it meaningful." (P2) Here we observe that the team is not relying on their own assumptions and understanding, rather they see design as an opportunity to learn and draw meaningful insights.

P3 mirrors this sentiment, commenting on their broadened perspectives towards design:

> "What I have learned about design – well in general, that it's a much broader subject than what you commonly think it is. Usually when you hear 'design', you think about the looks of a device or something, but in this sense, design is much broader, because it's also the thinking process behind. Well, it can be the device design, the prototype, but it can also be thinking behind the innovation, for example. I think that's something that was maybe not that clear, or not that well known, before." (P3)

Not only does P3 acknowledge this shift in understanding, but they are actively excited to learn even more: "I would be very interested to learn more about the design thinking methodology, how it differs from the traditional scientific

approach, and how it can help to approach and solve problems." (P3) P15 adds, "Looking forward to learning more about design to have the best outcome possible." (P15) These perspectives show that once design was accepted within the scientific team, the desire to continue to learn drove future developments and allowed them to integrate both scientific and design methods to solve problems. P2 recognises that this integration means their team is no longer a traditional scientific team, and that parallels can be drawn from the business domain:

> "This is a pitch, not an academic story. Start with the problem and say up front, 'what we want is for you to tell us what to do with [our science] and hopefully buy some.' It's about problem, solution, all of that. It's what start-ups usually do." (P2)

One important aspect in learning about design was not only building experience with tangible methods ("how"), but also the motivation behind design ("why"). P4 comments, "What I learnt is to engage with customers. We did several workshops, and I learnt how I can do [design], and also why I should do it." (P4) This reflects not only an acceptance of design, but excitement about learning and deeply understanding. The design approach is not something that the team has rote-learned, it is now engrained into their mode of operating. As has been evidenced through each phase of this investigation, this is not an intuitive transition for a scientific team, as P1 reflects:

> "It's definitely that the user kind of dictates whatever we do. It's really that the emphasis needs to be put towards making a useful interface or a useful device for the user, right? And we as scientists do not think about these things. We try to solve problems and try to optimise research towards getting an outcome, but not really putting it in the hands of someone else to work in different conditions. That message is very important." (P1)

This message of putting solutions into the hands of the end-user has become central to the scientific team, to the point of "dictating whatever they do". However, the team's response goes one step further – they are not adopting a solely reactive approach to user feedback, but also proactively engaging with brainstorming and prototyping, for example, "After the field test we don't shut down – we learn and improve. I don't know any technology that did a field test

and just stopped after that." (P3) Not only were the team eager to pursue the field tests discussed in **Phase 6**, but they now had significant excitement about the design process to continue to progress with forward vision.

EXCITEMENT

This excitement and drive within the team led to many suggestions for how design and science can integrate in the future, beyond what they had already experienced through this project. For example, P2 describes design as not only beneficial, but integral to the scientific process:

> "[Design] is all necessary and needed at every step. As I mentioned earlier, good scientists do this without thinking about 'design' and 'science' separately. It is just broadly categorised in 'how to work well' – but admittedly not everyone does this. To maximise our chances, we should use design in every step." (P2)

Here design is seen as something that should be a natural part of "working well" as a scientist, and P2 further suggests that achieving this level of integration requires more learning:

> "Expose to-be scientists (students) to the methods and skills and understand the value of it. I would say get them involved with projects where they are made to do discovery work, act out the persona exercises, facilitate some workshops, so they can take on what works for them." (P2)

Similarly, P12 demonstrates perceptions of excitement in their suggestions to expand the reach of design beyond their own team, and into the broader scientific community:

> "Design is a powerful tool and has a place in the modern scientific environment. A focus on design could help tailor more public interest in university research if they are tied to problems the public is experiencing." (P12)

This shows a recognition that through the integration of design, the science is equipped to address real-world problem and deliver tangible solutions.

This excitement to learn more about design and bring solutions completely reshaped the team's approach to science, for example, "It gave me a totally different way of thinking than just solving scientific problems. Sometimes design

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thinking is as important as scientific research, especially when end-users are involved." (P8) This describes a scientific process where the end-user is central, as seconded by P13: "The design thinking framework is incredibly useful for focusing on user problems and validating your ideas." (P13) Returning to the issue of validity which first arose in **Phase 1** as a criticism of design, design is now seen as critical to *ensure* validity in an end-user driven scientific project. As P6 comments, "It's one thing to have a bunch of academics sitting comfortable in the lab – it's another to have a bunch of academics make a product and put it in someone's hands." (P6) P6 continues to explain the team's excitement regarding the strategic value that design brings to science: "The [design] process was very enlightening and constructive. It helped shape the strategy of the project and ensured we had end-user at the front. I felt very positive about it." (P6) The learning experience is described positively, where design has taken a role to drive the science. P1 adds, "Science solves the problem; Design helps it to be implemented cleverly and efficiently." (P1) This summarises the integration and cooperation which was achieved between design and science within this team – two domains working through different approaches, to achieve a common vision.

4.2.8 RQ1: Summary

Reflecting on the overall journey of the design intervention, the overarching transition in perceptions is from a sceptical and uncertain approach to design, evolving into a desire to learn more, embracing design with excitement. However, the transition is not linear – at different stages in the engagement, there are fluctuations in response to various triggers, for example, an increase in uncertainty when a design workshop led to a project's cancellation (Phase 3) and again when faced with reframed problems and the call to pivot (Phase 5). Here we observe that through a design engagement with a scientific team, the perceptions towards design do change at various stages, and the shift in general proceeds towards positive perceptions and the ultimate embracing of design – a slow transition that demanded the value of design be proven and the practical utility of the design approach be demonstrated. We also observe that the participants who engaged the most with the project (and consequently, with design activities) exhibited the most positive perceptions towards design, as observed by an increased proportion of positively coded data. This reinforces the

evidence-based approach to evaluating design in science – its value must be proven through experience in order to fully embrace design, and the appreciation of design is higher when there is more palpable experience.

To explore this space further, the second research question will unpack the opportunities and challenges that emerge from a design engagement in a scientific project, in order to understand the specific design approaches which are perceived to bring the most value to science.

4.3 RQ2: Uncovering opportunities and challenges afforded by design

Section 4.2 identified that an overall shift towards embracing design occurred within a scientific team throughout a design engagement. The next section will now look deeper at the data in order to understand the cause of this positive shift by unpacking the opportunities afforded by design. It will also explore any challenges or conflicts that emerged which may have hindered the journey, as this will also contribute to the holistic understanding of where design brings value to science. This is in response to **Research Question 2:**

What opportunities and challenges are afforded by the application of design in a scientific project?

Opportunities in this research are defined as areas where design was observed to bring value to the project, be it personal value to the JSSL team, valuable outcomes for the JSSL research, or value delivery to the end-user. Some opportunities spanned multiple of these areas. Challenges in this research are defined as experiences or concepts that either created barriers for design adoption in the JSSL team or design principles that were difficult to integrate within a scientific context. Opportunities and challenges were identified through the process described in **Section 3.4**, where through the thematic analysis process opportunities became apparent and significant representative quotes were recorded. For reference, a summary and description of the identified opportunities and challenges can be found below in **Table 4.3**.

Table 4.3: Opportunities and challenges of adopting design practice in science

OPPORTUNITIES		
Section	**Opportunity**	**Description**
4.3.1	Enabling the research translation process	Converting research findings into tangible, real-world outcomes
4.3.2	Uncovering pathways for new capability	Developing new technologies that are distinct from existing solutions and add new value
4.3.3	Encouraging creativity and brainstorming	Facilitating an atmosphere of experimentation, exploration, and thinking outside-the-box in order to improve the quality of ideation
4.3.4	Facilitating effective communication through clear demonstrations	Design enabling communication through visualisations, prototyping, and pitching, establishing common ground / language
4.3.5	Problem exploration	Deeply understanding, unpacking, and challenging the problem to be solved
4.3.6	Deepening end-user understanding and engagement	Facilitating and creating space for end-user interaction, building empathy with the end-user in order to understand their needs and ultimately meet those needs
4.3.7	Strategic development and forward vision	Providing direction and guidance, grounding the project in terms of goals and values
4.3.8	Fostering teamwork and collaboration	Supporting the development of a multidisciplinary team, building team cohesion and unity, creating collaborative environments
CHALLENGES		
Section	**Challenge**	**Description**
4.3.9	Shifting mindsets from the technology-driven and knowledge-focussed nature of science	Existing modes of thinking and working within scientific practice that centre on the production of knowledge and technology outputs, which at times are at odds with the exploratory design process
4.3.10	Struggling with agility and pivots in a high-end science context	The necessary cost (financial, time, emotional) invested in to reach deeply technical development leading to hesitation to make changes that might waste said cost
4.3.11	Finding clarity of communication with both design and end-users	Disconnection between commonly used jargon and terminology in design, science, and Defence contexts; challenges of establishing flowing communication without confusion and disruptions
4.3.12	Working within the limits of contractual obligations	A sense of conflicting goals, contrasting the detailed goals described in a contractual agreement with the flexibility and agility that a design process demands

4.3.1   Opportunity 1: Enabling the research translation process

The first opportunity identified during this project was the ability of design to support research translation. The JSSL project revealed the disconnect between developing high-end science and translating that science into tangible outcomes.

It was at this point where design could play a significant role. The team understood that this was a central role of design, with one participant stating, "design innovation is involved in making sure this is useful" (P6). This journey of research translation meant reframing what was perceived to be useful about technology. For example, one participant in reflecting on the output of their project, stated, "we're trying to cover the blind spots… we want the right information at the end of the day instead of just numbers" (P2). In adopting a design innovation process, the definition of a meaningful output shifted – instead of "just numbers", the technology must produce the "right" numbers, as defined by the kind of information an end-user would need. Here we observe that while the nature of scientific outcomes is still deeply technical, design ensures that this technical detail provides meaningful information.

To elaborate, another participant reflected on what this looked like in practice, specifically in contrast to traditional research, saying, "the tech needs to solve someone's problem at the end of the day, whether it's cutting them time, or making their job easier… we're not just here to publish papers, we have to develop a product, and if the product's not resonating with the [end-user], there won't be any continuation" (P2). Here we see that this is not an ordinary research project where success is measured by publications, rather, the project was driven by solving a real end-user problem through design. It is also interesting to note the desire for "continuation" – in a field that is typically driven by the "publish or perish" mentality, there is still the fear of "perishing", but the solution is more than just "publish", rather, "solve someone's problem". By the end of the journey, adopting a design mindset to research completely reframed the way the JSSL team saw their work. One participant reflected in their final survey comments, "it gave me a totally different way of thinking than just solving scientific problems. Sometimes design thinking is as important as scientific research, especially when end-users are involved. In some sense, it is even more complex as the process is non-linear" (P8). The team embraces the complexities and intricacies of a design process – not unlike those of a scientific process – and can see how they directly bring value to a project centred on problem-solving and translation.

4.3.2 Opportunity 2: Uncovering pathways for new capability

Uncovering novel pathways of exploration and new knowledge is a key element of scientific research, and in the case of the JSSL, the adoption of design practice enhanced this. The team was already positioned in novel science, as P14 comments, "we're a research organisation, we're at the front of the latest in research. It gives us an edge" – it was at this cutting edge that design operated. Not only was the desire to be at the cutting edge, but to look beyond the edge towards delivering future capability for their end-users. P3 reflects, "when they come to a uni, they don't want to see what's now, they want to see what's possible in the future". This motivation was present from the start of the project, but it was only through design that the practical approach on how to deliver novelty was revealed.

In understanding the role of design in producing new capabilities, P3 compared incremental technological development and the kind of novel research at JSSL:

> "I think both sides need to be open, so that we learn from the user, and the user learns from the technologies, and they take that on board, like, "we haven't done it that way before, but with that new technology, wow, we could do it a completely different way" … it can be *very* successful, I think, if both parties agree to it, and we go back-and-forth, and then we get the best possible outcome." (P3)

Here we see that design brings meaning to novel research by facilitating a mutual understanding of capability. Instead of the "solitary genius" archetype of scientific development, we see scientific research taking the form of a conversation. Design is the back-and-forth revelation of novelty – new technology from the science side, and new applications from the end-user side. P12 describes this concept further: "design is a useful pursuit and helps novel research concepts gain traction with the broader community" (P12). It is this traction that drives new capability – instead of research solely for the pursuit of knowledge, we see research that resonates with human needs.

4.3.3 Opportunity 3: Encouraging creativity and brainstorming

Despite the highly technical nature of the JSSL projects, adopting a design approach fostered space for creativity in the midst of high-end scientific development and encouraged creative brainstorming. The team was looking to develop innovative solutions, with P6 commenting, "I'm just trying to push the box in our thinking – I think we need to be new and creative and out-of-the-box" (P6). Design became a way of thinking for the team to enable this "outside-the-box" tactic, as expressed by P13 in the concluding survey:

> "Design thinking teaches creativity and pushing boundaries. It's great when research stalls or when some out of the box thinking is needed for new projects / ideas. It also validates ideas and non-user-centric models should be quickly adapted or discarded." (P13)

In this instance, design is seen to bring value to science in situations where research and development reach a dead end, as a means to explore new and creative opportunities. Not only so, but design is seen as a driver of quality ideas, where metrics such as user-centricity are provided to ensure projects deliver value (this notion will be explored further later). This experience led to a reframed perspective on what design means:

> "Usually when you hear "design", you think about the looks of a device or something, but in this sense, design is much broader, because it's also the thinking process behind. Well, it can be the device design, the prototype, but it can also be thinking behind the innovation." (P3)

The horizons of what it means to adopt a design process have expanded for the team, as they embrace design as a way of thinking. This invites innovative and creative outcomes for science.

Design was not only seen as a way of thinking but also a creative way of working. P3 describes that the team adopted an iterative approach to prototype development, where the team would "take stuff out, put new components in, and discuss about how to put them, where to put them, how to change them… And then we go back to the drawing board to see how we can adjust to real world situations - what do we need to change, what works well in the field, what doesn't work well, what needs to be adjusted" (P3). This ideation approach facilitated responding to feedback, group brainstorming conversations, and iterative

improvement of the design, all common principles of design prototyping. Instead of each team member working on their own elements of the project, collaborative group work and creative brainstorming became the norm. P2 describes the urge to start working this way:

> "Sure, we need to deliver on [the contract], but obviously there's this kind of bigger picture … where the big opportunities are, and really the future. So, we need to make a start on that. I'm not sure how, but we're going to start as a team. In our **Project A** team I've made an open forum session, a sort of scrum meeting where everyone sort of chips in. I want everyone's voices to be heard. I think the engineers in our team are focussing a lot on building a lot for the contract but not really thinking about where to innovate or how to innovate in the future. So, I want them to speak up more… getting them to get on the whiteboard, start sketching stuff, throwing out ideas - even crazy ideas at this stage." (P2)

In this description of the Project A team's new way of working, we observe a desire for multidisciplinary collaboration between all team members and an embracing of creative and unexpected ideas. P2 describes this as enabling the team to think of the future, "where the big opportunities are".

4.3.4   Opportunity 4: Facilitating effective communication through clear demonstrations

Design played a critical role in establishing common ground through effective communication between the JSSL team and the end-users. The team recognised that there was significant distance when it came to meaningful communication with their end-users, and that design could potentially bridge this gap: "We don't know exactly how to properly show and provide the results and measurements that are meaningful for them in a way that really serves all the purposes they are doing. So, I think that link is going to be from your side to provide that" (P1). In response to this drive, the JSSL team was encouraged to use pitching and interaction prototypes to more effectively demonstrate their ideas and technology. P3 described what this new way of collaborating looked like:

> "Having that concrete demo, that prototype in front of you – you see very concretely what it actually is and what it does. That will hopefully trigger a lot of discussions – even from some people who are not hat familiar with

the technology, who just want to see how the [data] looks on the screen, or who just use the [device] without even caring about how it works. Getting feedback from them in terms of the interface, that would be quite helpful." (P3)

P3 describes a richness of discussion and feedback that would otherwise be lost behind technical detail. This perspective resonated more broadly across the team, with several members reflecting on prototype demonstration as valuable for proof of concept (P11, P12), tangible representation of products (P11, P6), gaining feedback (P10), and visual communication (P4, P10, P12). The team also reflected that learning about prototyping alleviated pressure on their ability to perform and showcase – using a prototype brought value in and of itself. P2 explains, "it's better to see the device and what it does rather than have me talk about it" (P2) – with less pressure and more clarity, the quality of the user engagement is heightened.

An additional communication approach that emerged in the JSSL was visualisation as a reflection-in-action tool, or what Schön (1983, p. 76) refers to as "conversation with the situation". Increasingly, as the JSSL project progressed, the team was drawn to creative, emotive, and visual expressions of information as opposed to the traditional academic presentation style. As P13 expressed, "[we will create a] dashboard showcase of whatever [the end-user] needs to know… whatever visuals they need, since a photo tells a thousand words" (P13). The team understood that in a context with complex problems, highly technical information, and end-users that potentially cannot relate to the technical details, clear visual communication is incredibly valuable. This notion was observed in several other instances throughout the project, where the team started moving away from using slide decks towards real-time whiteboard brainstorms and discussions, adopting scenarios and storyboards to express user experiences amongst themselves, and using sketches and mock-ups to communicate progress updates to end-users. Through exposure to a design process, the team grew comfortable with more expressive modes of work and ultimately were able to communicate more effectively with each other and with their end-users.

4.3.5 Opportunity 5: Problem exploration

The JSSL project revealed the value of design in bringing clarity and direction to the problem exploration process. This was a unique approach to scientific discovery that the team was not used to, as explained by P6: "This is seeing things differently which allows us to see the problem differently. It's a completely different way of thinking about deep tech" (P6). Indeed, a user-centred and problem-driven approach was unfamiliar to the JSSL, which at times caused tension when it came to technical development. For example, P3 explains how the Project D team "dived into the project, started it, then realised that it was actually not really needed or was not actually solving a problem" (P3). In this case, driving technical development without deeper consideration of the problem space ultimately led to Project D's cancellation. However, it soon became apparent that reframing the problem space was not detrimental to the research and development in JSSL, rather it provided valuable context. P3 describes this transition and how "the experiment didn't change, but the problem it is solving has changed… we restructured our problem statement without changing the technology" (P3). Design did not derail technical development, rather, direct it.

This experience of adopting design for problem exploration led to a mindset shift, as P4 explains:

> "Previously I thought it was more about my technology. But now I know that we need to put the problem statement and demonstration in the middle so we can get feedback from the end-users throughout the journey" (P4).

Albeit necessary, this was not an easy mindset shift for two reasons. Firstly, it was at odds with traditional modes of scientific exploration which focus on the solution, as P11 describes, "design was useful to develop problem statements. Although, I sometimes had difficulties in avoiding jumping directly to a solution" (P11). Further, there was an additional hurdle of working at the cutting edge of technology. JSSL was aiming for high-end science breakthroughs, which meant the entire operating space (both from the end-user and JSSL perspectives) was unfamiliar. P3 explains this challenge: "very precise knowledge of the scenario, problems, and needs of the end-user is required. In my opinion, this becomes very difficult in the case of disruptive technology as compared to an evolutionary

progression of existing technology" (P3). Striving for "disruptive technology" meant the entire project was uncharted territory. However, it soon became clear to the team that the best way to navigate this uncertainty was to lean into user engagement: "the fact that we're doing these co-design workshops is what is making it faster to get to the problem" (P2). By the end of the JSSL project, the team not only learnt how to reframe problems, but their entire perception of their own value offering. As P6 explains, "we see these projects as building blocks to an overall capability, to reach a broader and more strategic collection of problems... [the end-users] definitely agree with smart sensing, we just need it to be working on problems that matter" (P6). Design as an approach to problem exploration allowed the team to imagine beyond their specific projects, strive to deliver holistic value to the end-user, and ultimately broaden their horizons for building technology capability.

4.3.6 Opportunity 6: Deepening end-user understanding and engagement

One of the most critical opportunities afforded by design was the facilitation of user understanding and engagement. While traditional scientific projects often follow an exploratory pursuit of knowledge, delivering valuable outcomes to the end-user was the main focus of the JSSL engagement. This meant that the connection between JSSL science and end-user needs had to be mediated. Design was able to provide this mediation, as P1 expressed when asked about what they learnt about design:

> "[I learnt that] the user kind of dictates whatever we do. It's really that the emphasis needs to be put towards making a useful interface or a useful device for the user, right? And we as scientists do not think about these things. We try to solve problems and try to optimise research towards getting an outcome, but not really putting it in the hands of someone else to work in different conditions. So, I guess that the message is very important." (P1)

This messaging invited the JSSL team to challenge their assumptions about what success looks like in science, and encouraged a unique user-centred approach.

Design enabled transformation between the technology, and the value it would provide – turning information into insights. The team recognised that the quality of

their technology meant nothing if it wasn't understood or valued by the end-user, as P4 expresses, "end-users don't talk to the raw sensor data – they want insights, they want knowledge" (P4). Similarly, P13 commented, "the missing piece is analysing that data into something human-useful… I don't want to waste time coding a design [the end-users are] not happy with" (P13) – this approach ensured that the hard work of the team would not go to waste towards an undesirable solution. Through design, the team learned to "fail fast, fail often", as P3 remarks, "If we can prototype faster, we can put it into the field, and learn from that test – as opposed to keeping on developing without testing" (P3). To develop the science without truly understanding the value provided to the end-user was no longer an option. P2 emphatically expresses just how significant this notion was for the team when they explained, "you need to go with the end-users' perspective. So, if you need to pivot, I think we need to pivot!" (P2).

Delivering valuable scientific outcomes first required an understanding of the user needs and an ability to communicate effectively – as P11 summarises, "**design is the interface between the science and customer. It helps to ensure that the customers' needs are met**" (P11). This is where empathy was critical – instead of a nebulous perception of the end-users, design enabled detailed understanding of their needs. P3 explains how the method of personas assisted in this understanding: "personas can be very useful and helpful to imagine the problem which we are aiming to solve… the ability to put oneself in the shoes of an end-user and really understand the needs of that user to successfully interact with the developed technology" (P3). This sentiment was prevalent throughout the JSSL, with some referring the persona as a member of their core team, and others framing the value of their project based on whether user needs can be met, for example, "there are a lot of questions to ask [the end-user] … if we deliver something they can't use, what's the point!" (P4). This marked a dramatic shift from the initial and traditionally scientific mindset of the team, where design enabled a new understanding of what it means to develop valuable science.

As the JSSL project progressed, there was a shift in both the conversation and composition of weekly team meetings. Instead of being centred on technical updates, the focus became responding to end-user feedback and determining the

best field tests and driving questions to gain even more insights. The team also began to invite end-user representatives to their meetings and into their lab work sessions. This dual approach of developing both the science and the user understanding required some nuance, as P6 describes, "We need to build capability that is resilient enough to pivot and be agile, without getting pulled in so many directions that we can't build any capability. We need that middle ground" (P6). To ensure "middle ground" is achieved, there required constant interfacing with the end-user, field testing, and regular feedback, where "we do a bit, we check in with them, have a meet-up, make sure we're heading in the direction they want, and adjust from there. All the projects have been shaped by the collaboration workshops. So yeah, that's kind of how we make sure we stay on track" (P11). The engagement between the JSSL team and end-user representatives grew more frequent and produced richer insights, with design as the interface to ensure "staying on track".

4.3.7   Opportunity 7: Strategic development and forward vision

Design did not only support the JSSL team with the delivery of innovative outcomes, but it also provided strategic direction and vision for the journey along the way. Given the novel context of the JSSL collaboration, there was significant initial uncertainty, but the team was encouraged to lean into the uncertainty and press forward to achieve clarity. P3 explains what this process felt like, when asked about whether or not design helped their team:

> "I think [design] helped… in the sense of the spaghetti you put up on the wall at the beginning. Because you started somewhere, and then over time we figured it out, it crystallised to us, "okay this is the most important bit, this is actually where we can have impact, this is the direction we should go" and then we went with that." (P3)

Here P3 references Newman's design squiggle (affectionately nicknamed "design spaghetti" by the JSSL team) and how it describes the chaos that can be perceived when embarking on a new design experience. But P3 also reflects that it was within that chaos where design was able to provide direction and focus. P1 describes a similar experience:

> What impact has design had for the JSSL... bringing clarity and focus to the table… I think you are going to be really giving us that north, that

direction towards our stakeholder, right? So, I'm strategically thinking towards the future. All of that comes from your skill set, in combination with [the end-users'] needs, and our skills. You are there in between us to create that strong bridge." (P1)

By acting at the interface between the end-user and the JSSL, design was a driving force for future thinking and strategy. This "strong bridge" described by P1 reveals that design was perceived to bring about connections and stability, a "true north" in an unfamiliar context.

After experiencing the value of design first-hand, the JSSL team was eager to incorporate design as central to their strategy. While the strategic planning session at the start of the JSSL engagement was focussed more on technical capability, a few months down the track the team embraced a motto of "unique approaches, unified vision" – where design and science each brought different valuable capabilities to the table, yet both sides were united in striving for the same end goal. P6 highlights how "Design runs through the strategy… design underpins everything" (P6), enabling this cohesive vision. This led to an increased confidence in the team, as P6 continues, "The process was very enlightening and constructive. It helped shape the strategy of the project and ensured we had end-user at the front. I felt very positive about it" (P6). This confidence provided reassurance for the JSSL as they adjusted their research and development approach to better engage end-users. For example, the team was traditionally used to holding onto a technology until it was polished and complete. However, the JSSL team adopted a co-design approach of "off-ramps". This involved the JSSL developing lower-fidelity prototypes and deploying them for field testing with their end-users, who would then return feedback to accelerate improvement, and also had an added benefit of the end-users themselves experiencing early exposure to and familiarity with new technologies. Releasing their science to these testing off-ramps could have potentially led to anxiety about whether or not the tests would be "successful", but having a strategic design approach reassured the team that learning from "failure" and testing was of even greater value. As P3 explains, "if you're scared to make a mistake, you really paralyse yourself. And when you do research, I mean, we're constantly failing actually …you try something, have an idea, it doesn't work, you

adjust, you try again, you adjust, until it actually works. So, it's almost, like, part of our daily life as a scientist!" (P3). Through design, the JSSL team was able to embrace iterative testing and learning, which catapulted their research and development forwards and ensured delivery on their ambitious vision.

4.3.8   Opportunity 8: Fostering teamwork and collaboration

One of the unique elements of the JSSL was its multidisciplinary nature, and design was able to not only encourage this multidisciplinarity but support team cohesion and unity throughout the journey. The team recognised that to truly meet the challenges ahead and develop innovative outcomes, they needed diverse perspectives to come to the table. As P12 explains, "the more varied the background of the people looking at a problem, the more likely at least one person is to see a novel solution to the problem" (P12). This was seen as both a strength and point of differentiation for the team: "we're anchored in STEM, but we also work closely with other disciplines. It's one of our strengths… The design innovation approach is quite a unique aspect of this collaboration" (P6). This sentiment resonated with the whole team, where the most common highlight identified in the Phase 3 journey mapping session was the formation of a diverse team and their ability to work together, and multiple responses in the Phase 4 survey highlighting that teamwork was a vital part of prototype development.

The design workshop sessions enabled the JSSL to make the most of their diverse backgrounds and come together as a team – as P3 aptly remarks, "how critical it is to have a diverse team to solve such a complicated problem!" (P3). Adopting a design approach meant that the team did not shy away from "complicated problems", but rather leaned into solving them. In reflecting on the workshop sessions, P13 comments that "the value is in the intersection of different ideas and backgrounds. Specialists across all fields bring new ideas to projects" (P13). The team was invited to work collaboratively instead of insularly, which allowed each participant's strengths to shine. Whenever challenges emerged, the reflective design approach invited the team to work through these challenges together, instead of building resentment. For example, following the cancellation of Project D, having a reflective journey mapping session invited the team to be honest with each other about their experience and celebrate the wins,

instead of just focussing on the losses. Following this, the team established "show and tell" sessions, replacing their project update meeting with a knowledge sharing and storytelling session once a month. P6 explains how "that's why we are having these sessions and this conversation – we want synergy" (P6) – the team was strengthened and unified by learning from each other.

Indeed, the principles of design went beyond the project work and into the way the team related to each other, with P13 suggesting that "leaders need to be facilitating design thinking not just in sessions but in their management processes" (P13). Design was perceived to be an essential part of effective teamwork and leadership. P2 described a future vision for what scientific teams could look like, with all members engaged and equipped – "I look forward to seeing an entire team of scientists who are all equipped with design thinking, rather than having one design member in the team… we need all scientists to have experienced this in their student days, so they are familiar with it" (P2). P3 shared a similar sentiment, with a suggestion on how this integrated approach might be achieved:

> "I believe a closer integration of the teams would be beneficial. Also, putting more emphasis on the similarities or overlap in the thinking process as a starting point for discussion would be appreciated. Thinking less compartmentalised and more as one big interdisciplinary team is something I would like to see." (P3)

By engaging with a design process, the team not only welcomed collaboration with each other but were eager to engage more closely with design, embracing similarities and learning from differences. P6 summarises this concisely, remarking, "this has been a wonderful collaboration of design and science – it really works" (P6).

4.3.9 Challenge 1: Shifting mindsets from the technology-driven and knowledge-focussed nature of science

One of the main challenges throughout the journey of integrating design in the JSSL was around the exploratory and knowledge-driven nature of science. The JSSL team members had predominantly scientific backgrounds, where significant value was placed on new discoveries and publications. This approach, while

certainly not a fault, at times led to conflict when it came to trying to embrace human-centred design. P6 reflects on this tension:

> "Science is also about establishing new knowledge and discoveries and needs to be able to take risks by going in directions that might not be perceived to be useful from a design perspective. The laser and the transistor may not have been invented if the design process was imposed at the early stages of that research. Many breakthroughs are solutions looking for problems for many years and then they change the world." (P6)

Design provokes exploration of ideas that are grounded in a deep understanding of the end-user and problem space, however as P6 comments, not all scientific discoveries are made within those parameters. Uninhibited exploration of new knowledge is considered to be a characteristic and innately valuable part of science – as P2 explains, "that's why you work with academics, they develop something that you haven't thought about before" (P2), even if it leads to the aforementioned "solutions looking for problems". Not only is the pursuit of knowledge valued in science by its very nature, but it is seen as an opportunity to catalyse forward leaps in ideas that one day "change the world". At times design acts at odds with this pursuit of knowledge, which was a challenge in the JSSL journey.

Due to the significant value placed on the pursuit of knowledge, and the fact that the majority of the JSSL team had traditionally scientific backgrounds, there were challenges in inviting the team to shift into a design mindset. P5 reflects on finding this experience difficult:

> "I was out of my comfort zone there. I tend to be more of a back-room scientist, pondering the problems but not actually... sort of up there on the front… there are challenges with the group in terms of co-design, where people who have come from an engineering or science-y background are trying to do planning on a very linear scale, and that is very hard to break away from." (P5)

This linear approach involves setting sights on an end goal or achievement at the end of a research project, which is often nebulous in a design project. P6 describes this contrast as how "the scientist and engineer wants to be very definitive… but we want to make sure the problem is front and centre for the

user" (P6). Seeking clarity and definitive information helps ensure accuracy and validity in science, but this meant that the JSSL team hesitated to lean into the uncertainty of design – often the very place where innovative ideas are born. P2 describes how despite being given end-user feedback, they were hesitant to accept any assumptions at all around the user experience:

> "I tried to think about the end-user perspective, but I'm not the end-user, so there's a limit to the knowledge, and the knowledge is only as much as what feedback [end-user representative] has given me. So, to go beyond that, I think I'm making guesses, and I don't want to do that" (P2).

This perspective reveals the rigour with which P2 and the team approached their work, but in this instance, it formed a road block to design thinking. This strict focus on certainty was also reflected in the way the team prepared presentations. During pitch preparation in Phase 6, the team struggled with the balance between technical detail and providing use case context for their projects. P14 expressed seeing great value in presenting significant technical detail to the end-users, remarking, "if they don't know what [the technology] is, how will they understand the benefit of [its features] and all the stuff we do?" (P14). The team struggled to reconcile their traditional understanding of scientific value with what was required for their pitches – that the depth of their research would be lost if the audience cannot understand it nor relate it to their own experience. This issue is exacerbated in a high-end science context, where even the fundamentals of a technology can be challenging to express in accessible terms. As P6 remarks, "you don't want to get so deep in the trenches that you lose the big picture" (P6).

This challenge is not always solely a mindset shift – at times there exist genuine systemic barriers that prevent adopting design, regardless of the willingness of the participant. This is a complex issue, as P2 describes when asked for their opinion on how science and design might best be integrated:

> "Expose to-be scientists (students) to the methods and skills and understand the value of it. I would say get them involved with projects where they are made to do discovery work, act out the persona exercises, facilitate some workshops, so they can take on what works for them. Unfortunately, the truth is that there is very little chance you will change current scientists. We are so buried in our ways it probably will not be

accepted as much. We are also stuck in a career trajectory that does not allow us to change, and if we stop publishing, we don't have a job tomorrow." (P2)

The complexity here is quite aptly illustrated – it is not always stubbornness that leads to a resistance to change, rather, a systemic issue that prevents deviation from the norm. Indeed, P2's suggestion of early exposure and design learning could be a significant factor in breaking down these barriers.

4.3.10 Challenge 2: Struggling with agility and pivots in a high-end science context

The challenges around integrating design and science extended to an unavoidable fact of high-end technology development – that research in this space requires extensive financial, strategic, operational, and technical investment. Often, all of this must happen before end-user feedback can be engaged to determine whether the investment was worthwhile or not. As P2 describes,

> "Doing the stock-standard stuff is not what they're after, they want to do something crazy. And that's hard, because if you do something novel, well that takes a long time unless you have a strong expertise for many years. So that's the challenge I'm up to: 'how do we do something novel?'" (P2)

There is significant time investment required when working at the cutting edge, which can act at odds with the rapid iteration and flexibility demanded by design thinking. This is especially pertinent when faced with a pivot or dramatic change to the project, as P6 reflects,

> "it's fine to say, 'let's not go forward with that [project]' but it comes at a cost! You have to build infrastructure, you have to invest in a test bed, you have to buy equipment, you have to put in place personnel, you build teams – that's an expensive cost!" (P6).

The JSSL team recognised that this risk was something to avoid, but this meant that their technical development had to slow down, as P2 describes,

> "We hit the ground running by doing a lot of technical work trying to meet some milestones, but I suppose what's really important is to make sure we're on the right path and get end-user perspective, otherwise we may invest too much into a technology that is not even needed!" (P2).

This led to hesitation from the JSSL, with some participants "freezing" their work: "I don't want to spend a lot of time redesigning the current set up without working with what [the end-users] are using and wanting" (P13).

Technical constraints in a high-end science context also added to this sense of hesitation. After all, the JSSL team were predominantly experts in physics, specifically photonics and smart sensing – so if user feedback was to demand a solution outside of that specific scientific scope, they would be poorly equipped to meet it. P6 warns of this during one conversation, asking their colleagues to "be careful to keep [the conversation] in the sensing world" (P6). Should the conversation leave "the sensing world", the JSSL would potentially be removed from the said conversation altogether. The JSSL team was concerned about the effect these technical constraints might have on their ability to deliver value to the end-user, as P1 describes, "[the end-users] are perhaps dreaming of what they want, without really considering the technical input. It's a bit of a gap there, I noticed" (P1). Similarly, P2 highlights the challenge of "how to get our capabilities matched to those needs – not easy!" (P2). The JSSL is an example of a design project where, while empathy and user needs are paramount, the team's ability to address those needs is bounded by scientific capability.

The JSSL team ultimately understood that agility and responding to user feedback was critical, but this recognition was not without emotional consequences. P6 reflects on a specific instance of this, where the cancellation of Project D in response to user feedback had a negative effect on the team mindset: "it was a setback because there was some emotional scarring there! Having to let [a team member] go, and you feel like you've spent a lot of money" (P6). Confronted with losing team members and financial investment, it was difficult for the JSSL team to reconcile design having a positive role in their project development. However, as the project progressed, the team grew to appreciate design (as described in the response to RQ1) which led to holding on to technical developments with a looser hand:

"You can go down one direction, and something comes up, so you slightly adjust for what you didn't see coming. I think that's just the nature of doing

cutting-edge research or trying to do something really new and novel"
(P3).

As P6 puts it, "it's the balance of being exploratory, moving forward, leading edge
– but also delivering capability. We can do it" (P6). This flexible and relaxed
approach to research and development enabled the JSSL to "bend, not break"
when faced with the unexpected.

4.3.11 Challenge 3: Finding clarity of communication with both design and end-users

In **Section 4.2** design was identified as a means for ensuring effective
communication through clear demonstrations such as prototypes and
visualisations. However, communication still remained a challenge for the JSSL,
especially when it came to using design terminology and clearly engaging with
end-users. P5 discusses the challenge of shifting away from technical
discussions during the Phase 2 collaboration workshop: "our persona was rather
silent… it was hard to keep talking about [our persona] when we were so
focussed on discussing the details of Project B" (P5). It was challenging for the
team to engage with design terminology when faced with the much more intuitive
option of having a technical conversation. P4 describes a similar balancing act
when explaining their approach to pitch preparation: "I'm trying to balance the
startup-style pitch and the academic approach. We don't want to bury [the
audience] in detail" (P4). Here, P4 recognises that when trying to demonstrate
value (as would be the case in a pitch), the kind of communication that they were
used to (academic presentations) would hinder clear communication and "bury
the audience in detail". This was not an isolated problem, with P6 regularly
providing feedback to their colleagues to shift their language. For example, during
a show-and-tell session, P6 asks their colleague, "in terms of the end-user,
without using physics language, what value does this technology give?" Once
again, we see that the natural instinct of the JSSL was to use "physics language",
and that speaking in terms of end-user value was a conscious and challenging
shift.

The JSSL team knew that understanding the language used by their end-user was important, and recognised that there was a significant disconnect. In response to this, it was interesting to observe that in Phase 3, the JSSL started a "military book club", sharing book recommendations that were either set in military contexts, or used a lot of military jargon. However, for this new understanding to be effective, it had to be mutual – a challenge that was at times outside the control of the JSSL team. P3 describes their experience with this issue in their concluding survey:

> "Challenges were arising in the communication or availability of our collaborators at RAAF. As the design thinking approach puts all the focus on the user, it is critical that the user knows the problems very well and is able to clearly and precisely communicate them to us. I see that difficulty as one of the big challenges of the end-user-focussed design thinking approach when applied to innovation, and I don't see an obvious solution." (P3)

The JSSL collaboration was new and unfamiliar for everyone involved, which at times led to a lot of uncertainty from all stakeholders. In this instance, P3 describes that in an already challenging communication context, if there is a lack of availability and clarity from the end-user around their problems, then it is even more difficult to achieve meaningful understanding. P3 also goes on to explain that given the cutting-edge research context of the JSSL, there was the added challenge of working with unfamiliar technology and "unknown unknowns" – where emerging research had the potential to be applied to problems that neither the JSSL nor the end-users were aware of. P3's suggestion to overcome this challenge is establishing a feedback loop of communication with the end-user: "they need to listen to us as much as we listen to them – they look at what we can do, and then come back with new use cases… it's a back and forth" (P3). As explored in **Section 4.2**, design did assist in establishing this type of feedback and communication, revealing otherwise "encoded" insights, here described by P6:

> "This is the story RAAF hasn't heard before. But at the moment, it's in code. Maybe this is where we need a design perspective, because the story is there, but they're not seeing the story" (P6).

In highlighting the importance of mutual understanding and common ground, P10 reflects on experiencing the same issue, except in relation to design language not end-user language:

> "In terms of challenges, I think design still needs to convince the scientific community of its usefulness, and the language they use to communicate with each other needs to be shared. Scientists speak in clear and concrete terms (or they try to), but design sometimes appears to speak more abstractly. So, I think the biggest challenge would be addressing this difference in communication." (P10)

And P16 expresses a similar sentiment: "design must understand the technical aspects of science, and science also needs to understand how design works" (P16). Both of these reflections highlight another layer of communication challenges, where the use of jargon and the gap between "technical" and "abstract" language proved to be a barrier to understanding. P11 attributes this gap to different motivations between design and science:

> "Tension can lie between the scientists wanting to follow the results, based on experiments, and design wanting to ensure the customers' needs are met… The activities of collaborating with the end-users were useful to avoid 'technology push' and discover the specifics of what is needed/useful." (P11)

While tensions are certainly evident, we again observe that common ground was found by adopting a collaborative design approach, leaning into the tension and recognising it as a space to filter out the ultimate shared aim of revealing "what is needed/useful".

4.3.12 Challenge 4: Working within the limits of contractual obligations

The reality of the JSSL collaboration was that they would ultimately be bound by contractual obligations to the sponsor. This was a challenge when it came to integrating design and science, since there were already conflicting drivers of scientific discovery and design exploration, and now contract milestones to consider. P4 describes this conflict:

> "Getting too much into the science in terms of project management could let people get lost. Because science sometimes has a different goal… I

think it's important to understand that the science is different to the actual product delivery, but that's not to say the science is not useful" (P4). Achieving balance was made more challenging given the project context, which was striving for cutting-edge innovation and novelty. P2 explains the layers of complexity, stating that "being ambitious is always the trickiest part about academic research contracts. But this is one where there's an end-user inside. So, I think getting that balance is the hard bit" (P2). The JSSL team was not only trying to reconcile their own technical development with end-user needs, but doing all of this while delivering on contractual milestones. This also meant that there were multiple stakeholders requiring demonstrable value out of the JSSL. P3 discusses the challenge of uncertainty around deliverables and where they could bring the most value when reflecting on the cancellation of Project D:

> "We thought it was something [the sponsors] want, and we followed their timeline exactly, and the milestones, and then it got dropped… You never know. There are external things like funding or whatever, their situation or agenda can change, so you can never be sure – you just try to do your best to convince them what the value is." (P3)

P3 describes how many factors such as funding and external agendas are outside the JSSL's control, and yet they are entirely susceptible to their impacts. If there isn't absolute clarity in the communication of expectations, it leads to disappointment and unmet expectations. As P6 reflects further on Project D, "in my mind, it *was* endorsed. We did what we thought was right" (P6).

Another challenge around working within a contract was the fact that design innovation outcomes are not always predictable from the beginning of a project. This was a challenge in terms of the project sponsors, because they required a definitive contract with specific deliverables in order to fund the JSSL. We reflect on the challenges of agility in section 4.3.2, but setting this aside, design pivots were not easy when the JSSL found themselves otherwise bound: "that's how it's written in the contract, so there's not much room to pivot" (P3). The team was also under "pressure to deliver… we want to see this become a longer contract" (P6) which meant that they hesitated before taking radical steps forward in their ideation process. When faced with new directions of exploration, the team was torn between their scientific pursuit of knowledge, and the security of delivering

on already agreed-upon goals. For example, P2 explains the challenge of problem reframing in Phase 4, which felt like an extremely risky step to take: "in the real world, it's difficult, because you've got promises in contracts and you have to deliver those, and then you've already made the promise for the next year, and then this [problem reframe] is coming in" (P2). The JSSL had already witnessed one project's cancellation and feared the same thing happening again, which at times led to conservative decision making at odds with cutting-edge innovation.

4.3.13 RQ2: Summary

Overall, exploring RQ2 revealed that the design process is not without highs and lows in the journey. Several opportunities were uncovered where design brought unique and significant value to science, specifically:

- Enabling the research translation process
- Uncovering pathways for new capability
- Encouraging creativity and brainstorming
- Facilitating effective communication through clear demonstrations
- Problem exploration
- Deepening end-user understanding and engagement
- Strategic development and forward vision
- Fostering teamwork and collaboration

These opportunities are unique areas where design is able to enrich and enhance science, extending from practical user engagement and problem understanding, all the way through to supporting a research team to collaborate and develop strategy.

The research also revealed multiple challenges:

- Shifting mindsets from the technology-driven and knowledge-focussed nature of science
- Struggling with agility and pivots in a high-end science context
- Finding clarity of communication with both design and end-users
- Working within the limits of contractual obligations

Some of these challenges were unavoidable (e.g. contractual obligations); others artefacts of complex stakeholder engagement (e.g. communication). Despite the challenges, the findings still exemplify the previously described outcome of excitement and embracing of design. This means that the challenges were hurdles but not barriers to the integration of design and science. Awareness of these challenges is valuable in understanding the realities of what a design and science collaboration could look like, and could assist in proactive preparation to mitigate them. As P2 aptly describes: "It's a challenge, but just because nobody has done it doesn't mean we can't!" (P2).

CHAPTER 5: DISCUSSION

5.1 Overview

Following on from the results and findings presented in **Chapter 4**, this chapter will provide a discussion of the results and recommendations for the integration of design practice to support innovation in scientific research projects. An assessment of the limitations of the research will also be presented, followed by suggested avenues for future research.

5.2 Recommendations for design and science in practice

The integration of design is a unique opportunity for innovation in science. This research explores the journey of a scientific team adopting a design process, with **Chapter 4** unpacking the changing perceptions towards design and the opportunities and challenges along the way. An informed and intentional approach to design practice ensures the best chance for success when engaging with scientific teams, capitalising on opportunities, mitigating challenges, and supporting the overall journey towards embracing design. There are three intended audiences for these recommendations:

- Design practitioners working with scientists and seeking to understand how their design practice could be most effective
- Scientists interested in adopting design and exploring where design can bring the most value to their projects
- Researchers working at the intersection of design and science, providing an example of embedded design research and outlining a framework that could be explored in further research

This section will provide five recommendations to support design and science practice, which are summarised below in **Table 5.1**. The recommendations emerged by synthesising the findings in **Chapter 4**. Specifically, all five recommendations are supported by the overall perception journey described in **Section 4.2**, as they suggest behaviours that alleviate scepticism towards design, highlight its positive value, and mitigate moments of tension that lead to

negative perceptions. The recommendations also relate to the findings of **Section 4.3**, with the specific opportunities and challenges that contributed to each recommendation listed in **Table 5.1**.

Table 5.1: Summary of recommendations for design and science in practice

Recommendation	Description	Relevant opportunities and challenges (RQ2)
Embracing design as a mindset	Focussing on key design principles such as user centricity, co-design, problem exploration, and creative thinking as opposed to forcing a fit into a process model	4.3.1 4.3.3 4.3.5 4.3.6 4.3.9
Drawing parallels and contrasts between design and science	Highlighting the similarities between design and science in terms of rigorous methodology, while also stressing areas where design provides a unique value proposition which science otherwise lacks	4.3.1 4.3.2 4.3.7 4.3.9 4.3.11
Recognising systemic challenges and barriers	Consistently remaining empathetic to the oftentimes unavoidable barriers to innovation due to the systems in place in scientific practice, navigating challenges with strategic flexibility	4.3.4 4.3.7 4.3.10 4.3.12
Adopting a team-centred approach	Extending the human-centred design approach to the scientific team, fostering team cohesion and confidence through reflective practice	4.3.4 4.3.6 4.3.7 4.3.8 4.3.11
Empowerment through experiential learning	Adopting design in both practice and strategy to equip scientific teams to learn design for themselves and empower them to succeed	4.3.1 4.3.3 4.3.7 4.3.8 4.3.9 4.3.10

5.2.1 Recommendation 1: Embracing design as a mindset

The first recommendation is the adoption of design as a mindset. There were three key mindsets which were revealed to be significant for design and science – user-centricity, problem exploration, and creativity. Design methodology was found to enable the flourishing of these mindsets, but specific methods proved less significant than the mindsets themselves. This is supported by Zafeirakopoulos and van der Bijl-Brouwer (2018, p. 54) who describe the significance of mindset in the transdisciplinary learning process, and that

flexibility and iteration are key to creating new ways of working in rigid disciplinary contexts. Similarly, Björklund (2019, p. 27) describes the way design principles and goals are more important than stepwise formulae:

> "Whichever process model you choose, it should be considered as a guideline and a source for shared vocabulary that smooths collaboration, rather than a depiction of reality. In practice, the design process is "messy", with feedback loops between different phases and some customization for each problem."

This flexibility was especially necessary within the context of the JSSL project, due to the inevitable impact of unpredictable scientific research and development timelines. It quickly became clear that forcing the JSSL project into a specific design process model would be impractical. Instead, the goal became to lean into the "mess", prioritising mindsets over models.

A scientific project summons the true breadth of what design practice means – as Dorst (2008, p. 10) describes, the "meta-activities" of a designer are a "major and crucial part of design practice". This was even recognised by one of the participants, who reflected at the end of the project:

> "Usually when you hear 'design', you think about the looks of a device or something, but in this sense, design is much broader, because it's also the thinking process behind." (P3)

It became clear that fostering a designerly mindset was of greater value than any one methodology. Hassi and Laakso (2011) propose such a flexible design process that centres on practices, cognitive approaches, and mindsets over methods. Similarly, Howard, Senova and Melles (2015) highlight the significance of design mindsets, suggesting that it would be reductionist to only consider design as a way of doing. They propose design as a "way of life" and a "way of work", permeating both personal and professional practice.

The first significant mindset that emerged was user-centricity. In contrast to a traditional design project, a scientific project adds an extra layer of complexity by bringing a third party (the scientific team / technology holders) between the designer and the end-user. Troxler (2022) describes the significance of design as a boundary object to coordinate multiple perspectives into new directions. In a scientific project, design holds a significant translatory role, creating common

ground between the two expert fields of technical experts and user experts. Such a complex collaboration only succeeds with close engagement through co-design. In light of these insights, the recommendation for practice is for practitioners to position design (methods, activities, and designers themselves) as a boundary object and facilitate frequent co-design sessions. While co-design is a common practice across many design projects, a scientific project demands even greater emphasis on co-design to ensure such diverse perspectives work in harmony instead of conflict.

Co-design also supports the second mindset of problem exploration, as open channels for communicating feedback allow both problem and solution to be refined in response to input from the users and the scientific team. This helps to mitigate the costly risks involved in deep technology development and direct the technology as it evolves, instead of retrofit existing science into use cases. The intricacies of this process meant that communication was both a challenge to overcome, and an opportunity to embrace. Initially, communication was a challenge for the scientific team, due to the steep curve of learning the language of both the user and design. This at times led to conflict and miscommunication when the same word meant multiple things across the three domains. However, this was alleviated over time as co-design led to greater familiarity and appreciation for the variety of terminology used across all stakeholders. A key recommendation for design practitioners, especially early in a scientific project, is being intentional around explicitly explaining any design jargon and ensuring all participants are on the same page. This also creates space for the team to derive their own shared language and meanings over time.

The third important mindset was encouraging creativity and thinking outside-the-box. Cross (2004) describes how designs frame their problems in a way that is conducive to new concepts. This is especially significant in a scientific context since most scientific problems would not traditionally lead to divergent thinking, rather, converging on a solution. In this instance, methodology supported the creative mindset, where design activities that intentionally pushed the team outside their comfort zone (e.g., creating personas, writing scenarios, developing pitches) facilitated more exploratory pathways for the science. Cross (2004)

continues to describe the way creativity arises in moments of conflict, especially in the tension between problem space and the end-user's goals for a solution. This was an uncomfortable tension for the JSSL, who were often tempted to jump to technical solutions whenever confronted with user feedback. The role of design in this space was to slow down this jump and instead encourage exploration, questioning, and reframing in the problem space. This led to more creative ideas as well as technical development that was more effective in addressing the user requirements. A recommendation to help facilitate this mindset is for practitioners to make clear distinctions between problem exploration and solution exploration phases, preventing the instinctual jump to solutions that is often the case in scientific projects. It is also important to reassure participants throughout the design journey, but most importantly during early divergent thinking when it can feel as though there is little progress being made and hence an urgency to jump to solutions arises. This can be done by creating working environments that are conducive to creativity, such as open brainstorming sessions and using constructive language such as the "Yes, and…" approach.

Returning to the three audiences to which these recommendations are directed, design practitioners working with scientists are encouraged to emphasise design ways of thinking or "knowing" (Cross, 1982), and remain flexible in terms of which specific design methods are adopted to achieve this thinking. Scientists are encouraged to approach design in a similar manner, as disseminating design as a mindset throughout team precedes mastering design as a practice. Finally, design researchers should consider the nature of a design intervention and what activities, conversations, and procedures should be in place to best facilitate design as a mindset, or potentially compare and contrast different approaches.

5.2.2 Recommendation 2: Drawing parallels and contrasts between design and science

One of the key aspects which contributed to the embracing of design within the JSSL was demonstrating parallels between the design process and the scientific process. Elements of the design process that were familiar to science assisted in the team's confidence in the validity of design – for example, the posing of and

responding to hypotheses, exploring problems experimentally, controlling variables (e.g., with user testing), and so on. These parallels positioned design as a credible strategy to enhance and support scientific endeavours, as opposed to a trivial distraction that felt too foreign to entertain. Additionally, this atmosphere had an unexpected positive effect on the design process from the facilitation side – being constantly "under the microscope" enforced accountability to a high level of rigour, and invited regular reflection to ensure each activity was intentional in its purpose. Practitioners and scientists adopting design are recommended to draw attention to the similarities between design and science by highlighting the scientifically rigorous nature of design methods, as this leads to a greater appreciation and adoption of design process.

The idea of drawing parallels extended beyond practice and into the everyday workings of the JSSL. A shift was observed from purely technical conversations, to more exploratory storytelling and empathetic language, especially concerning their end-users. This assisted the JSSL team in grounding their scientific work in the real world – it was no longer about building "x" piece of technology for "y" function, but rather, supporting a real user going through a real experience. Diamond (2018, p. 1854) suggests that there is value in storytelling in science, where researchers "translate their discoveries into narratives and metaphors". Further, the experience of storytelling and sharing personal experiences helps facilitate the necessary exploratory environment that a design process demands (Hepburn, 2022). The emergent recommendation is that sharing stories between participants can not only support the communication of scientific discoveries, but also facilitate greater empathy with users and each other.

Conversely, it was also observed that drawing *contrasts* between design and science was equally valuable. Whereas finding parallels allowed for establishing common ground and lowering resistance to adopting design, finding contrasts highlighted the unique value proposition brought by design that was notably lacking from science. This is supported by Zafeirakopoulos and van der Bijl-Brouwer (2018) who describe the role of transdisciplinary learning in inviting reflection and recognition of the limitations of siloed work. The core mindset to consider here was establishing an atmosphere of mutual respect. This involved

recognising areas where technical expertise needed to be the key focus, while also making clear the situations where design took the lead. For example, there were some instances where project meetings leaned almost entirely technical, but it was important to respect this as a necessity if the team were to reach the level of cutting-edge science that was being demanded of them. In other instances, when representatives from RAAF were present, although it was tempting for the team to dominate the conversation with technical demonstrations, design took a more leading role in ensuring the conversations were centred around user needs. Shifting between modes of thought is critical to the production of creative scientific solutions, as described by Pringle *et al.* (2016) – making space for both analytical thinking during technical conversations, then shifting to exploratory thinking when discovering new solutions. Further, Mesa, Tan and Ranscombe (2022, p. 2349) describe how design process adds a "lens of realism" to technical development, making it easier to imagine potential applications outside the laboratory. Therefore, practitioners are encouraged to explicate the unique value offering presented by design throughout a project. This can be done through giving case study examples where design has made a radical difference to the trajectory of the solution, or in more ad-hoc instances such as framing each design method in terms of the value provided. This ensures more streamlined shifting modes of thought, where there is still capacity for technical development, but design methods are fully embraced. Such respectful interplay ensures that design was still perceived to be a lucrative addition to a scientific project, without a counterproductive implication that science needs "fixing" and design "comes to the rescue". For researchers exploring embedded design practice, this is a unique nuance which can have an impact on the value provided by design, as well as the adoption journey of participants.

There has been extensive debate in literature arguing the similarities and differences of design, with some suggesting that they are completely distinct processes (Cross, Naughton and Walker, 1981; Willem, 1990; Galle and Kroes, 2014) and others that they share inherently the same cognitive processes (Farrell and Hooker, 2013, 2015; Mejía *et al.*, 2018). However, the findings of this research indicate that there is no "right" or "wrong" answer here, but that both the parallels *and* the contrasts between design and science bring value in

complementary fashion. These findings have framed the recommendation that drawing both parallels *and* contrasts between design and science highlights the unique offering provided to science, while also lowering the barrier to adoption.

5.2.3 Recommendation 3: Recognising systemic challenges and barriers

The reality of a complex project with multiple stakeholders is that there will almost indefinitely be systems, processes, and guidelines in place that can become barriers to innovation. In the case of the JSSL project, there was often conflict between following contractual obligations, the resourcing limitations of research and development, and the changing requirements presented by the end-user. For example, the project contract included certain deadlines and deliverables, which were impossible to predict early on in the design process. Another example is whenever the design activities or user feedback led to problem reframing and a new trajectory for technical development – this resulted in costly changes to equipment, infrastructure, and personnel. The team found it understandably difficult to pivot and be agile in an environment where there is always a high risk involved and a certain critical mass of technical development must be built. Randhawa *et al.* (2021, p. 34) describes the importance of adapting the design process based on changing objectives with what they call "strategic flexibility". This was critical in the JSSL project, as many obstacles were encountered. It was important to stay receptive and flexible in response to unexpected challenges, and to focus on the desired end goal and key design principles achieved, more than the orthodoxy of the process followed. This flexibility is an important recommendation for practice, as it ensures "progress over perfection" – taking the next best step at every moment is more important than following a strict plan.

To add further complexity, there exist cultural barriers towards innovation in science, as one participant reflects:

> "Unfortunately, the truth is that there is very little chance you will change current scientists. We are so buried in our ways it probably will not be accepted as much. We are also stuck in a career trajectory that does not allow us to change, and if we stop publishing, we don't have a job tomorrow." (P2)

The frustration here is quite aptly illustrated – it is not always stubbornness that leads to a resistance to change, rather, a systemic issue that prevents deviation from the norm. This is explored by Gonera and Pabst (2019, p. 110) who describe a "lower motivation to engage in creative and unknown / uncomfortable activities" due to the success factors of publications, funding, and patents seeming incongruent with design. P2 suggests a need to "expose to-be scientists (students) to the methods and skills [of design] and understand the value" – indeed, this suggestion could be a significant factor in breaking down these barriers by challenging them early in a scientific career journey. The importance of early and frequent engagement with design was proven throughout the JSSL. Even though the team were predominantly mid-career professionals and researchers, there was significance in having design step in at the very start of the JSSL collaboration. Despite holding an initially sceptical stance towards design, by the end of the project, many of the JSSL participants reflected positively on some of the very first design activities, such as the formation of personas. It became clear that after reflecting on the involvement of design over time, the was team able to let go of preconceptions and barriers that prevented embracing it.

Mesa, Tan and Ranscombe (2022, p. 2350) describe a common struggle faced by scientists:

> "Even if scientists working in applied research may have a general idea of how their technology could be applied, they struggle to integrate their research findings into a product that could work outside the laboratory. Rather than exploring applications for the scientist's technology, the designer's role, in our case study, was better suited at scoping out feasible prototypes that would demonstrate the viability of the scientist's technology to work in the context [they] had envisioned."

This struggle is a contextual one – for scientists whose experience lies almost solely within a lab environment, it is challenging to think outside this context, and hence there is the suggestion use design as a tool to support demonstrating viability instead of exploring applications (Mesa, Tan and Ranscombe, 2022). The JSSL project revealed that this approach was indeed valuable, but there emerged an additional recommendation of ensuring that the demonstration centres on

desirability along with viability. The demonstration workshop in Phase 5 of the JSSL project was a valuable opportunity for the team to showcase the technical viability of their prototypes. However, the real impact of the workshop was in connecting with the RAAF end-users in terms of applying the technology within a military context, and the direct value it would provide to them. The JSSL revealed that design plays a significant role in pushing contextual barriers by challenging scientists to position their technology within a user-centred frame of mind.

In response to the systemic barriers present in scientific projects, the recommendation for design practice is to adopt a deeply empathetic approach. Design centres empathy with the end-user as critical, but this research suggests that in the challenging context of a scientific project, empathy with the scientific team is just as, if not more, critical to success. Design is well positioned for this role – as van der Bijl-Brouwer and Dorst (2013, p. 18) describe, "strategic design innovation is becoming more human centric". Wouters (2022) supports this by describing the importance of empathy in participatory projects. This involves recognising the complex and sometimes unavoidable challenges that may pose barriers to participants fully leaning into the design process. Establishing an atmosphere of psychological safety and the freedom to experiment allows each participant to undergo their own journey of acceptance, while also experiencing the hard process of breaking down assumptions and cultural barriers. An optimistic recommendation is for design representatives to, whenever possible, strive to be involved in strategic planning or contractual meetings for a scientific project. In the case of the JSSL, this could have potentially provided the opportunity to explain the need for flexible deadlines and deliverables, and could help reduce the pressure on scientific teams to work within strict constraints. A further recommendation for design and science researchers would be to recognise that design and science both operate in complex contexts that cannot be separated from the work and must therefore be carefully considered.

5.2.4   Recommendation 4: Adopting a team-centred approach

Throughout the JSSL project, there were several occasions that revealed the impact of team dynamics. One example was following the cancellation of Project D at the end of Phase 2. The team was understandably shaken, which led to the

decision to focus Phase 3 on consolidating team vision. The journey reflections activity of Phase 3 reminded the team of their successes and their shared purpose, and allowed all participants to express their opinions in a supportive environment regardless of hierarchy or role. This was an example of "procedural leadership that gives participants confidence and converts conflicts into constructive interactions" (Mejía, Malina and Roldán, 2017, p. 684). The result was conflict turning into an opportunity for connection instead of contention. Regularly looking backwards (to celebrate and learn from the past) and forwards (to centre on shared goals and vision) in a design and science project ensures that a diverse team remains unified. Liedtka (2014, p. 44) describes how design thinking as a process lends itself to better teamwork and the celebration of diversity by "leveraging differences in positive ways". In a design and science collaboration, there are multiple perspectives at play – both in terms of stakeholder groups (scientists, designer(s), end-users) but also within groups (e.g., engineers, students, project managers, researchers within a scientific team). Such diverse participants will almost definitely have different perspectives, which can lead to emotionally-charged disagreements (Rekonen, 2017). These disagreements are not always avoidable, but are most effectively managed in a supportive team atmosphere. The main recommendation for practitioners is to respond quickly to obstacles along the design journey by facilitating reflective sessions, looking back on the learnings of the past, and looking forward to the goals of the future.

Aside from moments of conflict, the team was undergoing the stressful experience of participating in a high-stakes project while learning about design for the first time. This is where embedded design practice proved extremely valuable. Having a designer as part of the team (as opposed to an external consultant) allowed for building trust and rapport, which are of paramount importance when navigating an unfamiliar design context. This meant that core design principles such as learning from failure and open communication were much easier to embrace in the JSSL, because there was an atmosphere of psychological safety. Hepburn (2022, p. 305) describes design activities as "scaffolding to support participants to share, understand and most importantly, value the skills and knowledge of other participants engaged" – by engaging with

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a design process, the team grows in their appreciation of not only design, but each other, streamlining the adoption journey.

Another valuable tool to build team cohesion was extending elements of reflective practice to the scientific team. While reflective practice was used as a data collection method in this study, it naturally flowed into the way the JSSL worked as a team through regular feedback sessions and check-ins. Some participants even noted that the data collection interviews were a valuable opportunity to self-reflect on their own learnings and scientific process – an ad-hoc "think aloud" approach for unpacking psychological insights (Kulkurani and Simon, 1988). From a research perspective, it has been argued that including participants in the analysis process is central to making good sense of findings (Johnson *et al.,* 2017b) – reflective practice provides an opportunity for such inclusion. Thus, there emerges a two-fold recommendation for both practitioners and researchers – first of all, to be as embedded as possible within the team to establish rapport and psychological safety, but also to invite participants into reflective practice, creating space for processing their own design adoption journey. This is supported by Polk's (2015) description of transdisciplinary co-production, that suggests reflexivity supports "common frames for discussion". This informs a recommendation for researchers to not only use reflective practice themselves as a qualitative data collection method, but to extend this practice to their participants to gain richer and more diverse insights. While looking "forwards and backwards" supported team cohesion, looking "inwards and outwards" through reflective practice supported team confidence.

5.2.5 Recommendation 5: Empowerment through experiential learning

One of the most imperative recommendations revealed through the JSSL project is the importance of experiential learning. **Section 4.2** explored the transition that the JSSL team experienced, from an initially sceptical perception towards design, through to embracing design with excitement. This initial scepticism can be attributed to the strongly evidence-based and experimental mindsets of scientific practice, as Kosso (2011, p. 3) describes:

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"Refusing the authority of evidence and logic, either in the form of believing without evidence or believing in spite of contrary evidence, is not just turning away from science; it is turning away from good sense."

At the beginning of the JSSL project, design was a foreign concept to the scientific team, unproven and without evidence. This scepticism remained even after presenting the team with examples of previously successful design projects, as they struggled to translate case studies into their own scientific context. It was only through experiencing design for themselves that a shift in perceptions was observed. By the end of the engagement, it was found that team members who had higher and/or longer involvement in design activities (e.g., project leaders or team members who were present for the duration of the project) had a more positive perception towards design. Hepburn (2022) describes that design appreciation evolves through the hands-on process of learning-by-doing. The JSSL project revealed that it was only through first-hand experience of design at work that the team could accept and embrace design as a valuable offering. Further, a previous Design Innovation Catalyst study (Price, Wrigley, and Matthews, 2018) affirms the need for design to be practically demonstrated and experienced in order for its value to be understood by the team, even in the presence of an embedded designer. Therefore, a significant recommendation is to ensure that design projects are conducted in a participatory fashion – scientific teams need to have ownership of their design work and be completely involved in the process in order for the value of design to be truly appreciated. Scientists adopting design for the first time are encouraged to focus more on learning-by-doing, participating in hands-on design learning activities, rather than focussing too deeply on the intellectual arguments for design.

The underlying and perhaps most significant recommendation that is demonstrated by this process is the importance of not only experiential learning, but *empowerment.* This was not an example of a project where design came to "save the day", operating behind closed doors and producing a finished solution without any revelation of the process. Similar to how the "lone genius" model of science has proven to be outdated and insufficient for innovation, such an approach to design work would be similarly ineffective (Giacomin, 2014; Kolko, 2010; Simpson and Powell, 1999). It also would have been completely against

the evidence-based principles of science, and would have likely resulted in an even higher scepticism or even disdain towards design (Kosso, 2011). Rather, the JSSL project put design work into the hands of the scientists and invited them to "learn by doing". Maula *et al.* (2019, p. 53) describe a role for professional designers in providing "support and structures for actually incorporating design thinking processes and tools into day-to-day work". The recommendation here is to frame the designer as a facilitator of learning for the scientific team, where there is still reliance on the expertise, insight, and unique value brought by an embedded designer, but the designer invites and equips those around them to adopt design as a way of working. There is also a recommendation for researchers in design and science to explore the elements of psychology and team dynamics that either enable or hinder such an experiential learning environment.

The JSSL project has crystalised a recommendation for design in scientific teams that centres on empowerment. The designer facilitates design activities, but design ownership remains in the hands of the participants, allowing for a sense of responsibility, motivation, and ultimately, accomplishment. Trust and psychological safety are critical considerations for the embedded designer, with the intention to transfer knowledge and equip participants with methods and tools. The design process adopted does not necessarily follow a strict model, rather focusses on key mindsets and methodologies, with reflective practice as a support tool to inform the next best step. The design solutions that emerge are harmonious with technical developments, since the design and scientific research processes happen concurrently and are intertwined. By focussing on empowerment through experiential learning, design and science work in effective cooperation to catalyse innovation.

5.2.6 Summary

This research uncovered five key recommendations for design and science, aiming to support the work of designers working with scientific teams, scientists interested in design, and future researchers. The JSSL project provides an example of a process for facilitating design within a scientific context, all while supporting the team through a holistic learning journey. Instead of following a

strict design process model (e.g., double diamond or Stanford d-school process), the JSSL project centred on instilling key design principles and mindsets (see **Section 5.2.1**), while also integrating more team-focussed and strategic activities (see **Section 5.2.4**). This balance between practical and strategic elements supported the team to truly experience the difference that design could make to their scientific development, while also providing the team with support throughout the challenges along the way. In the spirit of this recommendation, the JSSL project is certainly not positioned as the only way to conduct a successful design and science project, however, it is an example of a design journey with an emphasis on both practice and strategy. The emphasis on either side fluctuates throughout the project based on the needs of the team and the stage of development. It is also important for future practitioners to recognise the potential for a long journey towards design adoption, with a positive perception towards design only emerging as a result of experiencing the process itself. **Table 5.2** below documents this journey by describing how design played both a practical and strategic role in the JSSL project.

Table 5.2: The practical and strategic role of design in the JSSL project

Project Phase		Phase 1: Understanding personas and scenarios	Phase 2: Ideation and collaboration workshop	Phase 3: Journey reflections	Phase 4: Understanding prototyping	Phase 5: Problem reframing	Phase 6: Demonstration and feedback workshop	Phase 7: Wrap-up
Activities and design methods employed		Creating user profiles, scenarios, and personas; Discussing user engagement through a focus group	Using personas and scenarios in a co-design workshop; Brainstorming ideas alongside end-users	Using reflective practice to create a journey map, looking to the past and future, and mapping highlights and setbacks	Learning about prototyping through an introductory workshop; developing low-fidelity prototypes	Reframing the problems in response to end-user feedback; Co-design sessions to refine project plans	Developing higher-fidelity prototypes; Preparing pitches and product demonstrations	Using reflective practice to evaluate the overall journey
Design as practice		Using design principles and methods to demonstrate user-centricity	Facilitating effective brainstorming through co-design sessions and ideation prompts	Instilling reflective practice as commonplace in the team	Demonstrating the value of prototyping solutions through sketches, storyboards, low-fidelity models, etc.	Checking in with user feedback and pivoting where necessary	Demonstrating prototypes, facilitating end-user feedback on the solutions, and teaching effective pitching techniques	Equipping the team to continue design work independently, beyond the engagement
Design as strategy		Allowing the team to learn about design methods through storytelling, metaphors, and analogies thus softening the impact of a new way of working	Streamlining the communication between disparate stakeholder groups	Supporting the team through difficult transitions, consolidating goals and vision	Introducing new terminology to support effective communication	Encouraging the team to embrace a "fail fast, succeed sooner" mindset	Celebrating successful development of solutions; supporting the team to communicate their ideas effectively	Supporting the team in their personal reflections across the whole project, and processing what design means for them
Perceptions towards design	Scepticism	■						
	Uncertainty	■		■		■		
	Pride		■	■				
	Optimism		■		■	■	■	
	Desire to learn							■
	Excitement							■
Recommendations		Embracing design as a mindset Drawing parallels and contrasts between design and science Recognising systemic challenges and barriers Adopting a team-centred approach Empowerment through experiential learning						

As seen from the example of the JSSL project outlined above in **Table 5.2**, design plays a significant role in both the practice and strategy of a scientific team. The adoption process involves a journey from initial scepticism and uncertainty, through to an excitement and desire to learn more, and the role that design plays at various points in that journey encourages positive forward momentum. Such a design project is facilitated by an embedded designer, in this case, a Design Innovation Catalyst (Wrigley, 2016). The embedded designer operates under the five key recommendations to support the adoption journey, and ultimately empower the scientific team to design for themselves. In this way, design acts as a catalyst for innovation in science.

5.3 Limitations of the research

This research was conducted with careful consideration and planning. However, as with any body of research, there are indeed limitations to the study.

First and foremost, it is important to recognise the breadth and diversity to be found within design and science projects, and indeed the diversity within scientific disciplines. The recommendations presented in **Section 5.2** were made after a deliberate and detailed study of a single case, which has been demonstrated as a scientifically rigorous methodology (Horner *et al.*, 2005). However, no two cases (or teams, or projects) are the same. This study provides a valuable starting point for understanding design practice within the scientific disciplines of physics, photonics, and smart sensing in a university context, but it cannot completely encompass the opportunities and challenges found in every unique project, and future researchers should remain mindful and receptive to new insights.

There is also the limitation of duration. A nine-month engagement was chosen for this study in order to understand the journey of embracing design in a scientific team, with the study ending after a key demonstration and prototype launch for the JSSL. The time frame of nine months was chosen intentionally to ensure feasibility for data analysis, while still allowing for longitudinal understanding of the journey. This reveals a limitation of the study in understanding in examining the perceptions, opportunities, and challenges beyond this point in time, after design was proven to

provide value in putting together the demonstrations. Potentially, after the hurdle of simply accepting design was overcome, more detailed and nuanced opportunities for design and science would have been revealed as the team grew more confident in their design practice.

Additionally, due to the qualitative and highly interpersonal nature of the recommendations, the findings are ultimately susceptible to the interpretations and opinions of the people involved. Indeed, as Björklund *et al.* (2017, p. 15) describe:

> "You will be hard-pressed to find anyone opposed to development and improvement in principle. It may, however, be equally hard to find people who agree on how we might go about pursuing these goals."

As discussed in the recommendations, one role of the designer is to streamline the adoption experience and establish common ground, but ultimately this is not a guarantee.

Another limitation in this study is the nature of my own role as the researcher. First of all, having a science undergraduate background was valuable in establishing common ground with the JSSL and understanding a certain level of technical detail, however this meant that in starting this research I was relatively new to design (compared to, say, an industrial design student who transitioned into the design innovation field). This could potentially be a limitation due to inexperience as a designer, however I strove to mitigate this through detailed research and literature review prior to commencing the case study, as well as drawing on the support and expertise of my supervisors. I also sought to consider my unique background as a positive, allowing me to have a completely open mind as to what the project could look like, remaining flexible and learning throughout the journey.

That being said, there are still challenges and limitations that emerge from the nature of the practice that was adopted. Taking the dual role of design facilitator and researcher allowed for positioning as a collaborator instead of outsider, providing access to a unique and rich depth of insights. However, this posed the challenge of balancing design activities and researcher activities while striving to give due attention to both, as van der Lugt (2022, p. 134) describes:

"In research-through-design, the design team members also participate in the research as co-researchers, who, during the design process, are sensitive to gathering information about the research question…it is challenging to maintain both the creative flow of the process and at the same time record the reflections."

Such a process ultimately relied on my own reflective practice and decision making, revealing the potential limitation of bias in a highly participatory context. Nonetheless, this approach was critical in establishing trust with the team and ensuring the design interventions were effective.

Some practical and systemic barriers emerged throughout the project with little that could be done to avoid them. First of all, while the JSSL participants were very diverse in terms of age and disciplinary background within STEM, there was a significant gender imbalance, with many more male than female participants. Since I did not choose the composition of the JSSL, this could not be mitigated in the participant set without excluding a significant proportion of the team. The data analysis was conducted using anonymised data wherein any identifying information such as gender was not taken into consideration, however we cannot ignore the potential limitations of gender bias.

Another limitation was in the constantly evolving nature of the JSSL team, with participants joining part-way through the project, others leaving before its completion, and all having various levels of engagement. This was mitigated by consistently examining participant input as a whole data set, to ensure that the findings did not rely on any single perspective. However, an ideal project would have had consistent participant involvement throughout.

Complex stakeholder relationships played a significant role – the actors within the project were not just the JSSL and myself, but also RAAF as both end-user and project sponsor. The role of RAAF as project sponsor meant that a certain level of rigidity and obligation was added to the relationship. The JSSL was not only engaging with RAAF as their end-user, but also as the ones who decide whether or not the contract and funding goes ahead. This very likely affected the decisions made by the JSSL team, as well as determining what workshops and end-user

engagements were allowed to go ahead. Randhawa *et al.* (2021, p. 34) describe a necessary "strategic flexibility" that is required for design projects, stressing the importance of adapting the design process based on changing objectives and influences. Indeed, if the design process were to fall apart in the face of any of the above obstacles, then it would not be suitable for the rapidly changing context of high-end science.

5.4 Recommendations for future research

This study details one area within a potentially unlimited scope of research exploring the interplay of design and science. There is still much to explore, both in striving to address some of the limitations expressed in **Section 5.3**, and in building upon the findings of this research.

An area of study that I would have loved to explore (had there been more scope and time) is the perspective of RAAF as the end-user and sponsor throughout this project. Similar to the challenging context of high-end science, the military also poses unique challenges and understanding the role of design in this space would be critical in defence science projects.

Extending the scale of the JSSL project could involve bringing on a larger team of designers, who could then feasibly track the project from its inception through to deploying solutions to RAAF. As discussed in the limitations, this was not practical for this study, but could provide a very rich and nuanced analysis, and bring more diverse design perspectives to the table, increasing the calibre of design practice.

Another recommendation for future research is in understanding more depth in the experience of the scientific team. This study used qualitative data methods to understand the perspectives of different participants, but an interesting avenue could be allowing the scientific team to each complete their own reflective journals, adding a layer of authenticity, and comparing the insights that are expressed publicly versus privately. This would also likely relate to an interesting examination of the effect of different roles, and how design is perceived between students, to team leaders, to engineers, and so on.

Along these lines, it would also be valuable to examine a more quantitative element to the study – how does the *science itself* evolve in response to design? This is challenging to complete rigorously without having a controlled variable (i.e., two concurrent projects, one where design is employed and one without) but could be a significant area of exploration. This also would likely assist in demonstrating the value of design for scientific projects to STEM professionals, who may be more receptive to quantitative research.

Finally, taking a broader lens could involve a comparative study in understanding design (and innovation more broadly) in different scientific contexts. This could involve comparing and contrasting pure academia, academia-industry partnerships (such as JSSL), technology parks, startup incubators, and so on. This would provide interesting learnings in terms of the effect of the project context and objectives on design best practice.

CHAPTER 6: CONCLUSION

6.1 Overview

To conclude the thesis, this chapter will provide a summary of the contributions that emerged through the research, followed by the personal reflections of the candidate, from the perspective of both an embedded designer and a doctoral researcher.

6.2 Summary of contributions

This research was motivated by the growing urgency for scientific innovation over invention. Specifically, the "valley of death" (Markham, 2002) presents a real threat to scientific research where there is often a disconnect between the production of new knowledge and the delivery of real-world impact. Design has been implemented and proven to be a valuable strategy to achieve innovative outcomes, and its application to science is timely in the face of the imminent "molecular age" (Linstone, 2011). Choi and Pak (2006) describe a shift beyond multidisciplinarity towards transdisciplinarity in science, where the cross-pollination of diverse perspectives is essential to tackle the complex challenges of the future. It is in the face of these challenges that we see the call for design.

This thesis began by establishing a literature foundation for the future of design and science. First, there was an exploration of the philosophies of science, in order to understand the deep-rooted mindsets and methodologies that are central to the way scientists work. It was found that there is a prevalent valuation of the pursuit of knowledge and "purist" approaches to science that resist deviation from the scientific method. However, the literature proceeded to reveal that when it comes to innovation, this approach quickly disintegrates in favour of multi- and transdisciplinary practice. This began as the blurring of boundaries between scientific disciplines themselves, but soon evolved to include engineering, humanities, and other more diverse fields. An opportunity for design was thus presented – design innovation was demonstrated to be a proven approach for transformation and impact in multiple domains. The principles and practices of design innovation were explored, highlighting a significant case for implementing design innovation in scientific research.

This revealed a literature gap and research opportunity for this study in exploring the adoption of design within a scientific team, in order to understand the value brought to and perceived by scientists. It was decided that a qualitative case study (Yin, 1981) approach would be suitable to explore this opportunity, as it allowed for the rigorous study of change over time, enabled richer insights through embedded practice, and supported the provision of future recommendations. During this study, the researcher was embedded within a scientific team as a Design Innovation Catalyst (Wrigley, 2016), facilitating design interventions while simultaneously conducting research into the engagement between design and science.

The aim of this research was to investigate how design can be leveraged in scientific projects as a catalyst for innovation. This was broken down into three research objectives to act as drivers towards the aim:
1. Facilitate a design innovation engagement within a scientific project
2. Evaluate the engagement through a scientific perspective
3. Provide a recommendation of design practice for innovation in science

In order to achieve these objectives, two research questions were presented and addressed. The research questions that form the foundation of this thesis are presented in **Table 6.1** below, along with a summary of the respective contributions to knowledge.

Table 6.1: Research questions and associated findings

Research Question	Contributions to Knowledge
1. How is design perceived by scientists engaged in a scientific project?	• Demonstrated that the journey towards design adoption is complex and that fully embracing design can take time • Highlighted the significance of empowerment and experiential learning as a critical factor in alleviating scepticism and ensuring design is accepted within a team • Established the importance of empathy and psychological safety as critical to the design adoption journey in the face of challenging systemic and cultural barriers in science • Provided an example process for future embedded design practitioners to follow for scientific projects seeking to adopt design to deliver technical solutions that meet end-user needs • Identified key moments of tension that are experienced in design and science projects as areas on which future practitioners and researchers should focus

2. What opportunities and challenges are afforded by the application of design in a scientific project?	• Provided suggested workshop plans and design methods that can be used to generate opportunities and respond to challenges • Demonstrated key design principles that play a significant role in fostering innovation in scientific projects, such as user-centricity, problem exploration, co-creation, and creativity • Recommended the positioning of a design as a mindset more than a methodology – the process is not as important as the principles • Established the importance of a team-centric approach to design practice to ensure opportunities are captured and challenges are mitigated • Demonstrated that design can support strategic development and forward vision in scientific projects with complex stakeholder relationships • Determined that highlighting the parallels (e.g., rigour, experimental approach) and contrasts (e.g., qualitative methods, user-centricity, etc.) between design and science is important to showcase how both fields can complement each other in a project • Revealed that communication is both an opportunity and a challenge in a design and science project, and that design can support effective communication between disciplines and with end-users, but that common ground and shared terminology must be established first

Table 6.1 highlights how the research objectives have been achieved. The first research objective was achieved through the embedded design practice, as it involved facilitating design innovation activities and interventions within a scientific team over a nine-month period of time. The second research objective was addressed through RQ1, which closely examined how a design engagement is perceived from the perspective of the scientific team experiencing it. Finally, the third research objective was addressed through the response to RQ2 as it revealed the opportunities and challenges of applying design within a scientific context. These informed the recommendations for future practice (see **Section 5.2**) that provide a grounded and holistic approach to implementing design in scientific projects.

6.3 Implications

The main implications of this study lie in the recommendations for design and science practice, presented in **Chapter 5**. However, as a research work, there are also implications for the respective fields of design and science, and indeed their

intersection. As described in **Section 5.2**, there are implications for three intended audiences – design practitioners working with scientists, scientists interested in adopting design, and researchers working at the intersection of design and science. This section will detail these implications in terms of research and practice.

This research provides a framework and example for the study of design and how it is perceived in its context as a phenomenological study. A team's journey of adopting design is a complex one, but this study demonstrated the suitability of a case study approach using mixed qualitative methods and affirms the social constructivist positioning. The methods selected were suitable for ascertaining depth of insights ranging from explicit to latent, and the qualitative approach allowed for nuanced perspectives to emerge. Notably, the significance of reflective practice was highlighted as it not only formed a mode of data collection, but informed the most appropriate next steps in both research and practice – a flexible approach that is recommended for future embedded researchers. There is also the potential to extend the reflective practice model to the participants of the research, as described in **Section 5.4**. Further, this research demonstrated the suitability of design innovation applied to a transdisciplinary research space. Design provided both flexibility and necessary rigour, connecting research to industry.

The practical implications of this study include providing concrete methods for driving innovation in transdisciplinary teams. While this study was limited to one case within the specific scientific disciplines of physics, photonics, and smart sensing, the design practice employed did not focus on any technical science – all technical work was conducted by the scientific team, and the design activities remained "technology-agnostic". The findings of the study can therefore be applied to other scientific disciplines, and demonstrate the value of design as a strategy for both organisational transformation and innovation. More specifically, the detailed approach revealed a niche understanding of what does and does not work in the field of science, by exploring both challenges and opportunities experienced by scientific teams. It was also demonstrated that design enables the connection of scientific teams with end-users by providing common ground and a methodology for effective stakeholder engagement. By adopting design, new and unexpected ideas emerge from the scientific process that remain coherent with research goals – design was able to

direct, instead of derail, scientific research and development. The role of the embedded designer was significant, providing a demonstration of how to streamline and facilitate the design experience. The ultimate goal of this role was to foster empowerment and experiential learning, and an example was provided of the necessary enabling activities and behaviours to achieve this. Through exploring the journey of a scientific team adopting design, and the opportunities and challenges experienced along the way, this research supports the role of design as a catalyst for innovation in science.

6.4 Personal reflections

Continuing in the spirit of reflective practice which was so central to this study, I would like to take the opportunity to share some reflections on the journey of this research. These should not be considered as findings, but rather a personal exploration of my research experience, intending to spark curiosity in and encourage future researchers and practitioners.

Joore, Stompff and van den Eijnde (2022, p.12) describe the interesting dual role of a designer and researcher:

> "The researcher is focused on understanding the world as we know it; the designer is focused on developing alternative futures. Applied design research combines both and deals with what is desired and thus tells us the current problems."

As a doctoral candidate, I experienced both sides of this journey – a researcher striving to understand and learn new knowledge, while simultaneously holding the role of a designer within a scientific team supporting the development of future scenarios. Indeed, as Joore, Stompff, and van den Eijnde (2022) describe, this resulted in the revelation of current problems and tensions. Balancing these spheres was an enlightening experience. On the one hand, as a designer, it was easy to become frustrated in the face of challenges (many of which are discussed in **Section 4.3**) – I often questioned my capabilities or debated whether it was all worthwhile. It would have been naïve for me to have expected to face no obstacles in joining a scientific team as the only designer, attempting to radically transform the way the team has worked for years. However, it was by looking at these challenges through the lens of

a researcher that I was able to see the real value in experiencing them first-hand. I believe that it was by not shying away from the difficult questions and the "messy" parts of design, that I was able to provide well-rounded and realistic recommendations for design and science practice in **Chapter 5**. I hope that I can encourage future practitioners and researchers to anticipate, prepare for, and even embrace uncertainty – as the JSSL affectionately calls it, this is all part of the "design spaghetti".

My journey was also not without personal challenges – I was completing a doctoral candidature during a global pandemic, balancing both personal illness and radical life changes during the second year of my PhD, and underwent multiple full restructures of my supervisory team. However, the most challenging part was that, like the JSSL, I too found myself on a journey of design adoption. Having come from an undergraduate science background, conducting design research was a significant learning curve. However, I found this an extremely valuable challenge. From the beginning, I strove to be receptive to new ideas and set aside any preconceptions of how a design or science process should look like. Further, I believe this allowed me to be empathetic to the journey that the JSSL was going through because I, too had experienced that journey in recent memory. I recalled learning about design for the first time, comparing it to the scientific method, starting from a place of scepticism and even cynicism, and ultimately learning to embrace design innovation after experiencing it for myself and seeing its real value. It was incredibly rewarding to see my colleagues in the JSSL go through this experience too, and as seen in **Chapter 5**, it informed the empathetic basis of psychological safety that runs through the majority of my recommendations for future practice.

One of the most significant reflections from this entire process is not any specific recommendation for design and science practice – it is the overarching reassurance that design and science can, indeed *should*, work together. As one participant reflects, the JSSL is looking forward to expanding the reach of design beyond their team and into the broader scientific community:

> "Design is a powerful tool and has a place in the modern scientific environment. A focus on design could help tailor more public interest in university research if they are tied to problems the public is experiencing." (P12)

The JSSL now operates under the motto, "unique approaches, unified vision", recognising that design and science offer uniquely valuable methods, but in working together, fuel the delivery of leading-edge innovation. Since the conclusion of my case study and embedded practice, the JSSL has brought on multiple designers as members of the team and continued to use design as integral to their strategy and operations.

I am truly thankful for the experience of conducting this doctoral research. Wouters (2022) describes how design research creates space for creativity paired with scientific rigour. To have had this opportunity to combine my love for science with my desire to be creative has been invaluable, and has shaped not only my career but the way I think about the world. I am also humbled by the opportunity to have supported brilliant scientists in their innovation journey, and to have seen design and science, the two fields I love so dearly, come together in a remarkable way. I cannot summarise any better than P6 – "this has been a wonderful collaboration of design and science – it really works."

REFERENCES

Aaltio, I. and Heilmann, P. (2010) Case Study as a Methodological Approach. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 66-76.

Adikari, S., Keighran, H. and Sarbazhosseini, H. (2016) 'Embed design thinking in co-design for rapid innovation of design solutions', in *DUXU 2016: Design, User Experience, and Usability: Design Thinking and Methods*, pp. 3–14.

Ambrosio, C. (2016) 'The Historicity of Peirce's Classification of the Sciences', *European Journal of Pragmatism and American Philosophy*, 3(2).

Andrzejewski, A. *et al.* (2018) 'Brainstorming sessions - towards improving effectiveness and assessment of ideas generation', in *Proceedings of the 38th International Conference on Information Systems Architecture and Technology*, pp. 128–137.

Apud-Bell, M., Dasan, A. and Childs, P. (2018) 'A combination of design- and scientific- led processes can be a successful approach towards building innovative projects', in *International Conference on Engineering and Product Design Education*.

Archer, B. (1976) *The Three Rs*, *Design in General Education*. doi: 10.1111/j.1552-6909.1995.tb02370.x.

Aronson, J. (1994) 'A Pragmatic View of Thematic Analysis', *The Qualitative Report*, 2(1), pp. 1–2. Available at: https://nsuworks.nova.edu/tqr/vol2/iss1/3.

Atkins, R. K. (2006) 'Restructuring the Sciences: Peirce's Categories and His Classifications of the Sciences', *Transactions of the Charles S. Peirce Society: A Quarterly Journal in American Philosophy*, 42(4), pp. 483–500.

Avenier, M.J. (2010) 'Shaping a constructivist view of organizational design science', *Organization Studies*, 31(9–10), pp. 1229–1255.

Azzam, C., Straker, K. and Wrigley, C. (2018) 'The Interconnected Process of Design and Science: A Method for Mapping Concepts and Knowledge', in *Design Research Society 2018*. Limerick, Ireland.

Bahari, S. F. (2010) 'Qualitative Versus Quantitative Research Strategies: Contrasting Epistemological And Ontological Assumptions', *Jurnal Teknologi*, 52(1), pp. 17–28.

Banathy, B.H. (1996). *Designing social systems in a changing world*. New York/ London, U.K: Plenum.

Baregheh, A., Rowley, J. and Sambrook, S. (2009) 'Towards a multidisciplinary definition of innovation', *Management Decision*, 47(8), pp. 1323–1339.

Barlow, C.A. (2010) Interviews. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 495-499.

Bartoloni, S., Calò, E., Marinelli, L., Pascucci, F., Dezi, L., Carayannis, E., Revel, G.M., Gregori, G.L. (2022) 'Towards designing society 5.0 solutions: The new Quintuple Helix - Design Thinking approach to technology', *Technovation*, 113(102413), pp. 1–14.

Bauer, H. H. (1992). Scientific literacy and the myth of scientific method. Urbana, IL: University of Illinois Press.

Beckman, S. L. and Barry, M. (2007) 'Innovation as a Learning Process: Embedding Design Thinking', *California Management Review*, 50(1), pp. 25–56.

Beckman, S. L. and Barry, M. (2009) 'Design and innovation through storytelling', *International Journal of Innovation Science*, 1(4), pp. 151–160.

Behrendorff, C., Bucolo, S. and Miller, E. (2011) 'Designing Disruption – Linking Participatory Design and Design Thinking in Technology Orientated Industries', *Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces*, (c), pp. 53:1--53:8.

Bergoray, D.L. and Banister, E.M. (2010) Reflexivity. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 788-789.

Bhattacharya, S. (2020) 'Science and innovation in the 21st century: new paradigms and challenges for policy design', *Current Science*, 118(3), pp. 348–349.

Björklund, T., Hannukainen, P. and Manninen, T. (2019) Tracking the impact of design. In: T. Björklund and T. Keipi, eds., *Design+ Organizational renewal and innovation through design.* Aalto: Yliopisto, pp. 75-90.

Björklund, T., Laakso, M., Senni, K. and Ekman, K. (2017). Setting the stage: From lonely riders to co-creators. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 15-18.

Björklund, T., Laakso, M., Senni, K. and Ekman, K. (2017). Towards passion-based co-creation. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 20-22.

Björklund, T., Laakso, M., Senni, K. and Ekman, K. (2017). The way forward. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 216-218.

Björklund, T. (2019) The foundations of design thinking. In: T. Björklund and T. Keipi, eds., *Design+ Organizational renewal and innovation through design.* Aalto: Yliopisto, pp. 19-45.

Björklund, T., Tuulos, T., Kuukka, A., Surma-aho, A., van der Marel, F., Huhtonen, H., Talvinko, M., Kirjavainen, S. and Keipi, T. (2021). *Design+ Sustainability*. Aalto: Yliopisto.

Biglan, A. (1973a) 'Relationships between subject matter characteristics and the structure and output of university departments', *Journal of Applied Psychology*, 57(3), pp. 204–213.

Biglan, A. (1973b) 'The characteristics of subject matter in different academic areas', *Journal of Applied Psychology*, 57(3), pp. 195–203.

Blatter, J.K. (2008) Case Study. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 68-71.

Borthwick, M., Tomitsch, M. and Gaughwin, M. (2022) 'From human-centred to life-centred design: Considering environmental and ethical concerns in the design of interactive products', *Journal of Responsible Technology.* Elsevier Ltd, 10(1), pp. 1–10.

Boyatzis, R.E. (1998) *Transforming qualitative information: thematic analysis and code development.* SAGE.

Boylorn, R.M. (2008) Participants as Co-Researchers. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 599-600.

Boynton, P. M. and Greenhalgh, T. (2004) 'Hands-on guide to questionnaire research: Selecting, designing, and developing your questionnaire', *British Medical Journal*, 328, pp. 1312–1315.

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology Using thematic analysis in psychology', *Qualitative Research in Psychology*, 3(2), pp. 77–101.

Bruseberg, A. and McDonagh-Philp, D. (2002) 'Focus groups to support the industrial/product designer: a review based on current literature and designers' feedback', *Applied Ergonomics*, 33(1), pp. 27–38.

Bryant, S. T., Straker, K. and Wrigley, C. (2018) 'The typologies of power: Energy utility business models in an increasingly renewable sector', *Journal of Cleaner Production.* Elsevier Ltd, 195, pp. 1032–1046.

Brodsky, A.E. (2008) Fieldnotes. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 341-342.

Brown, T. (2009) *Change by design: how design thinking transforms organizations and inspires innovation.* New Yor: Harper Collins Publishers.

Brunswicker, S., Wrigley, C. and Bucolo, S. (2013). Business Model Experimentation: What is the Role of Design-Led Prototyping in Developing Novel Business Models? In: M. Curley and P. Formica, eds., *The Experimental Nature of New Venture Creation*. Switzerland: Springer, pp. 139-151.

Bryman, A. (1984) 'The debate about quantitative and qualitative research: A question of method or epistemology?', *The British Journal of Sociology*, 35(1), pp. 75–92.

Buchanan, R. (1993) Rhetoric and the Productive Sciences: Towards a New Program for Research in Design. In: M.J. de Vries, N. Cross, and D.P. Grant, eds., *Design Methodology and Relationships with Science*, 1st ed. Dordrecht: Kluwer Academic Publishers, pp. 1-14.

Buckley, M. *et al.* (2012) 'Designing Radical Business Model Innovation: a Case Study', *Participatory Innovation Conference 2012*, (January), p. 6.

Bucolo, S. and Matthews, J. H. (2011a) 'A conceptual model to link deep customer insights to both growth opportunities and organisational strategy in SME's as part of a design led transformation journey', in A. Ip, et al. (eds) *Design Management Toward A New Era of Innovation: Proceedings of the 2011 Tsinghua-DMI International Design Management Symposium*. Hong Kong: Innovation and Design Management Association Ltd., pp. 243–250.

Bucolo, S. and Matthews, J. H. (2011b) 'Design led innovation: Exploring the synthesis of needs, technologies and business models', in *Proceedings of Participatory Interaction Conference 2011*, pp. 1–4.

Bucolo, S., Wrigley, C. and Matthews, J. (2012) 'Gaps in Organizational Leadership: Linking Strategic and Operational Activities through Design-Led Propositions', *Design Management Journal*, 7(1), pp. 18–28.

Camburn, B. *et al.* (2017) 'Design prototyping methods: State of the art in strategies, techniques, and guidelines', *Design Science*, 3(13), pp. 1–33.

Carroll, J. M. (2000) 'Five reasons for scenario-based design', *Interacting with Computers*, 13(1), pp. 43–60.

Cautela, C. *et al.* (2017) 'Design-intensive start-ups: A new application field for design thinking?', *Journal of Design, Business & Society*, 3(1), pp. 45–66.

Chalmers, A. F. (1999) *What is this thing called Science?* 3rd edn. Indianapolis / Cambridge: Hackett Publishing Company.

Chandra, P. and Patwardhan, R. (2010) 'Nano Euphoria: A reality check', *Tech Monitor*, Jan-Feb, pp. 33–37.

Chasteauneuf, C. (2010) Questionnaires. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 768-770.

Choi, B. and Pak, A. (2006) 'Multidisciplinarity, inter-disciplinarity and trans-disciplinarity in health research', *Clinical and Investigative Medicine*, 29(6), pp. 351–364.

Chun Tie, Y., Birks, M. and Francis, K. (2019) 'Grounded theory research: A design framework for novice researchers', *SAGE Open Medicine*, 7, pp. 1–8.

Connolly, M. (2003) 'Qualitative Analysis: A Teaching Tool for Social Work Research', *Qualitative Social Work*, 2(1), pp. 103–112.

Creswell, J. W. (2007). *Qualitative Inquiry and Research Design: Choosing Among Five Approaches.* SAGE Publications.

Cross, N. (1982) 'Designerly ways of knowing', *Design Studies*, 3(4), pp. 221–227.

Cross, N. (1993) A History of Design Methodology. In: M.J. de Vries, N. Cross, and D.P. Grant, eds., *Design Methodology and Relationships with Science*, 1st ed. Dordrecht: Kluwer Academic Publishers, pp. 15-27.

Cross, N. (2004) 'Creative Thinking by Expert Designers', *Journal of Design Research*, 4(2), pp. 1–10.

Cross, N. (2018a) 'Developing design as a discipline', *Journal of Engineering Design*, 29(12), pp. 691–708.

Cross, N. (2018b) 'Expertise in Professional Design', in *Cambridge Handbook of Expertise and Expert Performance*, pp. 372–388.

Cross, N., Naughton, J. and Walker, D. (1981) 'Design method and scientific method', *Design Studies*, 2(4), pp. 195–201.

Danish Design Centre (2001) *The Design Ladder*. [online] Available at: http://danskdesigncenter.dk/ en/design-ladder-four-steps-design-use [Accessed 8 Feb 2019].

de Leon, N., Sun, Q., Utriainen, T., Nordberg, M., Jones, R. (2018) 'Future states: design and science for sustainability', *CERN IdeaSquare Journal of Experimental Innovation*, 2(2), pp. 13–24.

de Vries, M.J. (1993) Design Methodology and Relationships with Science: Introduction. In: M.J. de Vries, N. Cross, and D.P. Grant, eds., *Design Methodology and Relationships with Science*, 1st ed. Dordrecht: Kluwer Academic Publishers, pp. 1-14.

Dean, T., Zhang, H. and Xiao, Y. (2022) 'The role of complexity in the Valley of Death and radical innovation performance', *Technovation*, 109(102160).

Design Council (2019). *Framework for Innovation: Design Council's evolved Double Diamond.* [online] Available at: https://www.designcouncil.org.uk/our-work/skills-learning/tools-frameworks/framework-for-innovation-design-councils-evolved-double-diamond/ [Accessed 20 Jul 2022].

Department of Industry, Innovation and Science (2018). *Global Innovation Strategy*. [online] Available at: https://industry.gov.au/innovation/Global-Innovation-Strategy/Pages/ default.aspx [Accessed 24 Jan. 2018].

Dewberry, E. and Sherwin, C. (2002) 'Visioning Sustainability through Design', *Greener Management International*, pp. 125–138. Available at: http://www.greenleaf-publishing.com/default.asp?ContentID=8.

Di Domenico, M. and Phillips, N. (2010) Participant Observation. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 652-655.

Diamond, S. (2018) 'Addressing the imagination gap through STEAMM+D and indigenous knowledge', *Proceedings of the National Academy of Sciences of the United States of America.*

Díez-Vial, I. and Montoro-Sánchez, Á. (2016) 'How knowledge links with universities may foster innovation: The case of a science park', *Technovation*, 50–51, pp. 41–52.

Doherty, R. *et al.* (2015) 'Climbing the Design Ladder: Step by step', *Revista D.: Design, Educação, Sociedade e Sustentabilidade*, 7(2), pp. 60–82.

Dorst, K. (2003) 'Exploring the Structure of Design Problems', in *International Conference on Engineering Design ICED 03*, pp. 1–18.

Dorst, K. (2006) 'Design Problems and Design Paradoxes', *Design Issues*, 22(3), pp. 4–17.

Dorst, K. (2008) 'Design research: a revolution-waiting-to-happen', *Design Studies*, 29(1), pp. 4–11.

Dorst, K. and Cross, N. (2001) 'Creativity in the design process: co-evolution of problem–solution', *Design Studies*, 22(5), pp. 425–437.

Dorst, K. and Dijkhuis, J. (1995) 'Comparing paradigms for describing design activity', *Design Studies*, 16(1992), pp. 261–274.

Dowling, M. (2008) Reflexivity. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 747-748.

Driver, A., Peralta, C. and Moultrie, J. (2010) 'An Exploratory Study of Scientists ' Perceptions of Design and Designers', in Durling, D. et al. (eds) *Design and Complexity - DRS International Conference 2010*. Montreal, Canada, pp. 1–12.

Driver, A., Peralta, C. and Moultrie, J. (2011) 'Exploring how industrial designers can contribute to scientific research', *International Journal of Design*, 5(1), pp. 17–28.

Edmondson, A. C. and McManus, S. E. (2007) 'Methodological Fit in Management Field Research', *Academy of Management Review*, Vol. 32(4), pp. 1155–1179.

Efeoglu, A. *et al.* (2013) 'Design thinking: characteristics and promises', *14th International CINet Conference on Business Development and Co-creation*, (September), pp. 241–256.

Eisenhardt, K. M. (1989) 'Building Theories from Case Study Research', *Academy of Management Review*, 14(4), pp. 532–550.

Ericsson, K. A. and Simon, H. A. (1998) 'How to study thinking in everyday life: Contrasting think-aloud protocols with descriptions and explanations of thinking', *Mind, Culture, and Activity*, 5(3), pp. 178–186.

Evans, M. (2011). 'Empathising with the Future.' *Creating.* 14(2).

Evers, J.C. and van Staa, A. (2010) Qualitative Analysis in Case Study. In: A. Mills, G. Eurepos and E. Wiebe, eds., *Encyclopedia of Case Study Research,* 1st ed. California: SAGE Publications, pp. 749-756.

Farrell, R. and Hooker, C. (2013) 'Design, science and wicked problems', *Design Studies.* Elsevier Ltd, 34(6), pp. 681–705.

Farrell, R. and Hooker, C. (2015) 'Designing and sciencing: Response to Galle and Kroes', *Design Studies.* Elsevier Ltd, 37, pp. 1–11.

Funtowicz, S. O. and Ravetz, J. R. (1993) 'Science for the post-normal age', *Futures*, 25, pp. 739–755.

Galle, P. and Kroes, P. (2014) 'Science and design: Identical twins?', *Design Studies.* Elsevier Ltd, 35(3), pp. 201–231.

Gasparski, W. (1993) Design, Science, and Philosophy: The Praxiological Perspective. In: M.J. de Vries, N. Cross, and D.P. Grant, eds., *Design Methodology and Relationships with Science*, 1st ed. Dordrecht: Kluwer Academic Publishers, pp. 1-14.

Giacomin, J. (2014) 'What is human centred design?', *The Design Journal*, 17(4), pp. 606–623.

Given, L. M. (2008) *The SAGE Encyclopedia of Qualitative Research Methods*. California: SAGE Publications.

Glaser, B. G. and Strauss, A. L. (1967) *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Chicago: Aldine.

Glynn, S. (1985) 'Science and perception as design', *Design Studies*, 6(3), pp. 122–126.

Gold, R. L. (1958) 'Roles in Sociological Field Observations', *Social Forces*, 36(3), pp. 217–223.

Gonera, A. and Pabst, R. (2019) 'The use of design thinking in transdisciplinary research and innovation consortia: Challenges, enablers and benefits', *Journal of Innovation Management*, 7(3), pp. 96-122.

Gregory, S. A. (1967) *The Design Method*. London: Butterworth.

Griffiths, M. and Tann, S. (1992) 'Using reflective practice to link personal and public theories', *Journal of Education for Teaching*, 18(1), pp. 69–84.

Haines-Gadd, M. *et al.* (2015) 'Cut the crap; Design brief to pre-production in eight weeks: Rapid development of an urban emergency low-tech toilet for Oxfam', *Design Studies*. Elsevier Ltd, 40, pp. 246–268.

Hassi, I. and Laakso, M. (2011). Making sense of design thinking. In: T-M Karjalainen, M. Koria, and M. Salimäki, eds. *IDBM papers vol. 1 – IDBM Program*. Helsinki: Aalto University, pp. 50-63.

Hatchuel, A. (2002) 'Towards Design Theory and expandable rationality: The unfinished program of Herbert Simon', *Journal of Management and Governance*, 5(3), pp. 1–12.

Hatchuel, A. and Weil, B. (2003) 'A new approach of innovative design: an introduction to C-K theory', in *International Conference on Engineering Design ICED 03*, pp. 1–15.

Heck, J. *et al.* (2018) 'Promoting user-centricity in short-term ideation workshops', *International Journal of Design Creativity and Innovation.* Taylor & Francis, 6(3–4), pp. 130–145.

Hepburn, L.A. (2022) 'Transdisciplinary learning in a deisgn collaboration', *The Design Journal*, 25(3), 299-316.

Hernández-Ramírez, R. (2018) 'On Design Thinking, Bullshit, and Innovation', *Journal of Science and Technology of the Arts*, 10(3), pp. 45–57.

Hong, Y. and Nam, T.-J. (2010) 'A method to get rich feedbacks from users in an interview for design concept decision', *CHI 2010*, pp. 3907–3912.

Hooker, C. (2018) 'A new problem-solving paradigm for philosophy of science', *Perspectives on Science*, 26(2), pp. 266–291.

Horner, R. H., Carr, E.G., Halle, J., McGee, G., Odom, S., Wolery, M. (2005) 'The use of single-subject research to identify evidence-based practice in special education', *Exceptional Children*, 71(2), pp. 165–179.

Howard, Z., Senova, M. and Melles, G. (2015) 'Exploring the role of mindset in design thinking: Implications for capability development and practice', *Journal of Design, Business & Society*, 1(2), pp. 183–202.

IBM Corporation (2018). *Feedback Grid* [pdf] IBM Corporation. Available at https://www.ibm.com/design/thinking/page/toolkit/activity/feedback-grid [Accessed 14 Jan. 2021].

IDEO (n.d.) *Design thinking defined.* [online] Available at https://designthinking.ideo.com/ [Accessed 20 Jul 2022].

Jaskiewicz, T. (2022). Learning from prototypes: From the design studio to the city. In: P. Joore, G. Stompff and J. Eijnde, eds., *Applied Design Research: A Mosaic of 22 Examples, Experiences and Interpretations Focussing on Bridging the Gap between Practice and Academics*. Boca Raton, FL: CRC Press, pp. 43-51.

Johnson, M.P., Ballie, J., Thorup, T. and Brooks, E. (2017) 'Living on the Edge: design artefacts as boundary objects', *The Design Journal*, 20(sup1), pp. S219-S235.

Johnson, M.P., Ballie, J., Thorup, T., Brooks, E. and Brooks, E. (2017) 'CO/DEsign: building a shared dialogue around analysis within co-design', *The Design Journal,* 20(sup1), pp. S4241-S4252.

Jones, G., Chirino Chace, B. and Wright, J. (2020) 'Cultural diversity drives innovation: empowering teams for success', *International Journal of Innovation Science*, 12(3), pp. 323–343.

Joore, P., Stompff, G. and van den Eijnde, J. (2022). Applied Design Research, Part 1: Eyes on the future. In: P. Joore, G. Stompff and J. Eijnde, eds., *Applied Design Research: A Mosaic of 22 Examples, Experiences and Interpretations Focussing on Bridging the Gap between Practice and Academics*. Boca Raton, FL: CRC Press, pp. 12-13.

Junginger, S. (2015). 'Organizational Design Legacies and Service Design', *The Design Journal,* 18(2), pp. 209-226.

Kimchi, J., Polivka, B. and Sabol Stevenson, J. (1991) 'Triangulation: Operational Definition', *Nursing Research*, 40(6), pp. 364–365.

Klahr, D. and Simon, H. A. (1999) 'Studies of Scientific Creativity: Complimentary approaches and convergent findings', *Psychological Bulletin*, 125(5), pp. 524–543.

Kocsis, A., Coddington, A., Prince, A., Giang, C., Symington, N., Graham, A., de Kruiff, A., Turner, C., Mattila, P., Thong, C. and Eggleston, J. (2017). Prototyping the prototype. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 51-64.

Kolko, J. (2010) 'Abductive Thinking and Sensemaking: The Drivers of Design Synthesis', *Design Issues*, 26(1), pp. 15–28.

Kosso, P. (2011) *A summary of scientific method.* SpringerBriefs in Philosophy.

Kostrzewski, M. (2018) 'One design issue – many solutions. Different perspectives of design thinking – case study', in Uden, L., Hadzima, B., and Ting, I. (eds) *KMO 2018: Knowledge Management in Organizations: Communications in Computer and Information Science.* Cham: Springer International Publishing, pp. 179–190.

Kretzschmar, A. (2003). The economic effects of design. National Agency for Enterprise and Housing, Copenhagen: Denmark

Krippendorff, K. (2006). *The Sematic Turn: A new foundation for design.* Taylor and Francis, Boca, FL.

Kuhn, T. (197) *The Structure of Scientific Revolutions*, 2nd ed. London: The University of Chicago Press.

Kulkurani, D. and Simon, H. A. (1988) 'The Processes of Scientific Discovery: The Strategy of Experimentation', *Cognitive Science*, 12, pp. 139–175.

Laakso, M. (2017). Orchestrating for collective creativity. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 166-177.

Lawson, B. and Dorst, K. (2009) *Design Expertise*

Lawson, B. R. (1993) 'Parallel lines of thought', *Languages of Design*, 1, pp. 357–366.

Lee, D. (2020) 'Learning from design-prototyping interaction for engineering innovation from a cross-functional perspective', *International Journal of Innovation Science*, 12(1), pp. 111–126.

LeRouge, C. *et al.* (2013) 'User profiles and personas in the design and development of consumer health technologies', *International Journal of Medical Informatics*. Elsevier Ireland Ltd, 82(11), pp. 251–268.

Levy, R. (1985) 'Science, technology and design', *Design Studies*, 6(2), pp. 66–72.

Liedtka, J. (2014) 'Innovative ways companies are using design thinking', *Strategy and Leadership*, 42(2), pp. 40–45.

Liedtka, J. (2015) 'Perspective: Linking Design Thinking with Innovation Outcomes through Cognitive Bias Reduction', *Journal of Product Innovation Management*, 32(6), pp. 925–938.

Linstone, H. A. (2011) 'Three eras of technology foresight', *Technovation*, 31, pp. 69–76.

Linton, J. D. (2008) 'Why big science has trouble finding big money and small science has difficulties finding small money', *Technovation*, 28, pp. 799–801.

Linton, J. D. (2009) 'De-babelizing the language of innovation', *Technovation*, 29, pp. 729–737.

Luo, J. (2015) 'The united innovation process: integrating science, design, and entrepreneurship as sub-processes', *Design Science*, 1, pp. 1–29.

Mabogunje, A., Sonalkar, N. and Leifer, L. (2016) 'Design thinking: A new foundational science for engineering', *International Journal of Engineering Education*, 32(3), pp. 1540–1556.

Mäkinen, S., Hannukainen, P. and Hyysalo, S. (2017). Physical representations as a common language. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 66-80.

Mangematin, V. and Walsh, S. (2012) 'The future of nanotechnologies', *Technovation*, 32, pp. 157–160.

Mankins, J. C. (1995) *Technology Readiness Levels: A White Paper*.

Margolin, V. (2007). Design, the future and the human spirit. *Design Issue.* 23(3), pp.4-15.

Markham, S. K. (2002) 'Moving technologies from lab to market', *Research Technology Management*, 45(6), pp. 31–42.

Markham, S. K. *et al.* (2010) 'The Valley of Death as Context for Role Theory in Product Innovation', *Journal of Product Innovation Management*, 27(3), pp. 402–417.

Martin, R. (2009). *The Design of Business*, 1st ed. Boston, MA: Harvard Business School Press.

Maturana, H. (1988). 'Reality: The search for objectivity or the quest for a compelling argument.' *The Irish Journal of Psychology*, 9(1), pp. 25-82.

Maula, H., Björklund, T., Maula, J. and Soule, S. (2019) Building design-driven organizations. In: T. Björklund and T. Keipi, eds., *Design+ Organizational renewal and innovation through design.* Aalto: Yliopisto, pp. 49-71.

McKechnie, L.E.F. (2008) Participant Observation. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 598-599.

McPhee, C., Bliemel, M. and van der Bijl-Brouwer, M. (2018) 'Editorial: Transdisciplinary Innovation', *Technology Innovation Management Review*, 8(8), pp. 3-6.

Mejía, G.M.*,* Nazir, C., Malina, R.F., Garia Topete, A., Londoño, F.C., Roldán, A.F., Farias, P. L. and Silveira, J. (2018) 'An emerging role for design methods in transdisciplinary practice', in *24th International Symposium on Electronic Arts*

Mejía, G. M., Malina, R. F. and Roldán, A. F. (2017) 'Towards an inventory of best practices for transdisciplinary collaboration', *Proceedings of the 23rd International Symposium on Electronic Art ISEA2017*, (June), pp. 681–687

Merrifield, B. (1995). Obsolescence of Core Competencies versus Corporate Renewal. *Technology Management,* 2(2), pp. 73-83.

Mesa, D., Thong, C., Ranscombe, C., Kuys, B. (2019) 'Integrating the product development process in scientific research. Bridging the research-market gap', in *Proceedings of the International Conference on Engineering Design, ICED*, pp. 2805–2814.

Mesa, D., Thong, C., Ranscombe, C., Kuys, B. (2020) 'Design and Science: A workshop-based approach for identifying commercial opportunities in universities', in *DRS2020: Synergy*, pp. 1116–1131.

Mesa, D., Tan, L. and Ranscombe, C. (2022) 'A Case Study Exploring the Role of Design in Maturing University-Developed Technology', in *International Design Conference - Design 2022*. Cambridge University Press, pp. 2343–2352.

Mills, A. J., Eurepos, G. and Wiebe, E. (2010) *Encyclopedia of Case Study Research*. 1st edn, *Encyclopedia of Case Study Research*. 1st edn. Edited by A. J. Mills, G. Eurepos, and E. Wiebe.

Miyazaki, K. and Islam, N. (2007) 'Nanotechnology systems of innovation — An analysis of industry and academia research activities', *Technovation*, 27, pp. 661–675.

Morgan, D.L. (2008) Focus Groups. In: L. Given, ed., *The SAGE Encyclopedia of Qualitative Research Methods,* 1st ed. California: SAGE Publications, pp. 352-354.

Mosely, G., Wright, N. and Wrigley, C. (2018) 'Facilitating design thinking: A comparison of design expertise', *Thinking Skills and Creativity*. Elsevier, 27, pp. 177–189.

Moses, H. *et al.* (2015) 'The anatomy of medical research US and international comparisons', *Journal of the American Medical Association*, 313(2), pp. 174–189.

Moultrie, J. (2015) 'Understanding and classifying the role of design demonstrators in scientific exploration', *Technovation*, 43–44, pp. 1–16.

Nicolau, D. (2004) 'Challenges and opportunities for nanotechnology policies: An Australian perspective', *Nanotechnology Law & Business*, 1(4), pp. 446–463.

Norman, D. (2013) *The Design of Everyday Things*, *Basic Books*.

Norman, D. (2010) 'The research-practice gap', *Interactions*, 17(4), pp. 9–12.

Nusem, E., Wrigley, C. and Matthews, J. (2017) 'Exploring aged care business models: A typological study', *Ageing and Society*, 37(2), pp. 386–409.

Ogunleye, J. (2016) Knowledge and Creativity. In: F.K. Reisman, ed., *Creativity in Arts, Science, and Technology: Research Papers on Knowledge, Innovation and Enterprise Volume IV*. Leeds, UK: KIE Conference Publications, p. 6-8.

Oldroyd D. (1986) *The arch of knowledge: an introductory study of the history of the philosophy and methodology of science.* Australia: New South Wales University Press; pp. 1-413.

Owen, R., Macnaghten, P. and Stilgoe, J. (2012) 'Responsible research and innovation: From science in society to science for society, with society', *Science and Public Policy*, 39(6), pp. 751–760.

Parkinson, D. and Warwick, L. (2017) 'Stimulating Thinking at the Design Pitch. Storytelling Approach and Impact', *The Design Journal*. Routledge, 20(sup1), pp. S4509–S4518.

Passera, S. (2017). Show Don't Tell. In: T. Björklund, M. Laakso, K. Senni and K. Ekman, eds., *Passion-based co-creation.* Aalto: Yliopisto, pp. 39-50.

Peirce, C.S. (1903). *An Outline Classification of the Sciences*.

Peralta, C., Driver, A. and Moultrie, J. (2010) 'Discovery and Creation: Explaining Collaboration between Designers and Scientists in Scientific Research', in *Design & Complexity: Design Research Society International Conference proceedings, Montreal*, pp. 1–11.

Peralta, C. and Moultrie, J. (2010) 'Collaboration between designers and scientists in the context of scientific research: A literature review', in *11th International Design Conference, DESIGN 2010*, pp. 1643–1652.

Perkins, D.N. (1981). *The mind's best work.* Cambridge, MA: Harvard University Press.

Phaal, R., O'Sullivan, E., Routley, M., Ford, S. and Probert, D. (2011) 'A framework for mapping industrial emergence', *Technological Forecasting and Social Change*. Elsevier Inc., 78(2), pp. 217–230.

Polk, M. (2015) ' Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving.' *Futures*, 65, pp. 110-122.

Popper, K.R. (1959). *The Logic of Scientific Discovery.* London: Routledge.

Popper, K.R. (1962). *Conjectures and Refutations: The Growth of Scientific Knowledge.* New York: Basic Books.

Pozzey, E., Bucolo, S. and Wrigley, C. (2012) 'Unpacking the opportunities for change within a family owned manufacturing SME: a design led innovation case study', in Rieple, A., Bohemia, E., and Liedtka, J. (eds) *Leading Innovation Through Design: Proceedings of the DMI 2012 International Research Conference*. United States: Design Management Institute (DMI), pp. 831–844.

Pozzo, R. (2004). *The impact of Aristotlelianism on modern philosophy.* CUA Press, pp. 41.

Price, R. A., Wrigley, C. and Matthews, J. (2017) 'Design-led innovation and sensemaking: opportunities to connect', *Design Management Academic Conference*, (January).

Price, R., Matthews, J. and Wrigley, C. (2018) 'Three Narrative Techniques for Engagement and Action in Design-Led Innovation', *She Ji: The Journal of Design, Economics, and Innovation*. Elsevier, 4(2), pp. 186–201.

Price, R. and Wrigley, C. (2016) 'Design and a Deep Customer Insight Approach to Innovation', *Journal of International Consumer Marketing*. Taylor & Francis, 28(2), pp. 92–105.

Price, R., Wrigley, C. and Matthews, J. (2018) 'Action researcher to design innovation catalyst: Building design capability from within', *Action Research*, 0(0).

Pringle, A., Sowden, P.T., Deeley, C. and Sharma, S. (2016). Shifting between modes of thought: a domain-general creative thinking skill? In: F.K. Reisman, ed., *Creativity in Arts, Science, and Technology: Research Papers on Knowledge, Innovation and Enterprise Volume IV*. Leeds, UK: KIE Conference Publications, p. 220-259.

Randhawa, K. *et al.* (2021) 'Design Thinking Implementation for Innovation: An Organization's Journey to Ambidexterity', *Journal of Product Innovation Management*, pp. 668–700.

Rekonen, S. (2017). Unlocking the Potential of Interdisciplinary Teams. In: T. Björklund, M. Laakso, K. Senni, K. Elkman, eds., *Passion-based Co-creation*, 1st ed. Helsinki: Aalto Design Factory, pp. 91-102.

Rekonen, S. (2019). The role of design in facilitating shared understanding in innovation projects. In: T. Björklund and T. Keipi, eds., *Design+ Organizational renewal and innovation through design.* Aalto: Yliopisto, pp. 117-134.

Riol, H. and Thuillier, D. (2015) 'Project management for academic research projects: Balancing structure and flexibility', *International Journal of Project Organisation and Management*, 7(3), pp. 251–269.

Rittel, H. W. J. and Webber, M. M. (1973) 'Dilemmas in a general theory of planning', *Policy Sciences*, 4(2), pp. 155–169.

Rittiner, F. *et al.* (2016) 'Using personas in ideation workshops', in *The Fourth International Conference on Design Creativity*, pp. 1–8.

Rowe, P. G. (1991) *Design Thinking.* 3rd ed. Cambridge, Massachusetts: MIT Press.

Rust, C. (2004) 'Design Enquiry: Tacit Knowledge and Invention in Science', *Design Issues*, 20(4), pp. 76–85.

Sale, J. E. M. and Thielke, S. (2018) 'Qualitative research is a fundamental scientific process', *Journal of Clinical Epidemiology*. Elsevier Inc, 102(2018), pp. 129–133.

Sanders, E. B-N. and Stappers, P.J. (2008) 'Co-creation and the new landscapes of design', *CoDesign*, 4(1), pp. 5-18.

Săvoiu, G. (2014) 'The impact of inter-, trans-and multidisciplinarity on modern taxonomy of sciences', *Current Science*, 106(5), pp. 685–690.

Schön, D. A. (1984) 'Problems, frames and perspectives on designing', *Design Studies*, 5(3), pp. 132–136.

Schön, D. A. (1983) *The Reflective Practitioner: How Professionals Think in Action.* New York NY: Routledge.

Seymour, R. (2008). Optimistic futurism. *Interactions.* May/June, pp.52-54.

Shai, O., Reich, Y., Hatchuel, A. and Subrahmanian, E. (2013) 'Creativity and scientific discovery with infused design and its analysis with C-K theory', *Research in Engineering Design*, 24(2), pp. 201–214.

Shneiderman, B. (2019) 'Creativity and collaboration: Revisiting cybernetic serendipity', *Proceedings of the National Academy of Sciences*, 116(6), pp. 1837–1843.

Simon, H. A. (1969) *The sciences of the artificial, (third edition), Computers & Mathematics with Applications.*

Simon, H. A. (1973) 'The structure of ill structured problems', *Artificial Intelligence*, 4(3–4), pp. 181–201.

Simon, H. A. (1992) 'Scientific discovery as problem solving', *International Studies in the Philosophy of Science*, 6(1), pp. 3–14.

Simpson, B. and Powell, M. (1999) 'Designing research organizations for science innovation', *Long Range Planning*, 32(4), pp. 441–451.

Skolimowski, H. (1966). 'The Structure of Thinking in Technology', *Technology & Culture* 7, pp. 371-383.

Spalding, A. (2010) 'Colour, humour and scientific method', *Clinical and Experimental Optometry*, 93(3), pp. 129–130.

Stanford d. school (2018). *Design Thinking Bootleg* [online]. Available at: https://dschool.stanford.edu/resources/design-thinking-bootleg [Accessed 20 Jul 2022].

Stevenson, T., Wrigley, C., & Matthews, J. (2016). *'A design approach to innovation in the Australian energy industry.' Journal of Design, Business &* Society, (2) pp. 49–70*.*

Stoecker, J. L. (1993) 'The Biglan classification revisited', *Research in Higher Education*, 34(4), pp. 451–464.

Stokes, D.E. (1997). *Pasteur's Quadrant – Basic Science and Technological Innovation*. Washington D.C.: Brookings Institution Press.

Thong, C. *et al.* (2021) 'Design innovation integrating deep technology, societal needs, radical innovation, and future thinking: a case study of the CBI A3 program', *CERN IdeaSquare Journal of Experimental Innovation*, 5(1), pp. 32–39.

Thurs, D. (2011). Scientific Methods. In: P. Harrison, R.L. Numbers, and M.H. Shank, eds., *Wrestling with Nature: From Omens to Science*, 1st ed. Chicago: University of Chicago Press, pp. 307-336.

Townson, P. *et al.* (2014) 'Making sense of purpose, direction and innovation: An embedded design led innovation case study in the Australian mining industry', *2013 IEEE-Tsinghua International Design Management Symposium: Design-Driven Business Innovation, TIDMS 2013 - Proceedings*, pp. 268–276.

Troxler, P. (2022). Dance? Dance! The contribution of practice-driven design research to the ballet of disciplines. In: P. Joore, G. Stompff and J. Eijnde, eds., *Applied Design Research: A Mosaic of 22 Examples, Experiences and Interpretations Focussing on Bridging the Gap between Practice and Academics*. Boca Raton, FL: CRC Press, pp. 63-71.

Valkenburg, R. and Dorst, K. (1998) 'The reflective practice of design teams', *Design Studies*, 19(3), pp. 249–271.

van Burg, E. *et al.* (2008) 'Creating university spin-offs: A science-based design

perspective', *Journal of Product Innovation Management*, 25(2), pp. 114–128.

van der Bijl-Brouwer, M. and Dorst, K. (2017) 'Advancing the strategic impact of human-centred design', *Design Studies*, 53(C), pp. 1-23.

van der Lugt, R. (2022). Systemic co-design: The designer as a facilitator of change. In: P. Joore, G. Stompff and J. Eijnde, eds., *Applied Design Research: A Mosaic of 22 Examples, Experiences and Interpretations Focussing on Bridging the Gap between Practice and Academics*. Boca Raton, FL: CRC Press, pp. 127-135.

van der Marel, F. and Mäkelä, M. (2019) Designers as change agents. In: T. Björklund and T. Keipi, eds., *Design+ Organizational renewal and innovation through design.* Aalto: Yliopisto, pp. 103-114.

Vehkavaara, T. (2003) '(Compilation) Peirce's classifications as diagrams', pp. 1–3.

Verganti, R. (2009). *Design Driven Innovation: Changing the Rules of Competition by Radically Innovating What Things Mean.* Harvard Business Press.

Visser, F. S. *et al.* (2005) 'Contextmapping: experiences from practice', *CoDesign*, 1(2), pp. 119–149.

Voit, E. O. (2019) 'Perspective: Dimensions of the scientific method', *PLoS Computational Biology*, 15(9), pp. 1–14.

von Glasersfeld, E. (2001) 'The radical constructivist view of science', *Foundations of Science*, 6(1–3), pp. 31–43.

Ward, A., Runcie, E. and Morris, L. (2009) 'Embedding innovation: Design thinking for small enterprises', *Journal of Business Strategy*, 30(2–3), pp. 78–84.

Willem, R. A. (1990) 'Design and Science', *Design Studies*, 11(1), pp. 43–47.

Wouters, E. (2022). A new mindset in research: Creativity, empathy, and participation lead to successful technological innovations in healthcare. In: P. Joore, G. Stompff and J. Eijnde, eds., *Applied Design Research: A Mosaic of 22 Examples,*

Experiences and Interpretations Focussing on Bridging the Gap between Practice and Academics. Boca Raton, FL: CRC Press, pp. 189-195.

Wright, N. (2018) 'The goDesign immersion program: Fostering design-led educational innovation in regional Australian schools Queensland University of Technology', *(Thesis)*, pp. 1–516.

Wrigley, C. (2013) 'Educating the "Design Innovation Catalyst" for Change', in Sugiyama, K. (ed.) *Proceedings of the 5th International Congress of International Association of Societies of Design Research (IASDR).* Japan: Shibaura Institute of Technology / Japanese Society for the Science of Design, pp. 3547–3557.

Wrigley, C. (2016) 'Design Innovation Catalysts: Education and Impact', *She Ji: The Journal of Design, Economics, and Innovation.* Elsevier, 2(2), pp. 148–165.

Wrigley, C. (2017) 'Principles and practices of a design-led approach to innovation', *International Journal of Design Creativity and Innovation.* Taylor & Francis, 5(3–4), pp. 235–255.

Yin, R. (1981) 'The case study strategy, as a serious research', *Knowledge: Creation, Diffusion, Utilization*, 3(1), pp. 97–114.

Yordanova, Z. *et al.* (2019) The Long Way from Science to Innovation – A Research Approach for Creating an Innovation Project Methodology. In: W. Abramowicz and R. Corchuelo (eds)., *Lecture Notes in Business Information Processing.* Switzerland: Springer International Publishing, pp. 371-380.

Zafeirakopoulos, M. and van der Bijl-Brouwer, M. (2018) 'Exploring the transdisciplinary learning experiences of innovation professionals', *Technology Innovation Management Review*, 8(8), pp. 50-59.

APPENDICES

8.1 Semi-structured interview protocols

Semi-structured interviews were used as a data collection method with project leaders in the JSSL. The following sections outline the starting / prompting questions used in each interview. However, it is important to note that the semi-structured nature meant that follow on questions were presented as the opportunity arose, and the trajectory of the interview often pivoted in response to participant input.

8.1.1 Phase 2: Ideation and collaboration workshop: Pre-workshop interview

1. Why are we doing this workshop?
2. What do you hope / expect will be the outcome of this workshop?
3. Do you think the personas will help?
4. Do you think it is / has been important for us to think about the user experience? If so, why?
5. What value does this bring, if any?

8.1.2 Phase 2: Ideation and collaboration workshop: Post-workshop interview

1. What was your role in this workshop?
2. How do you personally feel the workshop went?
3. What value did this workshop bring to the team?
4. What did you find helpful or unhelpful about the workshop?
5. What engagement (if any) did you have with RAAF attendees? How was it helpful / unhelpful?
6. What engagement (if any) did you have with DST attendees? How was it helpful / unhelpful?
7. Did the personas help? If so, how so?
   a. What was useful about the personas?
   b. What would you change about the personas?
   c. What challenges did you face in engaging with the persona?
8. What are the next steps for the JSSL team?
9. ***Project D only:***
   a. *Tell me happened with the project cancellation.*
   b. *Why do you think the project was cancelled?*

    c. Is there anything you would change about the way the project was
    happening?

    d. What value did this project bring to the team? To you personally?

    e. What are you hoping to work on in JSSL now?

8.1.3 Phase 4: Understanding prototyping: Post-workshop interview

1. What was your role in this workshop?
2. How do you personally feel the workshop went?
3. What value did this workshop bring to the team?
4. What did you find helpful or unhelpful about the workshop?
   a. What are your thoughts on the involvement of a RAAF representative?
5. Did your understanding of prototyping change during this workshop? What is your understanding of prototyping now?
6. How did this workshop make you feel about prototyping?
7. Did you find anything surprising about this workshop?
8. Do you have any concerns moving forward?
9. What do you hope to get out of the other workshops?
10. What are the next steps for Project A / B / C? What about for the JSSL team?

8.1.4 Phase 5: Problem reframing: Interview

1. What are your feelings / concerns at the moment as we reconsider the contract?
   a. Are you worried about anything?
   b. Are you optimistic about / hopeful for anything?
   c. What do you think we've done better this time?
2. What do you think the [reframed problems] are about? Why did they come up?
3. How did you feel when you first saw the [new problems]?
   a. Did this change? Why / why not?
4. What process did you follow to better understand the [problems]?
5. Do you feel like you understand how this relates to your work personally?
6. Do you think addressing the [problems] is more about RAAF's needs, or JSSL technology, or something else?

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   a. Do you think that thinking about the [problems] will help you better deliver value for RAAF?

7. What effect do you think this will have on the project teams? On JSSL as a whole?

8. Are you still unsure of anything?

9. What are you hoping to achieve from the next workshop?

10. Do you have any concerns about the next workshop?

11. What questions need to be asked?

12. What insights need to be gained?

13. What do you think is needed from this workshop to best equip you and the JSSL to continue prototyping?

8.1.5 Phase 6: Demonstration workshop: Interview

1. In general, how do you feel about collaborating online?

2. How has your team adapted to working from home?

3. How did you feel presenting over Zoom?

4. What challenges did you face in presenting your demonstration virtually?

5. Do you feel like working from home has affected your ability to engage with users? If so, how?

6. How did you feel about your preparation for this workshop?

7. How did you feel about the pitching sessions and tips?

   a. What did you find helpful? Unhelpful?

8. What process did you / your team use to prepare your demonstration?

9. Did you achieve what you had hoped from this workshop?

10. Did anything go wrong?

11. What did you learn during the workshop?

12. Was there anything that concerned you about the workshop?

13. Did anything surprise you about the workshop?

14. Did you find the feedback grid tool helpful?

15. What are the next steps for your team? For JSSL?

8.1.6 Phase 7: Wrap-up: Concluding interview

1. What have you learnt about design throughout this journey?

2. Where did you see design bring the most value?

3. Where do you think more value could be gained from design?

4. Was there any situation where you struggled to see the value of design?

5. What there anything challenging about design?

6. Has design helped you engage with your stakeholders? If so, how?

7. Do you think that close engagement with end-users is important in a scientific process?

8. Is there anything you would change about how design was implemented in the JSSL?

9. What's next for the JSSL?

8.2 Sample of reflective journal

As described in **Section 3.3.3**, the structure of the reflective journal included introductory content (date, aim of session, participants) along with two columns to capture "observations" and "insights". For ease and speed of note-taking, abbreviations and symbols were often used. Sensitive and/or identifying information has been redacted the below examples.

8.3 Survey questions

Surveys were provided to all participants in the JSSL at two stages – Phase 4 to evaluate their understanding of prototyping, and a longer survey at Phase 7 to recap their overall experience as part of the project.

8.3.1 Phase 4: Understanding prototyping: Survey on prototyping

Individually, reflect upon and answer the following questions. Do not think of specifics relating to your JSSL project, just talk about prototyping in general as you understand it.

1. What is a prototype? What is your current understanding of prototyping as a concept?
2. How do you approach prototyping? What activities, people, materials, software, languages, etc. are involved?
3. What goes into prototyping in your field? What do you need to do it successfully?
4. In your experience, what are prototypes used for?

8.3.2 Phase 7: Wrap-up: Concluding survey
DESIGN AT THE JSSL

1. What is your current understanding of design?
2. How would you describe your experience of design in the JSSL? E.g., what did we do? How did you feel about it? Etc.
3. How has your understanding of design changed throughout the JSSL journey?
4. Is there anything you are still hoping or looking forward to exploring about design?
5. In what parts of the JSSL journey did you see design being involved? For example, research direction, problem definition, project development, etc.
6. Do you think design has been helpful or relevant? If so, how?
7. Has design helped or impacted your work within your own smaller teams (be it JSSL project teams, or in other work)? If so, how?
8. What are your thoughts on engaging with different design activities (e.g., problem definition, prototyping, ideation, innovation, etc.)?

THE JSSL JOURNEY

9. What have been some challenges in the JSSL? How did we overcome them (if at all)?

10. What do you foresee to be challenges moving forward? How might we mitigate them?

11. What do you think makes the JSSL unique compared to other scientific teams / projects?

12. What do you think is the value of having a multidisciplinary team such as ours?

13. What do you see as the next steps for the team? How might design be involved in this?

ENGAGING WITH RAAF

14. What value do you think RAAF / Defence have seen from design specifically?

15. What value do you think RAAF / Defence have seen from JSSL as a whole?

16. What are your thoughts on engaging so closely with an industry partner (RAAF) in a project like this?

DESIGN AND SCIENCE

17. Does design have a place in scientific research? If so, in what part(s) of the process?

18. What value / outcomes do you think design can bring in a scientific process?

19. What are the tensions / challenges of a design and science collaboration?

20. What are your recommendations for the integration of design and science? Some points to consider: the roles of different team members, the people involved, the amount of focus on design, the amount of focus on tech development, the level of involvement of end-users, the nature / frequency of workshops, etc.

21. Looking to the future and in general, how could a scientific lab / group best utilise design? Why?

22. Any other comments or feedback?

8.4 NVivo analysis – example and coding scheme

8.4.1 Coding example in NVivo

8.4.2 Coding scheme

Table 8.1: Coding scheme for thematic analysis in NVivo

Themes	Codes	Description	Example
Design principles, tools and approaches	Creative approaches or methods	Situations where the team either exhibited creative behaviour, or expressed interest in creativity	"You need to try sometimes. Physics is there, science is there, but you need to be creative and also put a bit of, I guess, love into what you are doing."
	Impact of language and terminology	Examples of language and terminology causing conflict and/or communication being recognised as a key factor in the project	"I feel like we're learning their language enough... it's probably more specific within each project to find out all the technical terms they use. And obviously it's important to be able to communicate with them and get on the same page."
	Using brainstorming to explore ideas	Instances of brainstorming sessions, examples of the JSSL ideation experience	"I want them to speak up more, I want more away from the team leaders but more from the engineers and getting them to get on the whiteboard, start sketching stuff, throwing out ideas - even crazy ideas at this stage."
	Using metaphors and drawing parallels	Situations where storytelling, analogies, and comparisons were used to make sense of a design idea or express a new perspective	"If I'm building a house and I put in something I don't like, what I'll do is just change or move it, right? It's as simple as that."
	Value of demonstration	Demonstration through pitching and prototyping	"The live demo went extremely well. Everything worked fine and we showed capabilities far ahead of schedule."
	Problem exploration	Reframing and understanding the problems to be tackled	"I think our problem statement is a very challenging one but it's very clear what we need to achieve."
Design and science engagement	Challenges in the design and science collaboration	Areas of friction or tension between the scientific research process and design process	"We dived into the project, started it, then realised that it was actually not really needed or was not solving actually a problem."
	Making science useful, translation	Examples where design supported the translation of science into real world impact or solutions	"I think we hit the ground running by doing a lot of technical work trying to meet some milestones, but I suppose what's really important is to make sure we're on the right path and get end-user perspective, otherwise we may invest too much into a technology that is not even needed!"
	Novelty, new capabilities and frontiers	Design's role in uncovering new applications for science and highlighting the novelty of the technology	"That's why you work with academics, 'cause they kind of develop something that you haven't thought about before."

	Perceived value of science	The changing valuation of science and what was considered to be important about JSSL technology	"The ideal best-case is that we impress them, such that they resonate with what we are already doing."
	Unique constraints	Challenges and barriers unique to the design and science collaboration	"It was very difficult to go back and talk about our persona… we sort of then tended towards the technical rather than the actual application."
	Desire to deliver value	The JSSL team expressing a desire to deliver solutions for their end-users	"The tech needs to solve someone's problem at the end of the day, whether it's cutting them time, or making their job easier."
Perceptions towards design	Comments on responsibility	The JSSL team expressing sense of ownership of their work and of design	"I kind of embraced that and tried to capture the needs from this particular virtual persona into the conversation. In fact, I took a bit of a role there in really trying to dig in a bit more"
	Humorous approach towards design	Situations where design activites were perceived in a light-hearted or sarcastic mindset	"There we go! Write your name down on those post-it notes with a big smiley face and put it up."
	Pride and showcasing	High satisfaction in one's own understanding, skill, or achievements	"Perception, perception, perception! So, it is extremely important that we present ourselves well."
	Traditional roles and thinking	Resorting to more siloed perspectives and behaviours based on tradition and disciplinary context	"I think most of the conversations are technical but I think it's very natural. Because I think the people in the room were very technical."
	Scepticism, resistance to design	A reserved and doubtful perspective, showing cynicism and a clearly negative opinion	"I feel like I'm bootstrapping, I'm using the same data to come up with new results."
	Uncertainty, hesitation	Demonstrating a lack of confidence and/or clarity	"It was uncomfortable for us to send [the personas] out, but once we got the bounce back, we feel much more comfortable going in tomorrow."
	Optimism, sees potential	Showing hope and confidence for the future; a tentatively positive outlook	"The JSSL team is basically getting into this new framework or new architecture of doing innovation and innovative work… I don't think mistakes are 100% wrong, it's more like a test, more like a trial."
	Desire to learn, curiosity about design	An eagerness and anticipation to uncover and understand more; curiosity	"It has been a journey of learning as well, a learning experience for us. It's new, and there's a lot of questions, but in general the approach that we have been taking - going step by step, learning, introducing new concepts, things like that - has been very useful."
	Positive, accepting	A positive perception towards design, accepting the role it could play	"The design process was very enlightening and constructive. It helped shape the strategy of the project and ensured we had end-user at the front. I felt very positive about it."
	Excitement	Embracing and deeply valuing; clear appreciation and positive opinions; looking forward to the future	"The design thinking framework is incredibly useful for focusing on user problems and validating your ideas."

Strategic thinking	Forward vision, setting goals	Situations where the team was setting goals and expressed alignment with their vision	"It's a proposition that takes time, I'd say, but it is where all of us are working towards."
	Progress and development	Forward momentum; conversations about progress, timelines, workflow	"When you're on the wrong path … there was loss of interest, or there was not enough engagement, and then projects usually just end. So, I think staying aligned is very important."
	Risk management	Risk aversion, and/or actions taken to avoid risk	"This a huge investment for us, for the whole group, so we really want to continue doing our best."
	Systematic approach	Evidence of a procedural or stepwise approach to an activity	"We have our clear goals for the workshops, we have our targets and our day-to-day work, what we are doing in the lab."
	Teamwork, coming together	Situations where the team showed cohesion, connectivity, working together	"I put more emphasis on the effort that the team has made, it has been a GREAT input from everyone in the group, and we are progressing at light speed. It's fascinating to see all the results that every team member has been putting together and I think that's very valuable."
User engagement	Broadening user perspectives	Expanding the breadth of what a user experience could look like, or who a user might be	"Prior to the meeting, as I was mapping out the persona, the exercise forced me to read into some articles about how decisions are made through various ranks in the Air Force. I found this to be useful."
	Responding to feedback, pivoting	Responses of the team to receiving feedback from end-users	"You need to go with the end-users' perspective. So, if you need to pivot, I think we need to pivot!"
	Stakeholder relationships and collaboration	Conversations or anecdotes about stakeholder engagement and its complexities	"We want a bit more clarity on the technical aspects of all our projects and how to serve our stakeholders and collaborators in a "win-win" situation."
	Understanding user needs	Uncovering the needs of end-users and attempting to address them	"You're constantly having to go out there, talk to customers, update your perspective on requirements, it's always evolving, you have different customers, who give you different perspectives on what's needed."

Prof Cara Wrigley
Discipline of Design Lab; School of Architecture, Design and Planning
Email: cara.wrigley@sydney.edu.au

Dear Cara,

The University of Sydney Human Research Ethics Committee (HREC) has considered your application.

I am pleased to inform you that after consideration of your response, your project has been approved.

Details of the approval are as follows:

Project No.:	**2019/858**
Project Title:	**Design as a catalyst for innovation in science**
Authorised Personnel:	**Wrigley Cara; Mackay Carol; Straker Karla; Eggleton Benjamin**
Approval Period:	**12 November 2019 to 12 November 2023**
First Annual Report Due:	**12 November 2020**

Documents Approved:

Date Uploaded	Version Number	Document Name
05/11/2019	V2	Participant Information Statement
05/11/2019	V2	Participant Consent Form
05/11/2019	V1	Post-survey questions
05/11/2019	V1	Pre-survey questions
05/11/2019	V1	Semi-structured interview questions
05/11/2019	V1	Focus Group Workshop Plan

Special Condition/s of Approval

- It is a condition of approval that any additional approval required from the Departments of Defence and Veterans' Affairs Human Research Ethics Committee is obtained and kept on file prior to the relevant part of the research commencing.

Condition/s of Approval

- Research must be conducted according to the approved proposal.

- An annual progress report must be submitted to the Ethics Office on or before the anniversary of approval and on completion of the project.

- You must report as soon as practicable anything that might warrant review of ethical approval of the project including:
  - Serious or unexpected adverse events (which should be reported within 72 hours).
  - Unforeseen events that might affect continued ethical acceptability of the project.

- Any changes to the proposal must be approved prior to their implementation (except where an amendment is undertaken to eliminate *immediate* risk to participants).

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ABN 15 211 513 464
CRICOS 00026A

- Personnel working on this project must be sufficiently qualified by education, training and experience for their role, or adequately supervised. Changes to personnel must be reported and approved.

- Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, as relevant to this project.

- Data and primary materials must be retained and stored in accordance with the relevant legislation and University guidelines.

- Ethics approval is dependent upon ongoing compliance of the research with the *National Statement on Ethical Conduct in Human Research*, the *Australian Code for the Responsible Conduct of Research*, applicable legal requirements, and with University policies, procedures and governance requirements.

- The Ethics Office may conduct audits on approved projects.

- The Chief Investigator has ultimate responsibility for the conduct of the research and is responsible for ensuring all others involved will conduct the research in accordance with the above.

This letter constitutes ethical approval only.

Please contact the Ethics Office should you require further information or clarification.

Sincerely,
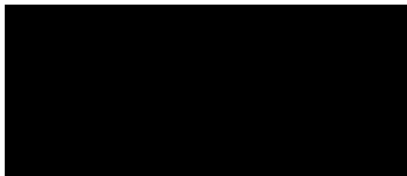
Associate Professor Jennifer Scott Curwood
Chair
Humanities Review Committee (Low Risk)

The University of Sydney of Sydney HRECs are constituted and operate in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007) and the NHMRC's Australian Code for the Responsible Conduct of Research (2007)

185-19 – Design & Innovation Research Engagement: Understanding the Role of Design in the Australian Defence Force

The Departments of Defence and Veterans Affairs Human Research Ethics Committee has authorised your research for two years **from 14 February 2020 to 14 February 2022** subject to your assurance in regard to the conditions below. Failure to abide by these conditions may result in ethical approval being withdrawn.

All completed forms are to be scanned and emailed to ddva.hrec@defence.gov.au

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I acknowledge and agree to the following requirements:

- The protocol number and title are to be quoted in all correspondence.
- The Committee requires confirmation that your project has begun, or notification that it has been delayed or abandoned.
- If data collection does not commence within twelve months of this approval, the protocol will need to be resubmitted.
- You acknowledge that the research is to be conducted in a manner which minimises adverse effects in accordance with the *National Statement on Ethical Conduct in Human Research* and the *Australian Code for the Responsible Conduct of Research*.
- The research will be conducted in accordance with the approved protocol; including the approved mechanisms for the recruitment of participants (ensuring that any inclusion and exclusion criteria are applied) and that you will ensure that no contact, accidental or otherwise, will be directed to deceased personnel or their families without appropriate Defence authorisation.
- Only approved investigators (those listed in the approved protocol) will access files and associated documentation in relation to the project file.
- Committee approval must be sought before any **amendments** to the protocol are instituted.
- If your research is to continue beyond the two year approval time, an extension of ethical approval is to be sought in writing.

Research Participants

- A copy of the *Guidelines for Volunteers* is given to every participant when they are recruited.
- All participant consent forms will include the committee's ethical approval number, committee contact details and period that ethical approval has been granted for.
- You must retain records of your participant's details, any withdrawals, reasons for that withdrawal (if known) and provide such information on request.

Reporting

- The Committee requires that you provide notification of any change in your contact details at ddva.hrec@defence.gov.au.
- The Committee must be informed of any **serious adverse events within 72 hours** or **adverse events within 30 days**.
- You are required to submit **annual progress reports**. Your first report is due by **14 February 2021**.
- A comprehensive **Final Report** which details the conduct of the project and its findings is to be submitted as soon as possible after the project has finished.

Research Dissemination

- Ethical approval is given subject to your explicit agreement to an intention to publish. Publication should be in a refereed journal or other source open to public audit. It would be appropriate to include in your submission for publication the phrase "Ethical clearance for this project was provided by the Departments of Defence and Veterans Affairs Human Research Ethics Committee." Should a security classification make publishing in an open source inappropriate, the Committee is to be notified in writing.
- All manuscripts and abstracts (and if requested presentations) will be submitted in advance in accordance with Defence and/or DVA procedures for clearance.
- Copies of manuscripts, abstracts and/or presentations will be submitted in advance in accordance with Defence and/or DVA procedures for clearance.
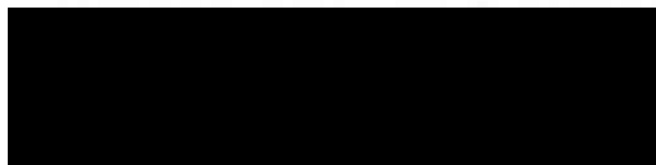
CARA WRIGLEY
Name

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