MONASH University

Brain-Computer Integration

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Abstract

Brain-Computer Interface (BCI) systems facilitate the flow of information between brains and computers. These systems hold the potential to foster human flourishing and self-actualization. However, contemporary BCI systems unnecessarily limit these potentialities as their design is approached from a traditional interaction perspective, producing command-response interfaces. This dissertation proposes to go beyond interaction and toward a paradigm of human-computer integration, moving from brain-computer interfacing to brain-computer integration. The potential of this paradigm is demonstrated through three prototypes: Inter-Dream, a system that integrates with the brain's autonomic physiological processes to drive users toward healthy sleep states; Neo-Noumena, a system that integrates with the user's affective neurophysiology to augment the interpersonal communication of emotion; and PsiNet, a system that integrates interpersonal brain activity to amplify human connection. Studies of these prototypes suggested the superiority of the integration paradigm in realising the multifaceted benefits of BCI systems, and this dissertation presents the Brain-Computer Integration Framework to help guide designers of future BCI integrations in this approach.

Declaration

This thesis is an original work of my research and contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, expect where due references is made in the text of the thesis.

Print Name: Nathan Semertzidis

Date: 6th September 2021

Publications During Enrollment

A significant majority of the research detailed through this thesis has been peer-reviewed, published, and presented to the wider Human-Computer Interaction (HCI) community. These works have also been presented at several academic venues. A list of these publications can be viewed below. A comprehensive list of publications, projects, and research progress can also be viewed online at www.nathansemertzidis.com

Peer Reviewed Publications

Full papers

- Andres, J., **Semertzidis, N.**, Li, Z., Wang, Y., Mueller, F. (2022) Integrated Exertion-Understanding the Design of Human-Computer Integration in an Exertion Context. *ACM Transactions on Computer-Human Interaction.*

- Mueller, F., Lopes, P., Andres, J., Byrne, R., **Semertzidis, N.**, Li, Z., Knibbe, J., & Greuter, S. (2021). Towards understanding the design of bodily integration. *International Journal of Human-Computer Studies, 152*, 102643.

- **Semertzidis, N.**, Scary, M., Andres, J., Dwivedi, B., Kulwe, Y. C., Zambetta, F., & Mueller, F. (2020, April). Neo-Noumena: Augmenting Emotion Communication. *In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-13).*

- Andres, J., Schraefel, M., **Semertzidis, N.**, Dwivedi, B., Kulwe, Y. C., von Kaenel, J., & Mueller, F. (2020, April). Introducing Peripheral Awareness as a Neurological State for Human-Computer Integration. *In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-13).*

- **Semertzidis, N.** A., Sargeant, B., Dwyer, J., Mueller, F. , & Zambetta, F. (2019, May). Towards Understanding the Design of Positive Pre-sleep Through a Neurofeedback Artistic Experience. *In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-14).*

Full papers under review

- Mueller, F., Andres, J., **Semertzidis, N**., Mehta, Y., Li, X., Matjeka, L., Marshall, J., & Benford, S. (2021). Towards understanding the design of intertwined human-computer integrations. *ACM Transactions on Computer-Human Interaction.*

- **Semertzidis, N**., Zambetta, F., Mueller. F. (2021). *Brain-Computer Integration. ACM Transactions on Computer-Human Interaction.*

Short papers

- **Semertzidis, N.**, Scary, M., Andres, J., Kulwe, Y., Dwivedi, B., Zambetta, F., & Mueller, F. (2020, April). Neo-Noumena. In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-4).

- Patibanda, R., **Semertzidis, N.** A., Scary, M., La Delfa, J. N., Andres, J., Baytaş, M. A., ... & Mekler, E. D. (2020, April). Motor Memory in HCI. In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-8).

- Danry, V., Pataranutaporn, P., Haar Horowitz, A., Strohmeier, P., Andres, J., Patibanda, R., ... & **Semertzidis, N**. (2021, May). Do Cyborgs Dream of Electric Limbs? Experiential Factors in Human-Computer Integration Design and Evaluation. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (pp. 1-6).

- Fang, X., **Semertzidis, N.**, Scary, M., Wang, X., Andres, J., Mueller, F. F., & Zambetta, F. (2021, October). Telepathic Play: Towards Playful Experiences Based on Brain-to-brain Interfacing. In Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (pp. 268-273).

- **Semertzidis, N. A.**, Scary, M., Fang, X., Wang, X., Patibanda, R., Andres, J., ... & Mueller, F. (2021, May). SIGHInt: Special Interest Group for Human-Computer Integration. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (pp. 1-3).

- **Semertzidis, N.,** Fang, Z. X., Lopes, P., Kunze, K., Pangaro, P., Mueller, F., Maes, P. (2022). What We Talk About When We Talk About Human Computer Integration. In Extended Abstracts for the 2022 CHI Conference on Human Factors in Computing Systems.

- Dickinson, R., **Semertzidis, N.**, Mueller, F., (2022). Machine In The Middle: Exploring Dark Patterns of Emotional Human-Computer Integration Through Media Art. In Extended Abstracts for the 2022 CHI Conference on Human

Factors in Computing Systems. **Honourable Mention for Best Case-Study Award**

Public Presentations

- *Towards Understanding the Design of Positive Pre-sleep Through a Neurofeedback Artistic Experience* was presented as a full paper at the 2019 Conference on Human Factors in Computing Systems (CHI).

- The results and findings of *Towards Understanding the Design of Positive Pre-sleep Through a Neurofeedback Artistic Experience* were reported in many news outlets, including: ABC News, Neuroscience News; HealthXpress; Engadget; EurekAlert; AffinityVR; Science Daily; Digital Trends; and China Daily.

- The results and findings of *Towards Understanding the Design of Positive Pre-sleep Through a Neurofeedback Artistic Experience* were discussed in an ABC radio interview, and the Triple-R radio segment "Sleep Talker Radio". These are both national radio stations with ABC being the official state-sponsored radio station of Australia, and Triple-R being one of the countries largest independent radio stations, run as a community radio station based in RMIT University, Melbourne, Australia.

- *Neo-Noumena: Augmenting Emotion Communication* was presented as a full paper at the 2020 Conference on Human Factors in Computing Systems (CHI).

- The results and findings of *Neo-Noumena: Augmenting Emotion Communication* were reported in many news outlets, including: Canberra Times; ZDNet; and the official OpenBCI newsletter;

- The results and findings of Neo-Noumena: Augmenting Emotion Communication were discussed in an interview with the Cairns Indigenous Community Radio Station, Bumma Bippera Media.

- Results and Insights from *Towards Understanding the Design of Positive Pre-sleep Through a Neurofeedback Artistic Experience* and Neo-Noumena: Augmenting Emotion Communication were presented and discussed during a co-organised workshop titled *Motor Memory in HCI*, as part of the 2020 Conference on Human Factors in Computing Systems (CHI).

- The research methods I employed in completing my research were presented at Monash University, Australia, as a guest speaker for the Advanced Research Methods course in October 2020.

- As part of the 2021 Conference on Human Factors in Computing Systems (CHI), I hosted the 2021 Special Interest Group for Human-Computer Integration.

- As part of the 2021 Conference on Human Factors in Computing Systems (CHI) I co-organised and assisted in running the 2021 workshop *Do cyborgs dream of electric limbs? Experiential Factors in Human-Computer Integration Design and Evaluation*.

- As part of the 2021 "Cognitive Sensations: Downloadable Brain" event I presented, alongside artist Rod Dickinson, an artwork we co-created titled "machine_in_the_middle". This was a recording of an interactive system which senses a wearer's brain activity to detect their emotional state, and then force a facial expression associated with that emotional state onto the wearer's face through electrical muscle stimulation. The artwork, reflection, and presentation can be found at: https://www.cognitivesensations.com/our-work/machine-in-the-middle

- As part of the 2022 Conference on Human Factors in Computing Systems (CHI), I hosted the 2022 panel discussion What We Talk About When We Talk About Human-Computer Integration.

- *Machine in the Middle: Exploring Dark Patterns of Emotional Human-Computer Integration Through Media Art* was presented as a full paper at the 2022 Conference on Human Factors in Computing Systems (CHI).

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I am thankful to the Faculty of Information Technology, Monash University for supporting my research with a Postgraduate Research Scholarship. Thank you to the Department of Human-Centered Computing at Monash for being so welcoming when we joined you all. I would also like to thank all my panel members at my PhD milestones, Prof. Patrick Oliver, Prof. Bernd Meyer, A/Prof. Joanne Evans, A/Prof. Bernie Jenny and Dr. Tom Bartindale, for their great insights, comments and feedback.

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And the best, I must admit, I have saved for last. Thank you Michaela. This is your PhD as much as it is mine. We did the whole thing together. Every thought, every concept, it is ours. Thank you for making me so much better than I could have ever been on my own. God knows I would have never been able to pull this off without your supreme intelligence and infinite creativity. You are my muse and this is for you. I hope we solve consciousness together one day, merge our minds, and exist as a singular entity inside an infinite network of information forever.

Contents

1 Introduction

This thesis explores the design of brain-computer integration systems, specifically considering , specifically considering how the design of these systems influence their resultant user experiences from a phenomenological perspective. Before proceeding, I highlight that key terms in this thesis share similar acronyms when abbreviated, that is: human-computer interaction and human-computer integration; and brain-computer interface and brain-computer integration. To offer clarity and avoid confusion I will define each as the following. The acronym HCI refers to human-computer interaction, the field of research chiefly concerned with studying the design and use of computational technology and exploring novel interactions between humans and computers - human-computer integration - abbreviated as HInt, refers to a theoretical subset or extension of HCI chiefly concerned with the design and phenomenological experience of systems that tightly couple with, or extend the human body (this abbreviation (Hint) has previously been used by Mueller et al., 2021). Brain-computer interface, abbreviated as BCI throughout this thesis, refers to technologies which mediate a channel of information exchange between the human brain and a computer. Finally, brain-computer integration, the field this thesis establishes and contributes to, will be referred to in full without abbreviation, so as to not confuse it with BCI. In this chapter, I briefly introduce the research motivation and articulate the thesis statement, research scope, contributions, and thesis structure.

1.1 Brain-Computer Interfaces and Human-Computer Integration

Since its widespread adoption, the computer has consistently been used as an analogy to describe the human brain (Kirkland, 2002). With this considered, one could say it was only a matter of time before we conceived the idea to plug one into the other. This is the chief interest of the technology known as the brain-computer interface (BCI). The term brain-computer interface refers to technologies that facilitate the direct transfer of information between brains and computers, and it has long been a trope of science fiction (Nam, Nijholt, & Lotte, 2018). Controlling machines with the brain, manipulating memories, mind control, mind uploading, consciousness cloning, dream exploration, instant communication, telepathy, cognitive enhancement, superintelligence, infinite knowledge, and even immortality are just some of the concepts countless artists, authors, and screenwriters have explored all from the seat of this infinitely useful device (Gilbert, Pham, Viaña, & Gillam, 2019).

However, with recent developments in technology, what was once science fiction is now not only science, but a consumer product with an exponentially growing market size (Kawala-Sterniuk et al., 2021; Wong, Merrill, & Chuang, 2018). In the last 40 years, BCI has gone from a laboratory novelty to an assistive technology empowering sufferers of diseases such as paralysis, to what is now becoming a trendy consumer device (Rupp et al., 2014; Vasiljevic & de Miranda, 2019; Wong et al., 2018). As such, many consumer electronic companies have begun to integrate BCI products into their production roadmaps (Gonfalornieri, 2021; Cattan, 2021), with some already released. Consumer BCI devices have often been presented as mind-operated remote controls, intended for gaming and interacting with other digital content through user brain activity (Krigolson, Williams, Norton, Hassall, & Colino, 2017; Hammond, 2011; Stegman, Crawford, Andujar, Nijholt, & Gilbert, 2020). While such devices indeed offer novel experiences, they are often just that - novel -, with BCI-driven control often tediously difficult to learn, slow to respond, and largely inaccurate in reading the user's intentions (Douibi et al., 2021; George, Smith, Madiraju, Yahyasoltani, & Ahamed, 2021; Mridha et al., 2021).

Considering these issues, more contemporary BCI companies are beginning to realise that the strength of the technology is not in specific and intentional control, but rather in the sensing of more ambiguous and experiential brain phenomena, such as states of cognition and consciousness. This has produced a shift in the marketing of consumer BCI as self-monitoring wellness technologies, with applications such as sleep monitoring, meditation and mindfulness training; as well as focus and productivity enhancement (Hildt, 2021; Stockman, 2020). Yet still, many of these products overlook the unique affordances offered by a technology that can access the user's brain, and often oversimplify complex cognitive phenomena as arbitrary wellness metrics; designing applications that I believe are just as well addressed through simpler and cheaper biosensing technologies.

In the context of such trends, many executives, developers, and even researchers have lamented the presence of a readily available and distributable advanced technology, with a severe lack of applications (Gonfalornieri, 2021; Cattan, 2021; Douibi et al., 2021). Furthermore, major industry voices, such as Thomas Reardon - head of Facebook's CTRL-Labs - have publicly stated that BCI is a technological dead-end that will be superseded by electromyography (EMG) - a technology that extracts and infers information from muscle signals (George, 2018). While this notion should appear laughable, considering brain activity supersedes EMG by containing within it the informational source of muscle activity read by EMG, if the way we design BCI systems does not change, this negative assessment of the future of BCI technology leading to a dead-end may very well be correct. But why is this the case? Do we as a species just collectively lack the imagination and creativity necessary to go beyond brain-based remote controls (Athanasiou et al., 2017; Leeb et al., 2007; M. Li et al., 2021)? I find this doubtful, especially when reconsidering the bountiful array of example applications provided to us through science-fiction.

Through this dissertation, I argue that it is not a problem of the technology being a dead-end, or insufficiently developed, that is stopping us from realising useful, interesting, impactful and life-changing BCI applications. Rather, I suggest that it is the absence of any formally articulated design knowledge to guide the development of BCI systems causing stagnation in BCI development. With the most recent general design framework for BCI design being published in 2003 (Mason & Birch, 2003), the state of the art for conceptualising BCI design has been limited to medical models with a dominant interaction design paradigm of technologies as tools whose relationships with humans are limited to command and response. To push the development of BCI systems beyond this conceptual position, I, through this dissertation, employ the emerging paradigm of "Human-Computer Integration" (HInt), a theory which concerns the design and phenomenological experience of systems which tightly couple with or extend the human body (Mueller et al., 2020; Farooq et al., 2018) to formulate a new framework to describe the design of BCI systems. It is through this framework that I ultimately argue that the future of BCI is not one of interaction between brains and computers, but one of *Brain-Computer Integration.*

1.2 Thesis Statement

In this thesis, I address the research question: *"How do we design brain-computer integration?"*. Here, integration refers to "human-computer integration" - an HCI paradigm that acknowledges that computers can be agential actors, allowing for the conceptualization of human-machine systems which merge to form one cohesive whole. To answer the question, I followed a research-through-design lead process, including the development of three prototypal systems iterating over different aspects of brain-computer integration. Designing and studying these systems allowed for the exploration of brain-computer integration from a range of perspectives. Through the analytical reflection of each of these perspectives, the qualities emergent from subsequent experiences these prototypes afforded were broken down and compared across each iteration, thereby leading to the creation of the brain-computer integration framework (figure 1). Ultimately, it is the aim of this work that future designers are inspired to consider and understand how their systems can interact, and ultimately integrate, with brain activity through the brain-computer integration framework. Furthermore, it is intended that this work illustrates how the design opportunities afforded by brain-computer integration can be realised through actionable design strategies for designing new systems.

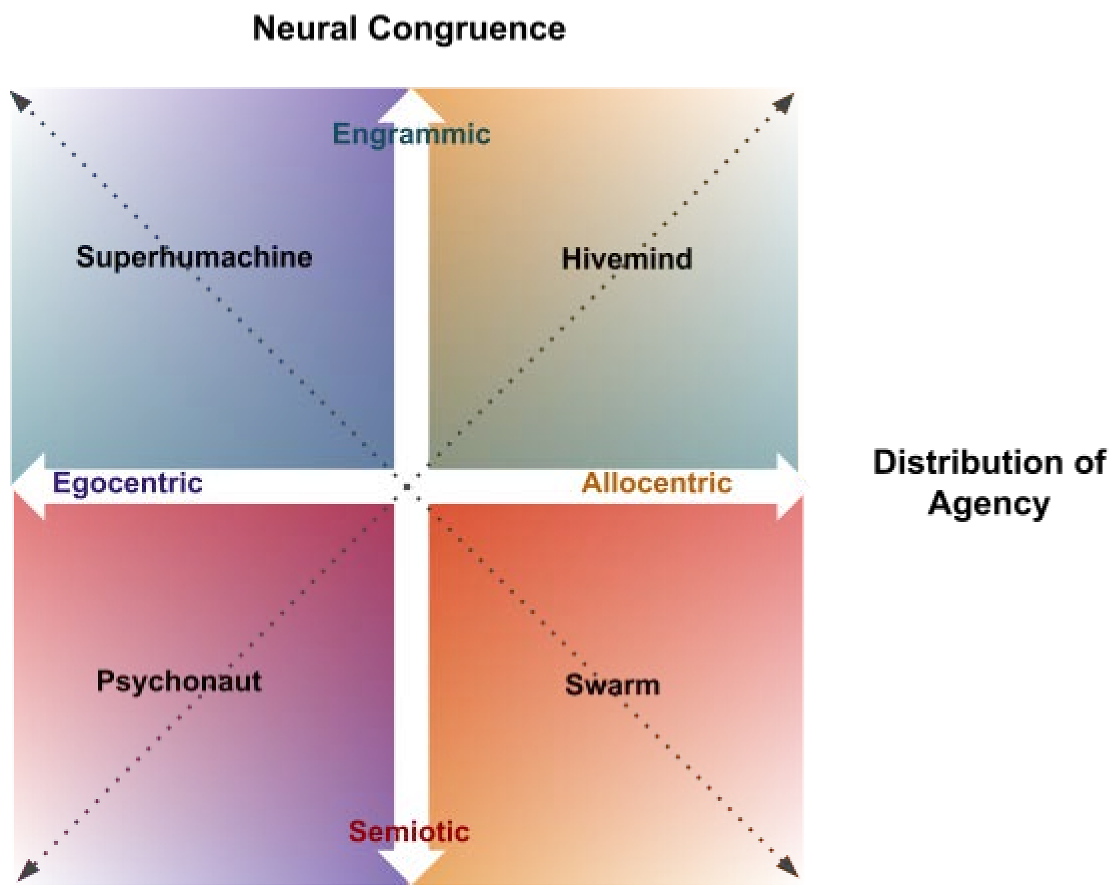

Figure 1. The Brain-Computer Integration Framework.

In order to answer the research question, the work presented here addresses four key objectives:

1. **Understand the interactions between brain activity and technology afforded by brain-computer interfaces, and identify opportunities for new knowledge emerging from the interpretation of the user experience afforded by brain-computer interfaces through human-computer integration concepts.** This objective was achieved through the literature review involving the critical analysis and discussion of related works reported in chapter two of the thesis. In consulting existing theory and the works of those who had come before me, I was able to identify where our understanding within the context of these concepts was most lacking, and thus where I should begin exploring the design space of brain-computer integration.

2. **Develop an appropriate method of investigating the research question.** Considering the literature critically analysed throughout chapter two, a research methodology was constructed acknowledging the conventions in the fields that informed this thesis; including HCI, the neurocognitive sciences, and psychology. It was in adopting these research methods that I was able to address the multidisciplinary research question core to this thesis, and I report these methods in chapter three.

3. **Explore the design space of brain-computer integration.** Three prototype systems were designed and evaluated through deployment and subsequent user studies. In turn, the design space of brain-computer integration was revealed through reflecting on each prototype, detailed in chapters four to seven.

4. **Create a theoretical framework articulating brain-computer integration.** Through completion of the above objectives, the brain-computer integration framework was synthesised, articulated in chapter 7. This framework emerged from the evaluation of all three case studies and their resultant findings, which were analysed across case studies thematically; ultimately surmounting to the brain-computer integration framework. In chapter 7, this framework is presented descriptively, and illustrates how it can be used to explain brain-computer integration systems. Further, in chapter 8, the framework is presented prescriptively, illustrating to designers how they should employ the framework to design for a given user experience they are striving toward. Finally, in chapter 9, the framework is validated through a validation workshop, demonstrating the validity of its descriptive and predictive abilities, and its usefulness to other BCI researchers and practitioners.

1.3 Research Scope

Considering the multidisciplinary nature of the present thesis, it is worth clarifying that the scope of this thesis has been articulated as follows:

- This work aims to understand brain-computer interfaces from a human-computer integration perspective rather than a solely interaction perspective. In the work “Next steps for Human-Computer Integration”, Mueller et al. (2020) state that integrated systems would benefit from the knowledge of how systems can operate just beneath or just above the user’s awareness, as well as just ahead or just behind the users intent, suggesting implicit - not requiring conscious effort or awareness - interaction to be an important part of integration systems. As such, this dissertation focuses on brain-computer interfaces that implicitly react to, or act on, brain activity (e.g. neurofeedback, brain state classification and neuromodulation), as opposed to traditional brain-computer interfaces that act as “controllers" (e.g. steady-state-evoked-potential based systems).

- It has been acknowledged that many technologies do interact with, modulate, mediate, and augment cognitive processes (Menary, 2010). For example, Clark suggests we are already cyborgs to some degree, since our brains are shaped throughout our lives to better interface with technology, and argues that devices such as smartphones have become an external addition to our cortex, functionally acting as “the other half of the brain” (Clark, 2004). Nonetheless, this thesis focuses specifically on brain-computer interfaces, as this technology arguably provides the most direct means of brain-computer integration. Additionally, while the term brain-computer interface includes a large variety of technologies (e.g. EEG, MRI, fNIRS, HEG) the present thesis focuses on EEG, as it is currently the most accessible and widely adopted of these devices (Abiri, Borhani, Sellers, Jiang, & Zhao, 2019; Chu, 2017).

- The technologies, prototypes, and designs investigated, developed, and evaluated through this thesis hold strong potential for application in clinical contexts. This is further evident when considering the origin of neural interfaces in the medical field. While this thesis acknowledges the strong motivation for understanding how these technologies can be applied to improve the lives of clinical populations, the direct investigation of this application is beyond the scope of this thesis. Rather, this thesis aims to investigate how such technologies and the experiences they bring might be widely adopted by the general population in an attempt to envision how these technologies may interact with and shape our everyday lives. As I argue that neural interfaces will one day be a ubiquitous technology, it is important to understand how to design these technologies for a general population.

1.4 Case Studies

To answer my research question, three case studies were conducted to provide the artifactual probes through which the brain-computer integration framework was created. Each case study sought to answer a sub-research question that represented a necessary step in understanding the design of brain-computer integration as a whole. The sub research questions ask “*how do we design integrated BCIs to ...*”: *regulate*, *communicate*, and *interpersonally integrate* brain activity, with the understanding of each of these processes being important steps in understanding the design of brain-computer integration as a whole. This each step was determined ad-hoc and iteratively, guided by the findings, insights, and directions for future work provided by the preceding case study. The prototype designed in each case study was designed for a unique application-domain related to the case study's research question, to help contextualise how brain-computer integration systems may be designed and deployed for real-world applications; demonstrated below in table 1.

Table 1. The three case study systems and their characteristics.

System	**Technology**	**Application**	**Aim**
Inter-Dream	BCI + virtual reality	Sleep	Facilitate healthy pre-sleep
Neo-Noumena	BCI + augmented reality	Communication	Augment emotion communication
PsiNet	BCI + transcranial electrical stimulation	Synchrony	Amplify inter-brain synchrony

In the following sections, an overview is provided for each case study, along with the sub-research question they were designed to answer.

1.4.1 Case Study I: Inter-Dream

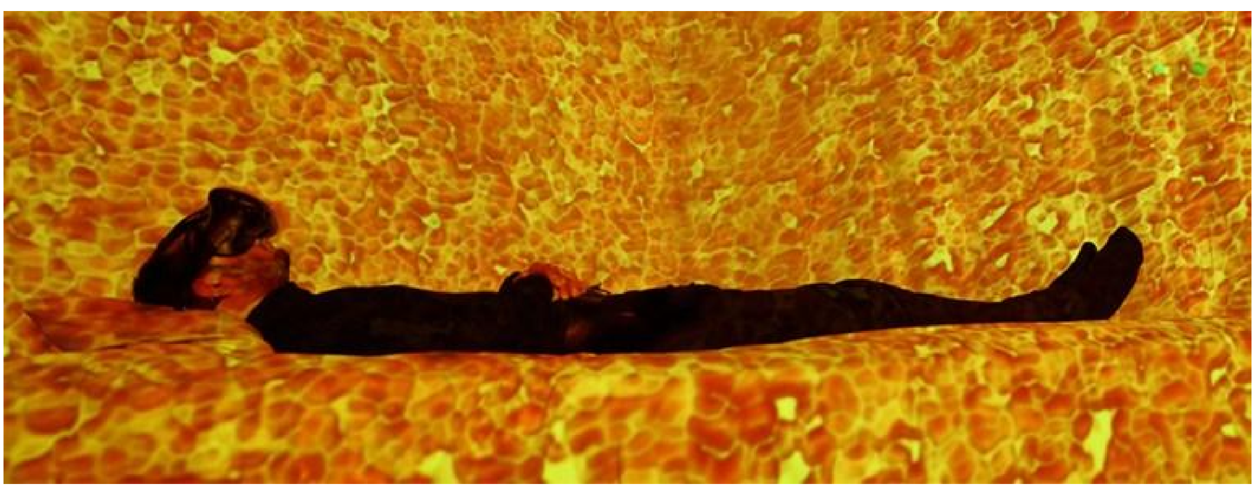

Figure 2. Inter-Dream, a neurofeedback driven installation that feeds brain activity back to participants in real-time through artistic representations of neural electrophysiology.

The first case study aimed to answer the sub-research question: "*How do we design integrated brain-computer interfaces for regulating brain activity?*". To do this, this case study explored how BCIs can regulate brain activity by studying the system "Inter-Dream" (figure 2), a multisensory, neurofeedback-driven, interactive art installation in which participants rest in a haptic bed whilst their brain activity is fed back to them in virtual reality. In a study of Inter-Dream, twelve participants individually rested, augmented by Inter-Dream. Results demonstrated: statistically significant decreases in pre-sleep cognitive arousal (t (1,11) = 3.11, p = .01, d = .28), negative emotion (t (1,11) = 3.25, p = .008, d = .90), and negative affect (t (1,11) = 3.64, p = .004, d = .90). EEG readings were also indicative of *restorative restfulness* and *cognitive stillness*, while interview responses described experiences of *mindfulness* and *playful self-exploration*. These results lead to forming the foundation of the brain-computer integration framework. Namely, the insights gained from the exploration of this first case study were that feedback and agency are two critically influential factors of a BCI system when considering the user experience. This case study is described in chapter four.

1.4.2 Case Study II: Neo-Noumena

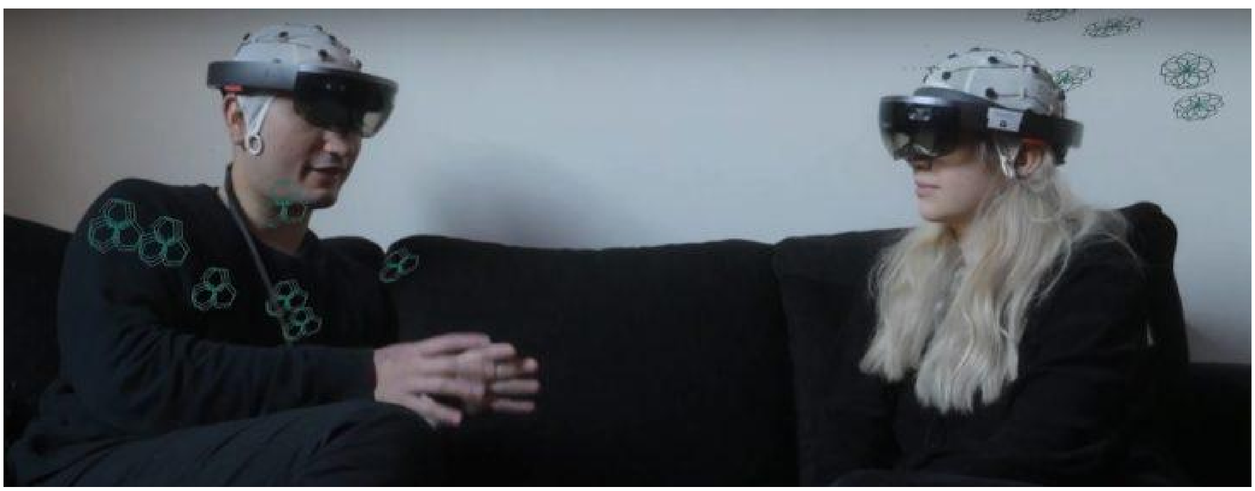

Figure 3. Neo-Noumena, a BCI-driven system that reads the affective brain activity of its user and dynamically represents it to others in mixed-reality to interpersonally communicate emotion.

The second case study aimed to answer the sub-research question: "*How do we design integrated brain-computer interfaces for communicating brain activity?*". To answer this question, this case study explored how BCIs can communicate brain activity (in this case emotion) by studying the system "Neo-Noumena" (figure 3). Neo-Noumena is a communicative neuro-responsive system that uses brain-computer interfacing and machine learning to read one's emotional states and dynamically represent them to the user and others in mixed-reality through head-mounted displays. In the study, five participant pairs were given Neo-Noumena for three days, using the system freely.

Measures of emotional competence demonstrated a statistically significant increase in participants' ability to interpersonally regulate emotions. Furthermore, participant interviews revealed themes regarding "*spatiotemporal actualization*", "*objective representation*", and "*preternatural transmission*". Through Neo-Noumena, the framework was extended through the realisation that brain activity could not merely be conceptualised as "feedback" but rather as abstract information. Thus, BCI processes can be likened to encoding-decoding processes through evoking Shannon Information Theory and Verbeek's post-phenomenological framework of human-technology mediation (Verdu, 1998; Rosenberger & Verbeek, 2015; Verbeek, 2005; Verbeek, 2015). Furthermore, the findings of Neo-Noumena suggested that BCI-related agency has a variable distribution between the agents and actors participating in the flows of information mediated by the system, informing the framework with the knowledge that agency was not only something possessed by users' brains, but also by other agents acting on or within the system, such as the environment. This case study is described in chapter five.

1.4.3 Case Study III: PsiNet

Figure 4. PsiNet, a network of wearable brain-to-brain interfaces that aims to synchronize brain activity between its users and strengthen interpersonal connections.

The third case study aimed to answer the sub-research question: *"How do we design integrated brain-computer interfaces for synchronising brain activity interpersonally?"*. This case study explored the interpersonal integration of consciousness through brain-to-brain integration of participants via the system "PsiNet" (figure 4). PsiNet is a networked wearable brain-to-brain system designed to amplify inter-brain synchrony across its users by sensing brain activity through electroencephalography (EEG) and by modulating brain activity through transcranial electrical stimulation (tES). The outcomes of an in-the-wild study suggest that brain-to-brain interfaces are feasible for supporting interpersonal connections. The analysis of electroencephalographic (EEG) data revealed a statistically significant increase in inter-brain synchrony, and qualitative participant interviews revealed three themes that describe a user experience, inclusive of "*hyper-awareness*"; "*relational interaction*"; and the "*dissolution of self*". The findings of this case study extend the framework through the realisation that brain signals can be received without the need for user interpretation, permitting the user to experience them as if they were generated by their own body. This finding, distinguished from the findings of the previous case studies in regard to how information is presented, ultimately lead to the formulation of the framework's axis "neural congruence". Furthermore, this case study demonstrated that sense of agency and sense of ownership are things that can be distributed between brains, which when considered with the results of the previous case studies, synthesised into the "distribution of agency" axis of the brain-computer integration framework. This case study is described in chapter six.

1.5 Contributions to Knowledge

This work makes the following contributions:

1. This research contributes to design knowledge by documenting the design of three experiences of brain-computer integration, along with the insights gained from the process of their development. The case studies and design prototypes demonstrate how brain-computer interfaces can be designed with human-computer integration in mind.

2. This research contributes to design theory by extending the existing paradigm of human-computer integration to consider how technology can be integrated with the human brain to participate in, mediate, and modulate its underlying neurocognitive processes through brain-computer interfaces.

3. This research presents the brain-computer integration framework. It is the first theoretical conceptualisation of how to design for the integration of neurocognitive processes from humans-to-computers, and humans-to-humans. The framework was derived through the synthesis of the findings of three case studies. Each case study consisted of recurring themes and functional mechanisms. These insights provide a high-level understanding of the design space and possible user experiences of brain-computer integration, while also beginning to explain the functional mechanisms that allow for these documented user experiences to emerge. These themes also influenced the production of design strategies, which ultimately inform designers in the development of

brain-computer integration systems and how to achieve the desired user experience exemplified in the themes.

1.6 Thesis Structure

The structure of the thesis is outlined below in table 2.

Table 2. Outline of thesis structure

Chapter 1	Introduction: This section presents an overview of the research topic, along with the articulation of the thesis statement, research scope, contributions, and thesis structure.
Chapter 2	Related Work: This section presents a review of related research that has informed, guided, and motivated the present thesis.
Chapter 3	Methods: This section illustrates the methodology applied toward the completion of the thesis.
Chapter 4, 5, and 6	Case studies Inter-Dream, Neo-Noumena and PsiNet. These chapters detail the development and evaluation of each prototype and the subsequent interpretation of the results they yielded.
Chapter 7	The brain-computer integration framework: This chapter synthesises the findings from the three prior chapters as a framework, articulating the design space of brain-computer integration.
Chapter 8	Design Strategies: This chapter reflects on the design of the three prototypes, and while considering the newly articulated brain-computer integration framework, provides design strategies for designers of brain-computer integration systems, helping designers navigate the design space.
Chapter 9	Validation: This chapter details the workshop which was conducted to

	validate the framework. The methods and results of the workshop are presented, along with a discussion of these findings.
Chapter 10	Conclusion and Future Work: This chapter concludes and summarises the thesis, with next steps for research in brain-computer integration also being outlined.

1.7 Summary

In this chapter, the concept of Brain-Computer Integration was introduced, along with motivation and rationale for its study, culminating in a research question, while outlining the overall aim and structure of the thesis. The next chapters will illustrate the surrounding literature and background research in greater detail, working to help articulate the gap in contemporary HCI research regarding the integration between technology and human brain activity. The study and evaluation of each prototype designed to address this gap will be detailed, leading to the cumulation of findings which will thereby be synthesised into the brain-computer integration framework, a set of design strategies, and a discussion of the future of brain-computer integration.

2 Related Work

This section delivers a review of the existing work preceding, informing and leading up to the present investigation which is this thesis. I begin by describing the current state of the art in contemporary HCI based BCI research and practice. This is followed by a description of existing frameworks, and the observation of the opportunity for new developments in BCI design knowledge through the adoption of a human-computer integration perspective. Finally, these points are considered to ultimately produce the research question of this thesis.

2.1 Brain-Computer Interface Research in HCI

While the majority of BCI research has been conducted in the context of neuroscientific, medical, and biomedical engineering research, BCI devices have also recently begun to be discussed in the context of HCI research. From a contemporary HCI lens, BCI is typically approached as a means for enhancing human-computer interactivity, rather than as a control interface.

2.1.1 BCI for Neurofeedback

In light of the recent emphasis HCI research has placed on enabling reflection and supporting meditative practices (Nunes et al., 2015; Sliwinski, 2019; Terzimehić, Häuslschmid, Hussmann, & schraefel, 2019), a large majority of BCI research in HCI has explored the representation of brain activity through various interactive technologies. These systems are typically designed to offer some form of neurofeedback, in which the system interprets an individual's neural activity and provides a representation of their mental state in real-time, which users can observe and learn to self-monitor or regulate, mostly for mindfulness training.

One example of this is “Inner Garden", where a living world is projected onto a desktop-sized sandbox using augmented reality (Roo, Gervais, Frey, & Hachet, 2017). This world is populated in accordance to how frustrated, or how meditative the participant is. Through monitoring any changes to this world, the participant receives information about their degree of focus in a neurofeedback loop, with the goal of encouraging mindfulness. Similarly, another example of this is “PsychicVR”, which pairs BCI with VR to produce an immersive playful experience; allowing users to make changes to a virtual 3D environment when in a focused state of mind, and thereby encouraging mindfulness (Amores, Benavides, & Maes, 2016).

A system that also attempts to enable the regulation of brain activity is “Lucid loop”, a neurofeedback system designed to simulate the experience of lucid dreaming and train participants in achieving lucid dream states (Kitson, DiPaola, & Riecke, 2019). EEG data is used to assess a participant's degree of focused attention or “lucidity”. This is then fed back to the participant through dream-like visuals generated via a deep convolutional neural network (DCNN) in real-time. Specifically, when participants exhibit lower levels of lucidity, the DCNN generates more “abstract” visuals to represent dreaminess. As the participants’ lucidity increases, so too do the clarity of the visuals generated, resulting in an open nature scene.

Taken together, these studies demonstrate the potential to enrich the human experience and promote a strong coupling between the processes of the technology and the user's underlying neural activity. With this considered, these BCI systems represent an alternative perspective in the application of BCI beyond its longstanding conception of a brain-based controller interface.

2.1.2 Social BCI

Beyond the use of BCI for neurofeedback, BCI research in HCI has begun to consider social affordances facilitated by the technology, and the unique user experiences they evoke. One early exploration of this notion is the work of Liu et al. who designed a system that uses EEG data to attempt to extract an individual’s experience of emotion from their neural activity (Liu, Sourina, & Nguyen, 2010). This information is then used to animate the facial expression of a virtual avatar to match the emotional state of the participant. Through this system, the authors demonstrate the efficacy of including an “emotional dimension” in virtual environments like those of game worlds. However, the system only emulates human facial expressions to communicate emotion, attempting to compensate for a lack of non-verbal emotional cues. Furthermore, some of these related systems demonstrated the efficacy of BCI technology in augmenting interpersonal connections. For example, “Breeze”, a wearable pendant that measures and displays breathing patterns, was found to increase connectedness and empathy with loved ones, as well as aid the user to control their breathing via BCI-driven neurofeedback (Frey, Grabli, Slyper, & Cauchard, 2018).

Several studies have taken the BCI-mediation of interpersonal connections further by involving interpersonal neural synchrony as part of the system’s functioning. These have mostly been artistic installations. For example, “Hive Mind'' is an installation in which two performers on a stage generate light pulses and sound in synchrony with the oscillations of their brains. This process creates a feedback loop where the performers’ and the audience’s brains enter synchronicity with the multi-modal presentation, by cyclically modulating each other until participants reach and share an altered state of consciousness. “SocioPathways” demonstrates how to apply inter-brain synchrony to game design. Players are represented as dots on a screen and their dots become closer to other players as they become more synchronous with each other (Nijholt, 2019). This process continues until the brains of the group converge on synchronous oscillation and all the dots move into a singular large clump. NeuralDrum is an inter-brain-synchrony-focused drumming game where the goal of the player is to hit objects in time with a musical rhythm (Pai, Hajika, Gupta, Sasikumar, & Billinghurst, 2020). By situating the experience within extended reality and employing players’ EEG activity, the game expands traditional drumming games by adding visual and audio distortion as players become more synchronous. Through this mechanism, the game becomes easier while players are out of sync, and harder as they become more synchronous.

Taken together, these studies demonstrate the potential for BCI to play an influential role in interpersonal interactions and relationships. Thus, these examples further challenge the longstanding conception of BCI as a brain-based controller interface, instead demonstrating how these technologies can be used as novel mediums for communication and empathy.

2.2 Brain-Computer Interface Frameworks

Despite the long history of BCI research, there has been little attempt to formally establish a framework for designing such technologies. The most current framework for BCI design was proposed by Mason and Birch in 2003, titled the “general framework for BCI design” (Mason & Birch, 2003). Through their framework, the authors define a generic BCI system as a system in which a user controls a device through brain activity in an operating environment, through a series of functional components. These functional components ultimately represent the steps of processing undergone by BCI-extracted brain information; ultimately being interpreted by a computer to control a device as intended; illustrated in figure 6.

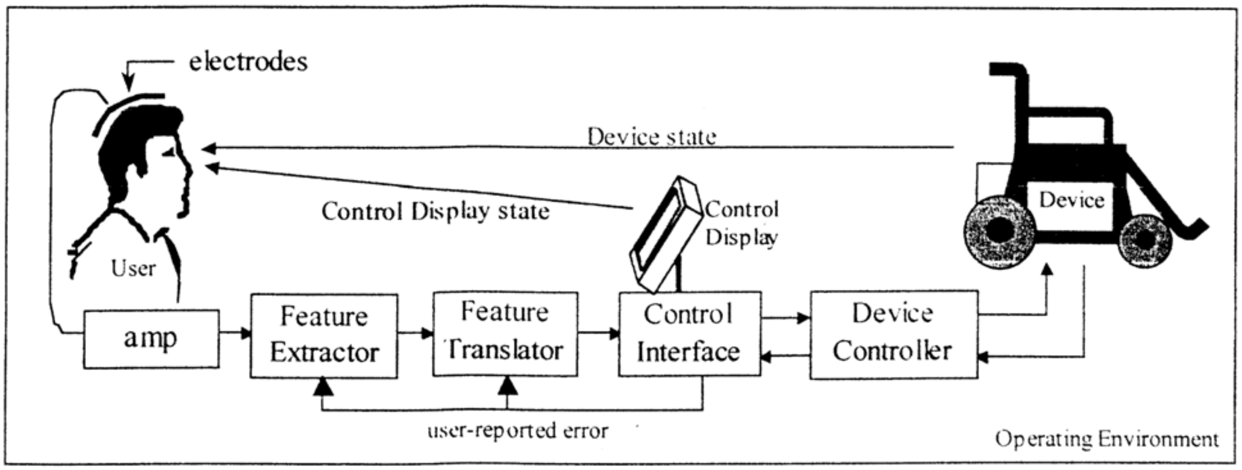

Figure 6. Mason and Birch's framework of a BCI system's flow of information, (2003). Each box represents what the authors call a "functional component", representing key signal processing steps necessary in translating brain activity to computer-actionable commands.

The process is described as involving the user, who consciously modulates their own brain activity in an attempt to control a device. This brain activity is sensed through electrodes, producing a signal that is amplified and then subjected to a feature extraction process, transforming raw data into values that operationalise the underlying neural mechanisms as a "feature vector", typically through one of the approaches outlined earlier in section 2.1.3 *BCI Paradigms*. The feature vector is translated into a logical control signal interpretable by the target device, processes this information and responds with a corresponding output which the user observes as feedback on their performance in controlling the device.

The authors justify their method of partitioning processes into functional components, stating that their choice of boundaries between these components facilitates objective comparisons between systems. This approach creates a common language that can describe the information exchange between a user and a device (Mason & Birch, 2003). They further suggest that this breakdown of the BCI process allows for specific objective measure and study of BCI systems, as well as individual functional components, allowing the development of standardized testing of components and benchmarking control interfaces (Mason & Birch, 2003). Ultimately, through their framework, the authors present a clear, detailed and modular description of the flow of information from a user's brain to a BCI-controlled device. However, while the basic steps in BCI signal processing as described by the authors remain relatively unchanged even in contemporary BCI technologies, there are many crucial aspects of BCI design that the framework fails to consider, perhaps due to the framework's antiquity relative to contemporary progress in BCI systems, being proposed in 2003.

Recalling that, until recently, BCI research almost exclusively focused on medical and assistive technology applications, it is apparent that there are inherent limitations in the scope and generalizability of this apparently "general" framework as a result of the historical context of its creation.

Specifically, the exclusively medical context surrounding the construction of this framework appears to restrict the application of any possible BCI design to be solely directed to the conscious, intentional and purposeful control of an external device (i.e. the BCI is a control interface). As a result, the framework fails to fully describe many of the BCI systems from HCI discussed above in section 2.2, which move beyond mere control by considering how the feedback of system output may recursively influence the system as a whole, but also by affording implicit interactions, in which the signal is not consciously or purposely controlled, but rather processes and interpreted without the user's intentional input. For example, consider the use of BCI activity by the aforementioned study by Liu et al. (2010) to detect emotion and animate an avatar's face in virtual reality, providing a passive channel of expression through the system's implicit interpretation of brain activity, rather than an active control channel. The framework also fails to consider BCI design intended for more than one user, which is becoming increasingly important with the rise of systems such as SocioPathways and Hive Mind discussed above in 2.2.2 (Nijholt, 2019). Similarly, while Mason and Birch state how extraneous variables in the "operation environment" may confound the desired operation of a BCI system, studies of more recent BCI systems such as Inner Garden and SocioPathways hint at the possibility that the situational context of the BCI system may be a powerful design resource for enriching the affordances offered by the system (Roo et al., 2017; Nijholt, 2019).

An additional aspect that I believe to be incredibly important to BCI design but is seldom described in Mason and Birch's framework is neurofeedback. While the framework acknowledges in passing the propensity for feedback between the system and the user, the framework disproportionately focuses on user input and control (or, the "encoding" process), in turn failing to articulate in any sufficient detail the potential influence the system has on the user. This is clearly an oversight for describing systems like PsychicVR and LucidLoop, which facilitate cognitive feedback loops (Amores et al., 2016; Alexandra Kitson et al., 2019). Similarly, the framework makes no reference or allusion to the user experiences produced by BCI systems, nor design choices that may shape the user experience, thereby drastically limiting the design space of possible BCI systems a designer may develop.

Considering these shortcomings of the framework, I acknowledge how well it describes the extraction of information from brain activity into a codified, computer-interpretable format, yet I also point out how it falls short in explaining the processes involved in the subsequent reception or interpretation of the resultant output signal. Typically, theories and models which describe the flow of information between bodies (i.e., information theory in electrical engineering and the encoding/decoding model of communication in semiotics) refer to these processes as encoding and decoding respectively (El Gamal & Cover, 1980; Genosko, 2015; Pillai, 1992). Thus we can say that while the framework does well in describing encoding processes in BCI design, the framework falls short in describing decoding processes in BCI design, as illustrated in figure 7.

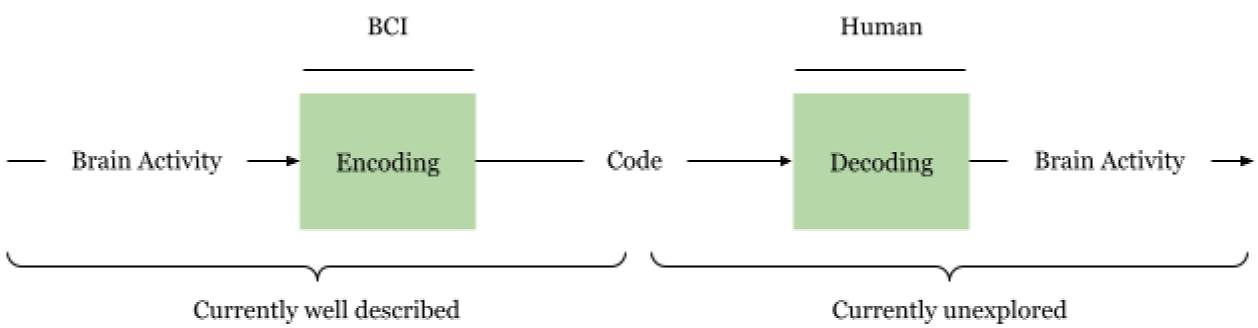

Figure 7. A depiction of the coding process of BCI systems. While current frameworks describe the encoding half of the process well, the decoding half of the process, namely concerned with how the signal is reintegrated into the recipient's brain activity, is largely unexplored.

While newer BCI design frameworks have emerged since Mason and Birch's model, they focus on very specific BCI applications such as medical risk management (Garro & McKinney, 2020) and games (Gürkök, Nijholt, & Poel, 2012),and also focus heavily on the encoding of the system, ignoring peripheral components such as other users, situational contexts, or the feedback effects afforded by the interaction between the user's brain interpreting the system's output, and the recursive resulting input being driven by a BCI-altered brain (Garro & McKinney, 2020; Gürkök et al., 2012). As such, I consider these frameworks to be good starting points for describing the information processing within a BCI system, and now look to other biofeedback frameworks to further inform a framework describing the design of BCI systems beyond this outdated emphasis on input.

2.3 Learning From Biofeedback Frameworks

While BCI research has seemingly overlooked the importance of the decoding process, the more general investigation of biofeedback systems within HCI has acknowledged the importance of understanding this process. The "attention-regulation process" (Niksirat, Silpasuwanchai, Cheng, & Ren, 2019; Salehzadeh Niksirat, Silpasuwanchai, Ahmed, Cheng, & Ren, 2017) appreciates how the design of feedback in terms of its “modality”, “instructional cues", and “judgement-free aesthetics" is instrumental in the system’s integration with the user’s cognitive experience (specifically facilitating focused attention for mindfulness meditation in their case). Similarly, in their review of biofeedback systems for stress, Yu et al. suggest that the presentation of a biofeedback display can influence how the user interprets the information embedded in its encoding, but also the experience itself, stressing that the encoding is not only a carrier of information but also a stimulus that can alter physiology (Yu, Funk, Hu, Wang, & Feijs, 2018). These frameworks acknowledge the propensity for an encoding to integrate with the recipient's neurocognitive processes when decoded, these frameworks often conceptualise feedback as something restricted to traditional screen-based interactions.

Moving forward, Lux et al. (2018) proposed an integrative framework for live biofeedback, in which the authors translate the Shannon-weaver model of communication toward the description of biofeedback systems (Lux et al., 2018). In doing so, their framework takes a similar structure to the illustration above in figure 8, specifically their inclusion of an information source; a transmitter that encodes information; a receiver that decodes the encoded message; and a destination, which processes the message. Furthermore, they move beyond screen-based interactions, suggesting that a feedback channel can address at least one of the human senses, such as sight (visual), hearing (auditory), or touch (tactile), etc. They add that these systems can cause a change in the user’s perception, behaviour, or regulation of the physiological activity that the feedback system is regulating. However, Lux et al. state BCI systems to be beyond the scope of their framework. Additionally, while the authors acknowledge different channels through which a system can integrate with the physiology of the user, the underlying mechanisms of how this is completed are not described, nor do the authors explore how changes in the code’s expression (which they call a feedback channel) influences the resulting experience.

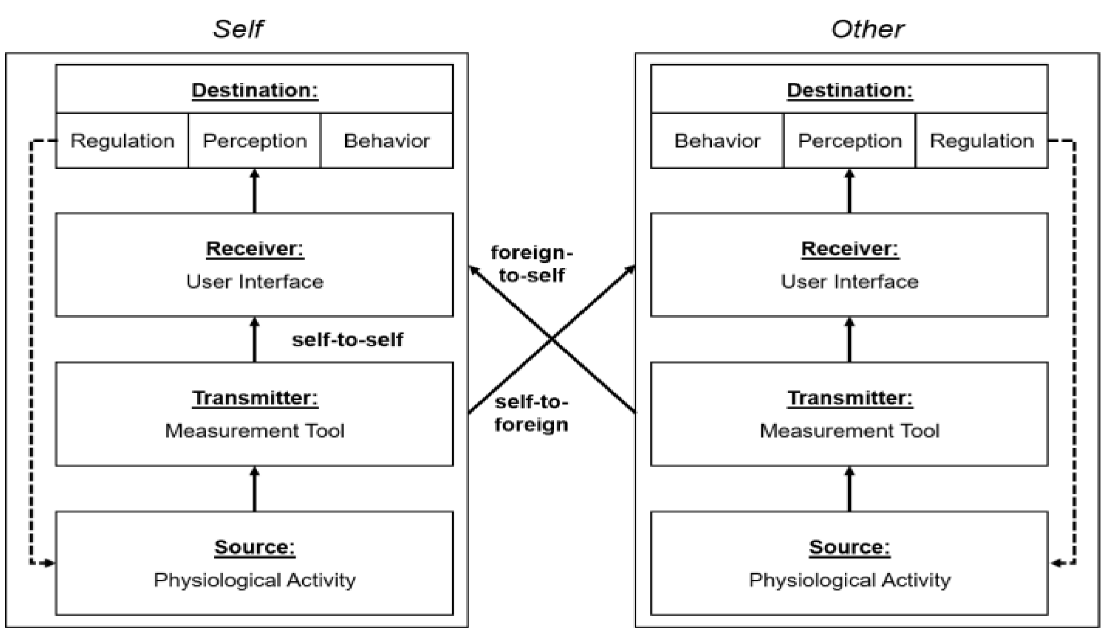

Fig 8. Lux et al.'s "Integrative Framework for Live Biofeedback" (Lux et al., 2018).

2.4 Need for Paradigmatic Shift

Considering the current state of BCI research and design knowledge, it is arguable that while the functions and mechanisms of the encoding processes of BCI systems have been steadily progressing since the beginning of the technology, little is known about the decoding process. A comprehensive description of the decoding process - the "sense-making" step in BCI interaction - would entail how system output relates to the user, influences agency, interacts with its situational context, and also, opens (or does not open) channels of information exchange between other users or systems. Furthermore, the subjective experience of these components at play together would ultimately come from the user experience, something that has not been discussed in any of the preceding frameworks.

Without understanding these important components of the design of BCI systems, future BCI design may very well be limited to over-engineered controllers, rather than the complex, almost neuroprosthetic extensions of human cognitive processes that the aforementioned HCI works have promised. As such, it is necessary that we establish a new perspective for understanding the design of BCI systems.

I argue that the traditional interaction paradigm in which previous frameworks were created, has led to the overemphasis on input and encoding, cursory examinations of decoding, and the extraneous variables interacting with codes themselves. That is, I argue these frameworks have been built with an épistémè that understands the relationship between human and computer as ontologically distinct and therefore of command and response. As a result, these frameworks place an emphasis on encoding human intentions into computer-interpretable commands, with the human individual being the sole actor or agent, and the machine being a predictable static tool. However, with current advances in technologies such as artificial intelligence and devices that overlap with the human body as wearables or implantables, the validity of a command-response human-tool relationship is becoming an increasingly antiquated paradigm.

As such, it is being argued that we are beginning to see human-technology relationships in which the two no longer interact, but rather, integrate. This distinction is likely why previous frameworks have been unsuccessful in fully describing BCI systems and their design, as the relationship between a BCI and its user may be better described as integration rather than merely interaction. With this considered, this thesis looks to the theory of Human-Computer Integration (Danry et al., 2021; Farooq, Grudin, Shneiderman, Maes, & Ren, 2017; Farooq & Grudin, 2016; Mueller et al., 2020;

Mueller et al., 2021; Mueller et al., 2020; Semertzidis et al., 2021), the growing paradigm which studies and describes these new forms of human-technology relationships, to form a foundational perspective on which to build a new and more complete framework of brain-computer interface design.

2.5 Human-Computer Integration

In 2017, a panel at the ACM Conference on Human Factors in Computing Systems (CHI) titled “Human-Computer Integration versus Powerful Tools” (Farooq et al., 2017) articulated what they deemed to be a new paradigm within HCI, “Human-Computer Integration”. The panel proposed a move in technology away from the “stimulus-response” paradigm we commonly think of when we talk about *interaction* and toward a “symbiotic partnership” between humans and computers, in which both parties are *integrated* and must be considered holistically.

Carrying forward the sentiment put forward in this panel, a Dagstuhl symposium was held in 2018, in which 29 leading experts from industry and academia came together over a five-day workshop to develop and discuss the future of Human-Computer Integration, or HInt (Mueller, Maes, & Grudin, 2019). The discussions during this workshop ultimately spawned an overarching work titled “Next steps in Human-Computer Integration” (Mueller et al., 2020). The paper defined HInt as “a new paradigm with the key property that computers become closely integrated with the user”, which included examples in which "humans and digital technology work together, either towards a shared goal or towards complementary goals (symbiosis)"; and "integration in which devices extend the experienced human body or in which the human body extends devices (fusion)". Learning from this work and applying its insights to the development of a new perspective for BCI design, I deduce two fundamental axioms from which the framework should be built. One is that we should assume both the human and the system as agents, or as the authors describe, “partners”, rather than ontologically distinct entities. The second suggests we should also consider the integration between humans and BCI as scaleable, suggesting that integration can occur beyond one machine agent and one human agent; as networks or assemblages including many of each, all in integration with each other.

Because the previously discussed BCI systems illustrate how technologies can recursively influence, and become influenced by, the user’s physiology (specifically their brain), it is arguable that the *fusion* aspect of HInt is particularly relevant to BCI design. Moving forward, more recent developments in HInt have built on *fusion*’s focus on the integration between humans and technology at the level of the human body. Specifically, Mueller et al. contribute the framework of designing “bodily integration” (Mueller et al., 2021). Through this framework, the authors elucidate how integration systems can be designed for close coupling with the user's physiological form and processes, ultimately enabling users to experience technology as an extension of their own body, or conversely, experience themselves as an extension of the technology, depending on how the system is designed. Their thesis is that in designing systems capable of bidirectional agential actuation between the user and the system, they facilitate a tight coupling in which the two can be experienced as a unified whole.

In further detail, the authors illustrate the contributing experiential factors of the system that ultimately decide the user experience on a two-dimensional cartesian plane, with the composite dimensions being "*bodily agency*", and "*bodily ownership*". The *sense of agency* dimension describes the degree to which the user feels themself to be the leading agent in the system's functioning, versus the machine holding this role. In essence, a user who is integrated with a system affording a high sense of agency would say "I did that"; conversely they may state "the machine did that" when afforded an experience with a low sense of agency. Similarly, the dimension *sense of ownership* describes the extent to which the user experientially identifies the system as themself. In essence, a user integrated with a system that affords an experience of a high sense of ownership would say "that is me"; and conversely "that is the machine" when afforded an experience with a low sense of ownership.

From these insights, I take away an additional two foundational axioms to consider in the construction of a new BCI design framework; specifically that the framework should consider the variability of the *sense of agency* and *sense of ownership* afforded by the system when designing BCI systems.

2.5.1 Humanistic Intelligence

It is also important to acknowledge that there are alternative frameworks or paradigms to conceptualise the merger between humans and machines other than human-computer integration that can be considered in informing brain-computer integration. This includes Wiener's "cybernetics", which functionally describes closed-loop machine systems (Wiener, 1950); Lickliders "Human-Computer Symbiosis", which postulates a future of very close coupling between human and the electronic member of the partnership (Licklider, 1960); and Clynes and Kline's conceptualisation of the "cyborg", a novel organism which deliberately incorporates exogenous components extending the self-regulatory control function of the organism in order to adapt it to new environments (Clynes & Kline, 1960). Of particular relevance to the present thesis is Mann's "humanistic intelligence" (HI), which is defined as an intelligence which arises from a human being in the feedback loop of a computational process, where the human and computer are inextricably intertwined (Minsky et al., 2013; Mann, 1998).

Much like how human-computer integration focuses on how computational machinery can form closed-loop intertwining with the human body through sensing and manipulating physiological functions, Mann presents humanistic intelligence as a signal processing framework that suggests that rather having computational or signal processing machines emulate human intelligence, the human becomes an integral part of an intelligent control system feedback loop. However, where these two perspectives differ is that while human-computer integration seeks to more broadly describe and understand the design of human-computer merger without a centralised pre-prescribed goal, humanistic intelligence is instead teleological as it presents itself as a framework for understanding control systems which are intended to assist or empower human intellect (Mann, 1998). This becomes particularly evident when considering the “six signal flow paths" of humanistic intelligence that intend to guide the design of human-machine symbiotic systems toward this teleology. These state that the system should be: 1) unmonopolising of the user’s attention, such as to allow one to attend to other matters while using the system; 2) unrestrictive to the user, allowing the user to be fully ambient while using the system; 3) observable by the user, meaning the output medium of the system should be constantly perceptible by the user; 4) controllable in that the user should be able to take control at any time if they so wish; 5) attentive to the environment, meaning that the system must be environmentally aware so as to provide the user with increased situational awareness; and 6) communicative to others, meaning that the system can be used as an expressive medium to allow communication between individuals.

While each of HI’s signal flow paths are not inconsistent with the concepts of which human-computer integration is concerned with, human-computer integration’s scope is wider in that it does not decree that flows must be manifested as they are prescribed by humanistic intelligence. Rather, HInt seeks to understand human-machine merger more generally and impartially (describing), and only prescribing design recommendations on a case-by-case basis to assist in producing an intended user experience (which may or may not be augmenting or empowering humans). For example, HInt does not always necessitate that systems be unmonopolising, as demonstrated in the case of Inter-Dream (discussed in chapter 4); HInt does not always necessitate that systems be unrestricted, as the paradigm also considers systems that manipulate the user’s body (Mueller et al., 2021); HInt does not always necessitate that systems be observable, e.g. the stimulatory of PsiNet is ambiguous and is even at times difficult to determine whether or not the system is producing output; HInt does not always necessitate that the system be always controllable, as HInt also considers systems that take control away from the user (Patibanda et al., 2022); HInt does not always necessitate environmental awareness, as this can be beyond the scope of some integration systems which interact with narrow and specific physiological processes; and HInt does not always necessitate that the system be communicative, as it can also include systems which form feedback loops on the level of the individual. With these distinctions in mind, Humanistic intelligence can thus be conceived of as distinct or possibly even a subset of human-computer integration, specifically a framework of human-computer integration systems for assisting or empowering human intellect (I.e., there is more than one way to “integrate", and humanistic intelligence is one of them). With that said, this thesis learns from humanistic intelligence in that its signal flow patterns provide guiding principles for designing brain-computer integration systems for empowering human intellect, however, the perspective of this thesis remains largely one of human-computer integration in that it seeks to maintain a broader, more impartial scope that also understands the design of brain-computer integration systems that do not necessarily align with the empowerment telos of humanistic intelligence.

2.6 Research Opportunity

Through examination of past research, BCI has had a long and varied history, originating from medical diagnosis, evolving into an assistive technology, and ultimately becoming what now is a promising channel for extending human neurophysiology and cognitive processes out into the technosphere; beckoning us to become more than human. Through the development of this technology, research has largely focused on extracting information from brain activity, ultimately guided by the epistemic foundation that BCIs are control interfaces. Furthermore, there has seldom been effort to articulate a framework for the design of BCI systems, and the examples that do exist are antiquated and only describe the encoding of brain activity to digitised signals, while failing to elucidate how humans decode these signals, as well as the phenomenological experience of the decoding process. As such, there exists no formally articulated design knowledge detailing what kinds of BCI systems can be made (beyond control interfaces) and what kinds of experiences their users can expect to have. I once again argue that the etiology of the contemporary lack of BCI design knowledge stems from previous BCI frameworks being based in a traditional interaction paradigm that considers human-computer relationships as one of command and response, ultimately limiting BCI to a control interface. As such, I argue that to progress beyond this conceptual dead end, it is required that a more contemporary BCI design framework be contextualised in a new paradigm for describing human-computer relationships. This proposed paradigm is Human-Computer Integration, and as such I name this new framework the *Brain-Computer Integration* framework.

In learning from the most recent core canonic works produced by HInt theorists (Mueller et al., 2021; Mueller et al., 2020), I have modified the implications for design practice the authors have offered into fundamental axioms on which to base the development of the Brain-Computer Integration framework I undertake throughout this thesis. This process ultimately resulted in four axioms, being:

1. Humans and technology in a BCI system must both be considered agents, imbued with agency, existing on a flat ontology (existing on an equal ontological level). Thus, both human and artificial agents are parts of a BCI system; working together as partners toward a common goal.
2. Integration in a BCI system must be scalable. Thus a BCI system can be assumed to contain few or many human and artificial agents, all integrated with each other.
3. Agency must be variable between agents within a BCI system. Thus, it is important to understand how agency is distributed across the agents constituting the system as a whole.
4. Ownership must be variable between agents within a BCI system. Thus, it is important to understand how ownership is distributed across the agents constituting the system as a whole.

Equipped with the axioms provided by this new paradigmatic perspective, this thesis seeks to develop a more complete framework for BCI design that fully describes not only BCI's encoding processes, but also the decoding processes, the system's interaction with extraneous factors, and ultimately, the user experience provided by these elements in concert.

2.7 Research Question

With the above considered, it can be summatively stated that the present thesis seeks to develop a novel framework for formally articulating the design of brain-computer interfaces from an integration perspective, rather than an interaction perspective. Doing so will provide the design knowledge necessary for the development of *Brain-Computer Integration* and BCI systems that integrate with the brain and its cognitive processes, rather than functioning as mere control interfaces. Thus, the present thesis seeks to answer the research question:

How do we design Brain-Computer Integration?

The following chapters detail the methodology adopted and studies conducted to address this question, as well as a presentation and discussion of the results this investigation provided.

3 Methodology

The following section details the methods employed in this thesis in order to explore the design space of brain-computer integration, and ultimately come to articulate the theoretical framework.

3.1 HCI and Research through Design

To understand the design space of integration BCI systems and ultimately formulate the Brain-Computer Integration framework, a variety of methods have been adopted from the research disciplines this thesis touches, including psychology, neuroscience, philosophy, design and HCI. At a higher level, the structuring of the studies and general approach to the completion of this thesis has been largely informed by the research paradigms of HCI. The rationale for this is that while it is possible the research methods conventional to other approaches (such as systems engineering or psychophysics) might be applicable in the present exploration, the questions this thesis seeks to answer specifically focus on the interaction (or integration) between the human subject, and computer systems, rather than understanding the two entities dichotomously, specifically, or in isolation. As HCI can be defined as a field of study focusing on the design of computer technology and interaction between humans and computers (*Handbook of Human-Computer Interaction*, 1988; Harper, Rodden, Rogers, Sellen, & Human, 2008), the method of this thesis aligns foremost with the methodological practices of HCI. Note, however, this thesis also adopts research methodologies of auxiliary disciplines such as psychology and neurocognitive sciences to maintain rigour when dealing with the mechanisms of integrated consciousness on the neural, cognitive, and psychological level (which will be discussed later in this chapter).

Considering the wide range of methodological approaches available within the field of HCI, this thesis engages with HCI centrally through the approach of "research through design" (RtD), which can be defined as the adoption of methods and processes from design practice applied toward the inquiry of new knowledge (Zimmerman, Forlizzi, & Evenson, 2007). The strengths of such an approach can be seen in that it is effective in synthesising many ideas together through processes of composition and integration due to its origin in design theory (Gaver, 2012; Zimmerman et al., 2007). As such, these properties have rendered RtD notoriously well suited for the formation of theory in novel and emerging contexts, while also being robust enough to support the later development of more mature and comprehensive theoretical constructs (Gaver, 2012; Koskinen, Zimmerman, Binder, Redstrom, & Wensveen, 2013). With these properties of RtD considered, it is notable that this approach aligns well with the topics central to the present exploration. This can be initially seen in that brain-computer integration as a theoretical construct is a synthesis of ideas from diverse fields of research, including computer science, information theory, psychology, and neurocognitive science. Furthermore, this approach was taken considering that RtD permits researchers to focus on "research of the future" (Zimmerman, Stolterman, & Forlizzi, 2010), allowing understanding of brain-computer integration as or before it emerges. This is important when considering that the present thesis focuses on a novel path of inquiry emerging from the design synthesis of cutting-edge technologies.

Considering the latter sentiment, a critique of RtD is that the field is dominated by the sentiment that "being first" or designing something "new" takes precedence in value, recognition, and motivation over in-depth analysis and critique (Zimmerman et al., 2010). As a result, it has been suggested that practitioners of RtD often squander the potential strengths of RtD in mature theory formation by instead shifting attention to the development of the next design prototype. This has been considered and avoided in that the primary contribution of this thesis is a mature theory. Furthermore, the approach of the present thesis is iterative and reflective, necessitating that the process of prototyping becomes the source of research outcomes. In turn, artefacts become a conduit for "transforming the world from its current state to a preferred state" (Zimmerman et al., 2007, 2010). Such a future-oriented focus consequently leads to an emphasis on the phenomenological experience, motivations, and mechanisms of interaction (or even integration), rather than realising a fully developed system or product.

3.2 Research-In-the-Wild

To complement the exploration of the future enabled by RtD, the present thesis also employs a "research-in-the-wild" (RITW) approach to the design of its constituent studies (Chamberlain, Crabtree, Rodden, Jones, & Rogers, 2012). Research-in-the-wild can be described as a research design in which studies take place outside of the lab, often instead being situated within communities or homes for extended periods of engagement. The strength of such an approach allows researchers to develop a deep understanding of the impacts and affordances technologies have on day-to-day life and in the "real world" (Brown, Reeves, & Sherwood, 2011). Its proponents argue that setting studies within home and community life presents a rich context for understanding challenges and possibilities of the technology of interest, as researchers can examine reactions to everyday activities (Balestrini, Gallacher, & Rogers, 2020; B. Brown et al., 2011; Chamberlain et al., 2012). Furthermore, participants are offered novel opportunities for participation as they also act to understand the technologically-facilitated interactions between people afforded to them by the novel technologies deployed in their home or community (Callon & Rabeharisoa, 2003). Since RITW includes naturalistic social interaction in its research design, it benefits this thesis by providing a rich contextual environment to understand the experience of integrated consciousness from its necessary interpersonal perspective (Balestrini et al., 2020; B. Brown et al., 2011; Callon & Rabeharisoa, 2003; Chamberlain et al., 2012).

Furthermore, it could be argued that the first case study, Inter-Dream, breaks from this RITW approach in that the system was not deployed for participants' longitudinal personal use, but instead in an installation space during an allotted time. However, I maintain that case study one still follows a RITW approach as it employs a subset of the approach known as "performance-led-research-in-the-wild" (Benford et al., 2013). In this approach, the design and presentation of an artefact is led by an artist following artistic processes. In turn, research findings emerge from reflection on the artefact and the participants' experience. Considering Inter-Dream specifically, the artefact was originally designed by the artists with the intention of producing an interactive public art installation that explored the speculative future concept of interpersonally sharing dreams through BCI. Nonetheless, the findings of this study prompted the adoption of a more traditional RITW approach in which systems are deployed to participants for longitudinal use (described in chapter four), which persisted for the remaining two case studies.

3.3 Qualitative Methods

Considering that the primary contribution of the present thesis is the formation of a theoretical framework, the following studies centred around a qualitative approach to data collection and analysis. This decision was further motivated in that the thesis intends to guide designers of future brain-computer integration systems.

Further, qualitative research has been acknowledged to be advantageous when trying to understand technology as an experience and as such has become a staple in HCI research methods (Adams, Lunt, & Cairns, 2008; Blandford, Furniss, & Makri, 2016; Prpa, Fdili-Alaoui, Schiphorst, & Pasquier, 2020). Similarly, analytical traditions within philosophy have long appreciated qualitative analysis to be an effective means of analysing experiential subject matter for the construction of theory (Adams et al., 2008; Prpa et al., 2020). Furthermore, psychological, and neurocognitive disciplines often utilise qualitative research methods for theory building, particularly in the establishment of an emerging concept or construct, allowing a matured framework to then be subjected to quantitative investigation when adequately parametrized (Morgan, 2015).

3.3.1 Semi-structured Interviews

To explore the experience of brain-computer integration afforded by the case study systems, they were deployed and used by participants in an in-the-wild setting. At the conclusion of the usage period, participants were then asked about their experience in semi-structured interviews.

Semi-structured interviews are a common data collection method within HCI research due to their strengths in providing rich, detailed accounts of user interactions with a given system (Blandford et al., 2016; Blandford, 2013). Such interviews involve a script of questions focusing on elements or themes deemed relevant a-priori, often informed by prior research. The questions are also open-ended, to allow for dynamic and emergent lines of enquiry that can be pursued during the interview allowing interesting and unexpected observations provided by participant experiences (Blandford, 2013). The interview itself typically follows the structure of an introduction; opening questions; core in-depth questions; and closure (Blandford, 2013). Such an approach to data collection allows HCI researchers to develop a deep understanding of people's perceptions and experiences. As such, the methods of the present thesis include semi-structured interviews to understand the experience afforded by the designed systems of each case study.

Other disciplines such as philosophy, psychology, and neurocognitive sciences have often relied on semi-structured interviews to help understand the properties of experiences or experiential constructs (e.g. What is consciousness? What does it mean to be? What is the experience of brain-fog like? What processes are involved in memory?) (Bitbol & Petitmengin, 2017; Flensner, Ek, & Söderhamn, 2003). In these cases, a phenomenological interview, a subvariant of the semi-structured interview, is typically employed (Høffding & Martiny, 2016). This process unfolds much like a general semi-structured interview as described above, but focuses in particular on posing narrative contextualised questions, modes of appearing (which refers to the participants' unique lived experience of the technology), and questions that encourage imagining variation from their experience (Høffding & Martiny, 2016). Such an approach allows for an analysis of the experience itself rather than being dependent on the technologies used to probe and explore this experience (Høffding & Martiny, 2016; Valenzuela-Moguillansky & Vásquez-Rosati, 2019). With this considered, the methods of the present thesis adopt a phenomenological approach to semi-structured interviews in the effort that we can understand brain-computer integration as a generalisable experiential phenomenon or construct in itself, which can be thought of independent from the specific technology, design, or prototype that helped produce it.

3.3.2 Diaries

Because the in-the-wild approach of this thesis involved extended periods of time in which participants interacted with deployed systems away from the researchers, interview data was supplemented with the collection of diary entries. This allows participants to record data in their own time, permitting the recording of detailed accounts when a particularly salient experiential event occurred (Carter & Mankoff, 2005; Janssens, Bos, Rosmalen, Wichers, & Riese, 2018).

3.3.3 Qualitative Data Analysis: Inductive Thematic Analysis

To analyse qualitative data, inductive thematic analysis was employed (Clarke & Braun, 2014). Through this analytical method, qualitative data are assessed systematically to identify patterns of meaning (or themes) emergent from a data set. By employing this throughout a data set, the researcher can extract and make sense of collective and shared experiences pertaining to the phenomenon of interest (Adams et al., 2008; Brown & Stockman, 2013). As I am collecting qualitative data from interviews and diaries to extract experiences facilitated by the use of a system, thematic analysis was employed to identify commonalities shared between these experiences, and to ultimately reveal the underlying themes that brain-computer integration is composite of.

The inductive thematic analysis of this thesis was achieved through a process in which several researchers independently reviewed transcripts and coded the data. Codes were iteratively clustered into high-level groupings agreed upon between researchers until they were consolidated into three final themes emerging from the data. The number of researchers involved in coding varied depending on the case study. This will be described in greater detail in the specific methods for each case study.

3.4 Quantitative Methods

Due to the multidisciplinary nature of the topics touched on in this thesis, several research methods have been adopted in the completion of the thesis that are auxiliary to HCI. These disciplines, namely psychology and neurocognitive sciences, typically employ quantitative means of data collection and analysis (Bauer & Dunn, 2012; Coolican, 2017; Maroof, 2012; Giles, 2013; Windhorst & Johansson, 1999). As such, this thesis, in addition to the qualitative methods discussed above, also employs the quantitative methods of psychometric analyses and quantitative EEG analysis (QEEG).

3.4.1 Psychometric Analyses

Psychometric analysis is a research method ubiquitous to psychology that employs Likert-scale questionnaires to measure a given psychological construct (e.g. arousal, anxiety, emotional intelligence, etc.) (Coolican, 2017; Cooper et al., 2012; S. Hammond, 2006; Irwing, Booth, & Hughes, 2018). This thereby allows for the statistical analysis of said construct in relation to some form of intervention or interaction with another construct (Cooper et al., 2012; Irwing et al., 2018). Through this thesis, I apply psychometric analysis as a means to help understand how the novel technologies presented in each case study interacted with well known psychological constructs, such as affect and arousal in Inter-Dream, and emotional intelligence in Neo-Noumena, to serve as a point of reference for interpreting qualitative results.

3.4.2 Quantitative Electroencephalography

Qualitative Electroencephalography (QEEG) is a research method common to the neurocognitive sciences that involve the quantitative analysis of the electrophysiological activity of the brain in order to draw some inference regarding affective, cognitive or conscious processes (Kaiser, 2005; Tong & Thakor, 2009). Considering that the focus of the present thesis is on brain-computer interfaces, it is necessary to consider the primary mechanisms of interaction in the design prototypes as also a means of data collection and analysis. As such, this thesis employs QEEG to better understand how the prototypes designed through this thesis, and the experience they facilitate, interact with the brain and in functional processes.

3.5 Study Design and Methods for Case Studies

In adopting the research methods outlined above, the present thesis seeks to develop three prototype systems as “case studies” to investigate brain-computer integration and how to design it. Through this iterative method, the design and research process allows for the thesis to gradually reach toward the realisation of brain-computer integration, understanding its components as they emerged through being informed by participant data, behaviour, experience and feedback. To achieve this, each case study is studied through a mixed-methods research design: functionally on the basis of participant use and biometric data; psychologically on the basis of participant measures of psychometric constructs that interact with the system; and phenomenologically on the basis of understanding the underlying themes that make up the user experience of the system. Through this I was able to gradually build a framework from the bottom up, from which the study of each component was informed by the revelation of its proceeding component while being grounded statistically, conceptually, and experientially. Additionally, this thesis takes inspiration from previous HCI research in using this approach to generate theoretical contributions (i.e. the generation of frameworks) through the study of their designs while also providing design strategies to drive and guide the design of related future systems (Andres, 2021; Byrne, Marshall, & Mueller, 2020a; Byrne, 2016; Jensen, Rasmussen, & Grønbæk, 2014; Z. Li, Wang, Greuter, & Mueller, 2020; Mueller et al., 2011; Mueller et al., 2021). It is through the application of these methods that my thesis contributes to HCI theory with the presentation of my Framework.

3.5.1 Methods from Case Study 1: Inter-Dream

The first case study aimed to answer the research question "*How do we design integrated brain-computer interfaces for regulating brain activity?*". To answer this question, this study explored the relationship between technology and brain activity in the context of sleep. This exploration was enabled through the study of the system "Inter-Dream": a sleep-focused, BCI-driven interactive art installation using virtual reality designed by PLUGINhuman. In this installation, participants lie on an interactive bed fitted with a virtual reality head-mounted display, while their brain activity is fed back to them through artistic visualisation and audio, in turn modulating their brain activity toward a state indicative of healthy pre-sleep (Semertzidis, Sargeant, Dwyer, Mueller, & Zambetta, 2019).

3.5.1.1 Participants

Twelve participants were recruited for the study, including nine males and three females, with a mean age of 33 (SD = 11.86). The sample was primarily recruited from the university and via word of mouth. All participants were considered of a non-clinical, healthy population. No participants had any prior experience with neurofeedback, and only two had prior experience with virtual reality.

The procedures of the user study were approved by the ethics board. Informed consent was collected from participants before their involvement. Sessions were completed individually, taking a total of 30 – 45 minutes per participant.

3.5.1.2 Materials and Procedure

Pre-Test. Prior to the use of the Inter-Dream system, an initial baseline measure of participant pre-sleep arousal and emotional states were assessed through the implementation of a battery of self-report psychometric scales: the Pre-sleep Arousal Scale (PSAS) and the Positive and Negative Affect Schedule – Extended (PANAS – X) (Nicassio, Mendlowitz, Fussell, & Petras, 1985; Watson & Clark, 1999). In responding to the items of the PSAS, participants were prompted to "describe how intensely [they] generally experience each of these symptoms as [they] attempt to fall asleep in [their] own bedroom". Similarly, in responding to the PANAS-X, participants were prompted to answer considering how they felt at that present moment. During this time, demographic data of age and sex were also collected. Completion of the psychometric battery was done in paper form, taking a total of approximately 5-10 minutes.

Inter-Dream Session. Following the completion of the psychometric battery, participants were then introduced to the Inter-Dream system under the guidance of the researchers. This involved explaining that the bed will provide haptic feedback, that sound will be played, and visuals will be displayed, with the latter component being modulated by the participant's brain activity. Participants were first made comfortable on the bed in a sitting position. The BCI was then fitted, and the participant was prompted to lie down. Regarding electrode placement, recording sites utilized were the TP9, AF7, AF8, and TP10 locations when considering the 10-20 EEG electrode placement system. These electrodes were chosen due to the static electrode configuration of the Muse EEG headband. Other electrode configurations could also have been adopted toward the same success. Nonetheless, recent studies have demonstrated Muse and its electrode configuration to be viable in the analysis of sleep related electrophysiology (Koushik, Amores, Maes, 2019). Once comfortably resting in a lying position, the VR headset was then fitted to the participant, thus beginning the neurofeedback loop. At this time, ambient auditory stimulation was also initiated, sequentially followed by the haptic stimulation of the sleeping platform. At this point, the multisensory experience of Inter-Dream was considered truly initiated and recording of EEG activity commenced. Participants then rested, augmented by the Inter-Dream system, for a total of 10 minutes. At the end of the session, EEG recording was stopped, and participants were gently informed of the session's end. The VR and BCI headsets were removed, and the participant was given time to adjust to the change in perception before leaving the bed.

Post-Test. Immediately after the Inter-Dream session, a secondary post-test measure of participant pre-sleep arousal and emotional states was made as conducted in the pre-test phase. However, in this phase, participants were prompted instead to respond to the scale items considering how they felt during their time throughout the Inter-Dream session. Again, completion of the psychometric battery was done in paper form, taking a total of 5-10 minutes.

Qualitative Interview. At the conclusion of their involvement in the study, participants were afforded the opportunity to partake in a qualitative interview. This involved open-ended questions on any subjective perceptions, thoughts, and feelings experienced by the participant during the Inter-Dream study. Of the 12 participants of the sample, eight agreed to participate in the interview phase.

Psychometric Scales. Cognitive and mood states predictive of sleep onset were assessed through the pre-sleep arousal scale (PSAS), and the positive and negative affect schedule (PANAS), respectively.

The PSAS is a 16 item self-report instrument designed to assess subjective cognitive and somatic arousal as a state, specifically in the context of pre-sleep (Jansson-Fröjmark & Norell-Clarke, 2012; Nicassio et al., 1985; Shahzadi & Ijaz, 2014). The scale consists of two subscales, somatic and cognitive arousal, with each subscale consisting of eight items. Each item exists as a statement describing a somatic or cognitive symptom associated with pre-sleep arousal (e.g. "Heart racing, pounding, or beating irregularly", "Can't shut off your thoughts"). Respondents rate how intensely they feel each symptom as they normally attempt to fall asleep on a Likert scale of 1 – 5, with one being "not at all" and five being "extremely". Individual measures of each subscale were made via the summation of responses made to its associated items. Psychometric validation has been demonstrated, showing a significant correlation with anxiety, depression and general indices of sleeping difficulty, as well as being able to discriminate insomniacs from normal sleepers (Broman & Hetta, 1994). Furthermore, tests of validity and reliability show satisfactory results, with Cronbach's $\alpha = .87$ and retest reliability = .89 (Jansson-Fröjmark & Norell-Clarke, 2012).

The PANAS-X is a standardized 60 item self-report scale developed to orthogonally measure levels of positive and negative affect and emotional states. The scale consists of 16 subscales addressing the major emotional and affective dimensions necessary to effectively describe subjective mood states. Each subscale is composed of a number of items, with the summation of that subscale's items being a measure of that subscale. Each item exists as a single word describing an emotion or affect (e.g. "sleepy", "disgusted", "excited"). Respondents rate how intensely they feel each notion on a Likert scale from 1 to 5, with one being "very slightly or not at all" and five being "extremely". Studies are generally supportive of strong psychometric properties, reliability and validity (Crawford & Henry, 2004; Melvin & Molloy, 2000; Thompson, 2007).

EEG Data. The electrophysiological activity indicative of sleep onset was assessed through the recording of EEG data. Fast-Fourier Transformations (FFT) of the raw EEG data were processed to power spectral density frequency bandwidths allowing for the calculation of absolute power values from which cognitive states can be inferred. Both the hardware and software discussed have been validated and demonstrated to be viable tools for electrophysiological measurement and research (Krigolson, Williams, Norton, Hassall, & Colino, 2017).

Qualitative Interviewing. The collection of qualitative data was completed through interviews. This involved the open-ended discussion of the participants' individual experiential narrative regarding the Inter-Dream system. Whilst primarily guided by the participant, the interviewer facilitated the initiation and sustenance with five prompts. These being: “How would you describe what you just experienced to an alien?”; “How were you feeling or what were you thinking during the beginning of the experience?”; “How were you feeling or what were you thinking once you settled into the experience?”; “Do you think the experience would have been different if you were using the system alone in your room?”; and “Is there anything else you would like to say?”. Interview data were collected via voice recording, and later transposed into text, after which responses were analysed via thematic analysis.

3.5.1.3 Analysis

Psychometrics of Presleep. To assess the within-subject effect of Inter-Dream on pre-sleep arousal and pre-sleep affect, a series of paired samples t-tests were conducted comparing pre and post-test scores for each scale. I found a statistically significant improvement between pre-test and post-test in participant measures of pre-sleep cognitive arousal (p = .01), negative emotion (p = 0.008), and negative affect (p = 0.005).

Inter-Dream Experience. In analysing the recounts of participant experiences through interviews three major themes were revealed. Analysis of this material was performed inductively through thematic analysis (Clarke & Braun, 2014), in which three researchers independently reviewed transcripts and coded the data. Codes were iteratively clustered into high-level groupings agreed upon between researchers until they were consolidated into three final themes emerging from the data.

3.5.2 Methods from Case Study 2: Neo-Noumena

The second case study aimed to answer the research question “*How do we design integrated brain-computer interfaces for communicating brain activity?*” To do this, this case study explored how BCI can communicate brain activity (in this case emotion) by studying the system “Neo-Noumena”. Neo-Noumena is a system that employs BCI-driven procedural content generation, visualized using mixed-reality, to augment interpersonal emotion communication through dynamic, proxemic, abstract representations of affect (Semertzidis et al., 2020).

3.5.2.1 Participants

Ten participants were recruited for the study, including 5 males, 2 females, 2 participants preferring not to say, and one trans person. There was a mean age of 34.14 years (SD = 14.95). Participants were recruited as dyads, who experienced the system in pairs throughout the duration of the study. These pairs included four couples and a mother and son. No specific demographic was targeted during recruitment; however, by chance, the final sample yielded a disproportionate number of individuals with psychologically related diagnoses. This included two participants diagnosed with ADHD, and one participant with a diagnosis of a depressive disorder. All three participants are currently undergoing psychotherapeutic treatment.

The procedures of the user study were approved by the ethics board. Participation in the study lasted for a period of three days where participants were given access to Neo-Noumena to use ad libitum.

3.5.2.2 Materials and Procedure

Introductory Phase. An initial baseline measure of emotional competence was assessed through the self-report psychometric scale “Profile of Emotional Competence” (Brasseur, Grégoire, Bourdu, & Mikolajczak, 2013). The 50-item test measures five core emotional competencies (identification, understanding, expression, regulation and use of emotions). These dimensions are measured for intrapersonal and interpersonal factor domains, producing a total of 10 subscale scores and three global emotional competence scores: an intrapersonal score ($\alpha = .86$), an interpersonal score ($\alpha = .89$) and a total emotional competence score ($\alpha = .92$).

Exploratory Phase. Proceeding this introductory session, participant dyads were given a pair of Neo-Noumena systems to take home, to be used for three days, at least once per day, for a minimum of an hour, synchronously with their dyad partner. On average, participants used the system once a day, for three days, most often during the evening, for approximately one hour.

Participants were encouraged to submit online journal entries after each session, documenting any information they thought may be relevant to the analysis of the experience, such as: where they were, what they were doing, how this interacted with the experience, as well as observations or insights they had made regarding their own or their partner’s emotions, and any interesting stories that came out of using the system.

Debriefing Phase. On returning to the system, participants were involved in an open-ended qualitative interview, focusing on their experiences of the system and how it facilitated emotional communication with their dyad partner. Finally, participants provided post-test responses to the same self-report psychometric scale used in the initial baseline phase, to determine differences in emotional competence.

3.5.2.3 Analysis

Emotional Competence. To assess the within-subject effect of Neo-Noumena on Emotional Competence, a series of paired samples t-tests were conducted comparing pre and post-test scores for each scale. I found a statistically significant improvement between pre-test and post-test in participant measures of "emotion regulation of others" ($t(1,9) = 3.24$, $p = .01$, $d = 2.13$). There were no observed significant differences in measures of the other subscales of emotional competence.

Neo-Noumena Experience. In analysing the recounts of participant experiences through interviews and participant diaries, three major themes were revealed: *spatiotemporal actualisation*, *objective representation*, and *preternatural transmission*. Analysis of this material was performed inductively through thematic analysis (Clarke & Braun, 2014) in which four researchers independently reviewed transcripts and coded the data. Codes were iteratively clustered into high-level groupings agreed upon between researchers until they were consolidated into three final themes emerging from the data.

3.5.3 Methods from Case Study 3: PsiNet

The third case study aimed to answer the sub-research question *"How do we design integrated brain-computer interfaces for synchronising brain activity interpersonally?"*. This study pursued the amplification of inter-brain synchrony as a means to integrate brain activity interpersonally, and investigated the amplification of inter-brain synchrony through brain-to-brain networking of participants via the system "PsiNet". PsiNet is a hybrid brain-to-brain interface that uses EEG to read user brain activity, and tDCS to transmit this activity to other users that are part of the network.

3.5.3.1 Participants

Nine participants were recruited for the study, four males and five females, with no participants identifying as non-binary or self-described. There was a mean age of 35 years ($SD = 14.34$). Participants were recruited as groups of three. This included families, housemates, close friends, and colleagues. Participants were recruited from a healthy, non-clinical population. To gather the sample, I advertised the study via my lab's mailing list and social media pages. Participants were given no extrinsic motivation or compensation for participation.

The choice of focusing on participant groups from a shared household was multifaceted. The sharing of a single IP address between participants was greatly beneficial in ensuring a stable connection between headsets during user sessions, as all headsets were connected on the same local network. Co-location also had the added benefit that all participants were more likely to be available at similar times, maximizing the time they could spend using the system together. Participants completed a medical questionnaire to ensure they did not exhibit any conditions listed in the exclusion criteria. Participants deemed fit to participate were included in the study.

3.5.3.2 Materials and Procedure

Following ethics board approval, groups were given PsiNet headsets. Each group was to use PsiNet at their own discretion over three days. Participants were free to go about their daily activities while wearing PsiNet. Participants were instructed to try and use the system for at least 15 hours total during their time with PsiNet.

Before receiving their PsiNet headsets, participants provided measurements of the circumference of their heads to ensure a good fit, connection to the scalp, and correct electrode placement. Three sizes were available to each participant: small (40-50cm), medium (48-58cm), and large (58-65cm), and each size could be adjusted by loosening and tightening screws supporting the headset's electrodes.

System use. Participant groups were sent their PsiNet headset in the mail. Participants were instructed to wear the system whenever possible. Each group consisted of three group members within a single household who were required to wear their headsets concurrently during each use session (the system did not provide stimulation unless all group members wore their PsiNet headset).

For each groups' first session, participants were guided on setting up the system through a teleconference meeting, in which the researchers ensured that PsiNet was properly fitted and that the system was running correctly. The researchers were able to remotely monitor the data, ensuring that the system was interfacing with the brain correctly and that the data being passed through the system was of good quality (e.g., if the electrodes were exhibiting good impedance and producing clean signal). During each following session, participants notified the researchers when they were about to begin using the system via a call or text, allowing the researchers to monitor the data stream to again ensure proper operation of the system, and good quality data, while also enabling us to troubleshoot problems and provide support. This support was necessary for all groups, as there were house-specific startup issues when participants used the system for the first time.

How PsiNet worked specifically was omitted, allowing participants to establish their own understanding. However, the first group contacted the researchers requesting more information about the stimulations and therefore knew the four different stimulation types. Participants were informed that "*there is no predefined task for* [them] *to complete with PsiNet. Rather, I* [encouraged them] *to use PsiNet at will in* [their] *day-to-day life to explore the system's affordances and experiment with it by trying different activities, reflecting on subsequent experiences*". During this three-day period, participants kept an electronic diary to document any noteworthy thoughts or experiences they had with the system.

Participants reported completing a variety of activities with the system, which included: working (writing, programming, completing assignments, and administrative work), playing games (card games and videogames), watching television, cooking, eating, and housework. All participants were working from home and thus were able to participate in the study while working.

Debriefing Phase. On returning the system, participants were involved in a semi-structured interview, focusing on their experiences of the system and how it facilitated experiences of inter-brain synchrony. These interviews—lasting an average of thirty minutes per participant—were conducted individually, using a videoconference, and they were recorded.

3.5.3.3 Analysis

Inter-brain Synchrony Change. To assess the effect of PsiNet's stimulation on group inter-brain synchrony, a two-tailed paired-samples Wilcoxon signed-rank test was performed of fisher's-Z transformed CCorr measures comparing transformed CCorr before and after stimulations. It was found that CCorr after stimulations were statistically significantly greater than CCorr before stimulations, with $Z = 794.00$, $p = 0.035$. The result had an effect size of 0.35 as calculated by matched rank biserial correlation.

PsiNet Experience. In analysing the recounts of participant experiences through interviews and participant diaries, three major themes were revealed: *dissolution of self*, *hyper-awareness*, and *relational interaction*. Analysis of this material was performed inductively through thematic analysis in which four researchers independently reviewed transcripts and coded the data. Codes were iteratively clustered into high-level groupings agreed upon between researchers until they were consolidated into three final themes emerging from the data.

4 Case Study I: Inter-Dream

This chapter details the first case study: Inter-Dream, a BCI-driven interactive art installation designed by the artist duo, "PLUGINhuman". With this case study, I explore my main research question through the sub-question: *"How do we design integrated brain-computer interfaces for regulating brain activity?"* Sleep was chosen as a starting point for our investigation in brain-computer integration due to sleep possessing clearly detectable neurophysiological markers that can be sensed with BCI technologies (with sleep studies historically being one of the first practical applications of EEG (Šušmáková, 2004)). In addition, sleep is also a state of consciousness that can easily be monitored to elucidate whether the system has any influence over it and its underlying physiological processes. With these properties considered together, sleep presents itself as a strong application domain for serving as a starting point for understanding bidirectional actuation between the human brain and the computer, the defining factor of bodily human-computer integration (Mueller et al., 2021). As the brain "actuates" the system through being electrophysiologically sensed, the brain is reciprocally actuated as it perceives the neurofeedback imagery it generates, ultimately modulating the user's state of consciousness and thereby serving as an initial example of brain-computer integration. With this considered, the study of Inter-Dream assists in answering the core research question of this dissertation in that understanding the properties, mechanisms, and affordances would ultimately establish a beachhead in understanding the properties, mechanisms, and affordances of brain-computer integration as a whole. A video demonstrating Inter-Dream can be found at: https://youtu.be/pBLuf3Pc238

The rest of this chapter describes Inter-Dream and the subsequent study of how this system interacts with the subjective experience of consciousness of the participants using it. Finally, I present the findings from the study, reporting them first in the immediate context of the prototype in isolation, and then generalising toward the brain-computer integration framework.

4.1 Associated Publication

The work detailed in the following section has been peer-reviewed and reported on in a full-length conference paper, 12 pages long, titled "Towards Understanding the Design of Positive Pre-Sleep Through a Neurofeedback Artistic Experience", which was presented at The ACM CHI Conference on Human Factors in Computing Systems (CHI) 2019 in Glasgow, United Kingdom.

4.2 Prototype

The design of the Inter-Dream system followed the approach of performance-led research in-the-wild (Benford et al., 2013). In this approach, the design and presentation of an artefact is led by an artist following artistic processes. In turn, research findings emerge from reflection on the artefact and the participants' experience. The prototype was originally designed by the artists with the intention of producing an interactive public art installation that explored the speculative-future concept of interpersonally sharing dreams through BCI. Following this, I then sought to explore how this system may alternatively be applied in exploring technological promotion of positive pre-sleep, leading to the present study. With this said, I stress that Inter-Dream was not specifically designed with the promotion of healthy sleep in mind. Rather, it was hypothesised that Inter-Dream would help promote positive *pre-sleep*.

The Inter-Dream prototype (fig 9) featured an interactive bed. The angle of the bed's sleeping platform could be adjusted; the position of the sleeper's head and feet could be raised and lowered using a remote control. Additionally, the bed could gently vibrate; this feature was also controlled via remote control. During each 10-minute session, the participant rested on the bed. One person at a time could engage with the system. After five minutes, the artists would manually adjust the position of the participant's head, raising the angle of the top section of the bed. After 7 minutes the artists would raise the lower part of the bed so that the participant's feet were supported in a slightly raised position. Additionally, at the 7-minute point, the artists triggered the bed to vibrate gently. These adjustments were made with the aim of creating optimal comfort for the participant. During each participant's experience, a musical score was played that had been specifically composed by the artists. This musical score was designed to be relaxing with soft elongated tones that may aid the participant in relaxing and being further immersed in a sensory experience.

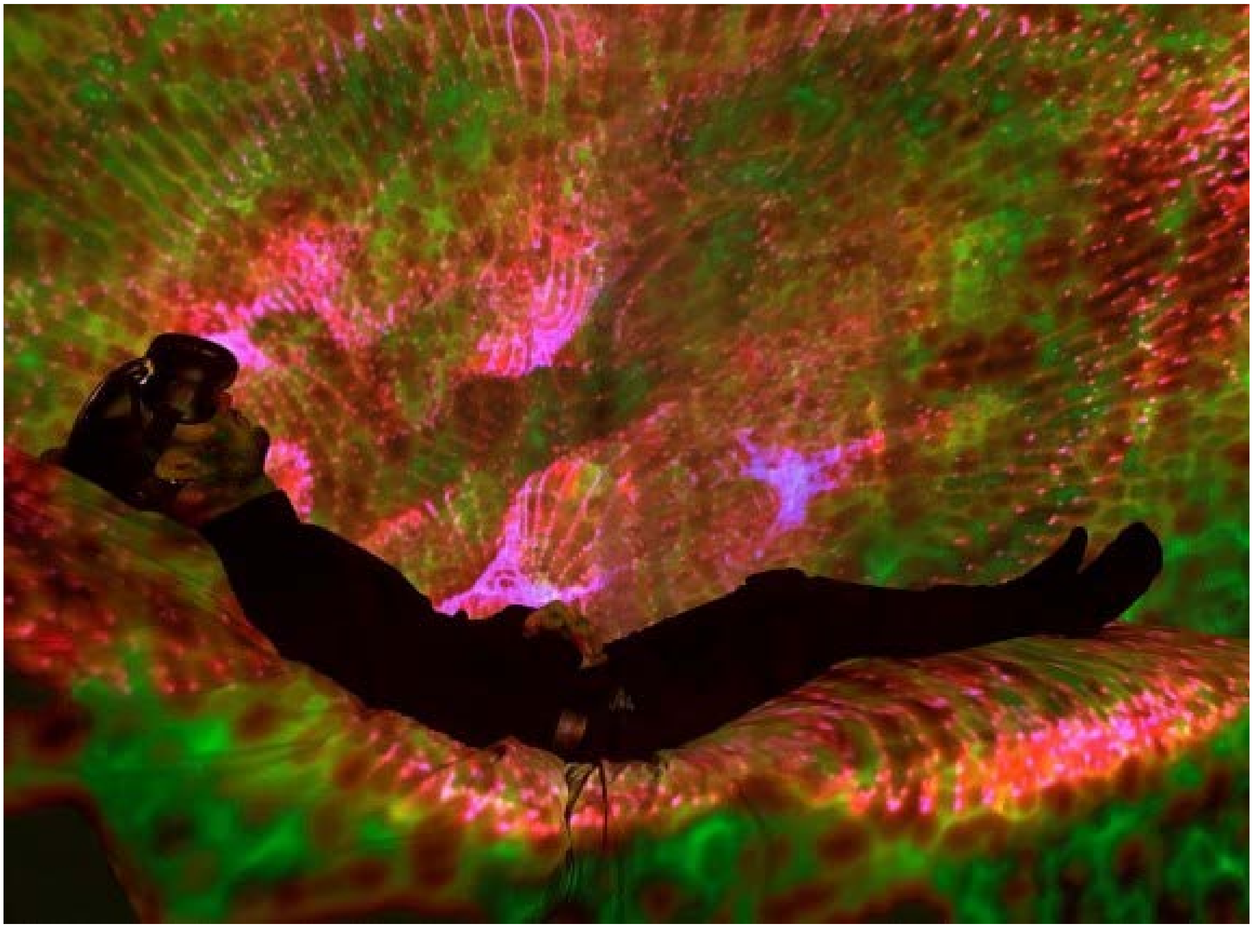

Figure 9. A participant rests within the Inter-Dream system.

The two walls at the back of the bed area were projection-mapped using a single projector. The projection showed visuals that were animated in response to the participant's brain activity. One person at a time could engage with the system. A "Muse" EEG headset (Krigolson et al., 2017)(figure 10) was used to non-invasively monitor the electrical activity of the participant's brain, emitted through the scalp. Raw EEG data was wirelessly sent to a mobile device via Bluetooth. From here, real-time absolute power values were calculated for Delta(δ) 1-4Hz, Theta(θ) 4-8Hz, Alpha(α) 7.5-13Hz, Beta(β) 13-30Hz, and Gamma(γ) 30-44Hz frequency bandwidths, while also performing automatic artefact removal. This data was then sent out to a central computer system. From the central computer, EEG data was interpreted through a custom program in TouchDesigner, a real-time graphic generation and projection mapping software. The interpretation of EEG data through TouchDesigner allowed for the real-time visualisation and artistic abstraction of the participants' brain activity as graphical imagery. This imagery was dynamically reactive to the EEG activity of the participant, changing in real-time in response to changes in absolute power across each frequency bandwidth communicated from the participant's brain. This was achieved by having the RGB colour values of the imagery modulated by the absolute power of each frequency bandwidth, with each bandwidth's value being associated with the intensity of a specific colour.

Figure 10. The Muse EEG headband that sensed participant's brain activity (left) and a sample of generated brain art (right).

Similarly, shape, contrast and amplitude were modulated by the overall intensity of EEG activity given by voltage. Specifically, higher levels of activity resulted in larger and more non-uniformed shapes, higher contrast and greater amplitude of the oscillating movement of the imagery. Taken together, this dynamically reactive artistic representation of the participant's brain activity forms the neurofeedback component of Inter-Dream. However, it is worth noting that while neurofeedback traditionally provides positive or negative feedback to desired or undesired brain activity, Inter-Dream in contrast implements a more experimental approach that is not precisely a measurement of cognitive states, but rather an artistic representation of EEG activity.

In addition to projection mapping (figure 11), this imagery was presented specifically to the participant through VR (with the former component being vestigial of the system's origins as a public interactive art installation). The imagery was displayed on both the projection and in VR simultaneously. Both media presented the same imagery, however, the version presented to the participant in VR was slightly simplified, lacking the "flare effect" which was intermittently present in the projected version. This disparity was motivated by a discovery made during the design of the system, in which a feedback loop was often initiated on participants seeing the flare. This was due to the flare being generated from very high overall levels of EEG activity, which was prolonged and further exaggerated by the brain's response to the vibrant visual stimulus, snowballing into a cyclical loop of intense feedback and high levels of neural activity sustaining each other.

Figure 11. The Inter-Dream installation during the absence of brain activity to drive it. Note the projection lacks any of the kaleidoscopic properties of the earlier images.

4.3 Results

The research design of the study yielded three overarching categories of data. These being: psychometric data, physiological data, and qualitative interview responses. As such, data analyses were performed separately for each of these three categories.

4.3.1 Psychometric Analysis

Preliminary exploratory data analysis was first conducted to obtain descriptive statistics for each subscale of pre-sleep arousal and emotionality measures across pre and post-test conditions. Means and standard deviations of scale scores are summarised for pre-sleep arousal in table 3, and emotionality in table 4.

Table 3. Means and Standard Deviations of Pre-Sleep Arousal Before and After Inter-Dream Experience.

	Pre-Test		**Post-Test**	
Scale	**M**	**SD**	**M**	**SD**
Somatic	12.75	3.84	11.42	2.96
Cognitive	21.25	8.75	18.67	9.35

4.3.1.1 Pre-Sleep Arousal

To assess the within-subject effect of Inter-Dream on pre-sleep arousal, a series of paired samples t-tests were conducted comparing pre and post-test scores for each scale. No statistically significant difference in the scores of somatic symptoms of pre-sleep arousal between pre-test and post-test conditions (t (1,11) = 1.22, p = .25, d = .35) were found. Conversely, there was found to be a statistically significant difference between pre-test and post-test in scores of the cognitive symptoms of pre-sleep arousal (t (1,11) = 3.11, p = .01, d = .28).

4.3.1.2 Emotion and Affect

To assess the within-subject effect of Inter-Dream on general emotion, a series of t-tests were conducted comparing pre and post t-test scores for scales of general positive and negative emotion. There was found to be a statistically significant within-subject decrease in general negative emotion (t (1,11) = 3.25, p =.008, d = .90) after the use of Inter-Dream, while no significant difference was found regarding general positive emotion (t (1,11) = -2.01, p = .07 d = .30).

Table 4. Means and Standard Deviations of Positive and Negative Affect Before and After Inter-Dream Experience

	Pre-Test		**Post-Test**	
Scale	**M**	**SD**	**M**	**SD**
General Negative Emotion	14.92	4.54	11.75	2.09
Basic Negative Affect	8.81	1.98	7.35	1.16
Fear	10.33	4.19	7.42	2.47
Sadness	8.00	3.59	6.83	2.62
Guilt	8.67	4.31	7.08	2.39
Hostility	9.08	2.47	8.08	0.90
Shyness	7.41	4.25	6.25	3.05
Fatigue	10.00	2.59	8.25	2.56
General Positive Emotion	26.75	7.82	28.83	6.51
Basic Positive Affect	15.67	4.98	16.33	3.62

Joviality	21.17	6.85	22.08	4.52
Self-Assurance	14.42	5.23	15.08	5.52
Attentiveness	10.92	3.09	12.00	2.89
Serenity	9.08	2.11	10.25	2.80
Surprise	5.08	2.19	7.75	2.83

Similarly, to assess the within-subject effect of Inter-Dream on basic affect, a series of t-tests were conducted comparing pre and post-test scores for scales of basic positive and negative affect. There was found to be a statistically significant within-subject decrease in basic negative affect (t (1,11) = 3.64, p = .004, d = .90) after the use of Inter-Dream, while no significant difference was found regarding basic positive affect (t (1,11) = -.76, p = .47. d = .15).

4.3.2 EEG Analysis

To explore general electrophysiological activity present during the use of the Inter-Dream system, absolute power values were calculated from the power spectral density transformations of raw EEG data, into the conventional frequency bandwidths of Delta(δ) 1-4Hz, Theta(θ) 4-8Hz, Alpha(α) 7.5-13Hz, Beta(β) 13-30Hz, and Gamma(γ) 30-44Hz. Measures of absolute power across time were averaged between participants to demonstrate general trends in cognitive activity across the use of Inter-Dream. To further explore which frequency bandwidths were most prevalent by measure of absolute power, a grand mean was calculated from the disparate absolute power means of each participant, summarised in Table 4.

Table 4: Means and Standard Deviations of Power for Each Bandwidth Spectrums Across all Participants (N = 11).

Spectrum	**M**	**SD**
Delta (1-4Hz)	.61	.52
Theta (4-8Hz)	.10	.35
Alpha (7.5-13Hz)	.29	.16
Beta (13-30Hz)	.21	.24
Gamma (30-44Hz)	.01	.29

4.3.3 Thematic Analysis

Here I describe the themes yielded via thematic analysis of participant interviews.

4.3.3.1 Passivity and Self-Exploration

Through the participants' narrative retelling of their experiences with Inter-Dream, it became evident that there was a pervasive notion of dynamic evolution or progression in the way they interacted with the system. Specifically, they communicated alternating dispositions of passivity and exploration. Most commonly, participants described self-appraisals of passivity when discussing their initial interactions with the system. This was evident in descriptions of "*trying to work out what was going on, waiting for it to change*" (P4), "*wanting to look at all the cool stuff that was happening*" (P3), and feeling "*kind of passive to whatever was going on and just, see what happens*" (P11). These responses demonstrate a degree of initial complacency toward the system, with the participants either attempting to understand its mechanics or perhaps solely appreciating the neurofeedback generated imagery. Nonetheless, these experiences shared commonality in that the participants initially assumed the role of passive external observers.

In conjunction to this, there was a notable shift toward playful self-exploration as participants became habituated to the system. When asked to describe thoughts or feelings after "*settling in*", participants made statements such as "*it was a great space to be exploring your states of mind and how to influence them [...] being with the experience rather than being on the outside*" (P5), "*I was thinking about things and I could see it was affecting the shape, or I think it was*" (P11), and "*I was thinking of colors to see if [the graphic] changed*" (P3). Furthermore, one participant suggested that "*it encouraged introspection, jumping to different thoughts more than usual because it made me a bit more excited about those thoughts ... I was more active in them and engaged with them more quickly*" (P6). When considered in contrast with descriptions of initial impressions of the system, these statements demonstrate an organic evolution from passive to active interaction with the system. Specifically, this active interaction can be considered as self-exploration of the mind.

This was made increasingly apparent when participants were asked if things would be different had they the opportunity to use the system at home. Responses to this prompt included "*I would curate the experience a bit more*" (P5), "*I thought there was a lot of things you could do with it if you got familiar with using it*" (P9), and "*maybe I could be a bit more genuine with myself, more indicative of my private mind*" (P6). Taken together, these narratives suggest a growing interest and engagement in the notion of self-exploration which increases the more familiar the individual becomes with the neurofeedback mechanics of the system.

4.3.3.2 Mindfulness

Another prevalent theme was the description of cognitive states consistent with those of *mindfulness*. This was often voiced as a redirection of thought away from life stressors and toward the present experience as a result of the system's neurofeedback reactivity. For example, participants stated: "*I was thinking about my maths assignment, and then the introspective nature changed my thoughts on the maths assignment, why do I feel the way I do about that assignment [...] and they were generally more positive*" (P6); "*I was trying to clear my mind but I don't think I really needed to because I was so focused on the imagery because it always changed. There wasn't much opportunity for my mind to wander off about any problems I had [...] And that's when I thought it's sort of a form of meditation because I'm clearing my mind*" (P9); "*I was drifting off to worries, mainly about work, and it [the change in visuals] brought me out of that*" (P4).

In particular, one participant with prior mindfulness experience had much to say in this regard. "*I've tried mindful activities and found them quite difficult. I tend to fidget. Having this visual focus, but it's abstract and doesn't have any literalness. I think I would find that more useful in helping me relax. Something that is [...] not like a television that tries to pull your mind in different directions [... but] a kind of peaceful experience that actually acts in the same way that mindfulness is intended to be, perhaps a little more accessible*" (P7). In this case, the participant explicitly draws connection between the system and the act of mindfulness, emphasising the propensity the neurofeedback driven visual graphic could have in grounding attention to a singular stimuli representative of their own mind.

4.3.3.3 Restorative Restfulness

A small number of participant responses indicated experiences of *restorative restfulness*. One participant voiced: "*I was expecting it to make me more drowsy, but actually I think I'm more alert and focused*" (P8). This notion was shared with another participant, who expressed that they felt "*not less alert but more alert, in a positive way [...] I had a migraine. I thought it would make it worse, but I think it made it better*" (P4).

4.3.3.4 Neurocentric Agency

Participants were also prompted to explain the experience of Inter-Dream as a "*thing in itself*". This was done by asking them to explain it as if they were describing it to an alien, implying to reduce it down to its most fundamental components. This prompt was intended to discern what components of the system the participant deemed most important to the experience. In response, there was an overwhelming focus on describing the connection between the visual imagery and their brain's activity. This was communicated in that participants described Inter-dream as: "*Brain activity represented as artwork, a creative image of brain activity that looks like art"* (P3); "*Some type of artistically imposed hallucination or art form of a visual hallucination, in a way connected to what you were thinking*" (P4); "*a creative experience involving stimuli to inflect a state of consciousness*" (P5).; and "*I saw patterns and colours of my thoughts*" (P9). As the focus of these responses is directed towards the elements of the system that the participant had agency over through the brain-computer interface, I describe this theme as *neurocentric agency*. In addition, these responses also suggest the participants saw this *neurocentric agency* as a form of artistic or creative expression.

This notion is further reinforced by responses from later stages in the interview, where participants were given the opportunity to make suggestions or voice opinions they thought important. Participants stated that: "*Although there were different positions with the bed I don't know if I controlled it […] I think the vibrations were distracting*" (P9); "*I was confused as to whether the bed was changing as a result of what I was thinking […] Was it planned or did I do that?*" (P6); "*I was thrown off a bit when it went bright red, it was like looking into the eye of Sauron*" (P8); and "*I felt that the music was separate from the experience and not engulfing*" (P5). What unites these responses is that they all address components of the system that the individual had no *neurocentric agency* over, a phenomenon that was typically met with confusion or perception of broken cohesion in the system.

4.4 Discussion

Here I provide discussion considering the results gathered from each of the three perspectives of the analyses and provide design strategies for applying these findings.

4.4.1 Arousal, Emotion and Affect

The results of the psychometric analyses regarding measures of pre-sleep arousal demonstrated a statistically significant decrease in pre-sleep cognitive arousal when participants' rest was augmented by the Inter-Dream system, whilst no significant change was seen for presleep somatic arousal. Similarly, results also suggested participants experienced a significant decrease in negative mood and affect while resting with the Inter-Dream system, but no significant difference in measures of positive emotion and affect.

Together, these findings suggest that the experience of Inter-Dream partially induced the psychophysiological pre-sleep states necessary for sleep onset. This would indicate that participants experienced a decrease in chaotic, invasive, or hyper-alert thoughts and worries; while the prevalence of irritating or distracting bodily sensations would have been consistent throughout. Additionally, participants experienced a negation of negative thoughts or feelings they had prior to entering the system, all the while not necessarily experiencing any elation or excitement as a result.

Possible explanations for the within-subject consistency of somatic arousal are twofold. Firstly, the initial mean of the pre-test condition was quite low ($M = 12.78$), being quite close to the minimum score the scale could possibly yield ($M = 8$). As a result, an expectation of any notably further drop in mean than what was witnessed yielding a significant result would not be likely. Second, and perhaps most likely, was the notion that there was a physical element of the system which participants found irritating, uncomfortable or distracting. This idea is supported by the participant interviews, with responses commonly reporting the feeling that components of the system they had no agency over were either distracting or detached from the experience.

4.4.2 Electrophysiology

Neural activity by measure of EEG absolute power spectral density produced results largely consistent with the literature's description of neural activity during healthy sleep onset. This was most evidently seen in the high power level of the delta frequency bandwidth relative to others, which is a defining characteristic of sleep-related activity (Kinreich, Podlipsky, Jamshy, Intrator, & Hendler, 2014; Lester, Burch, & Dossett, 1967).

The observed trend in the alpha power level across time was not consistent with that described in the literature (Kinreich et al., 2014; Lester et al., 1967). While it would be expected for alpha to drop dramatically toward the later stages of sleep onset, visual inspection of plotted alpha values over time suggested no such activity. However, considering the relatively short time frame of Inter-Dream sessions, and that no participants reported falling asleep during their session, the absence of an alpha drop would be expected.

4.4.3 Design Tactics

In considering the findings of the study, I propose a series of design strategies. These are intended to guide designers and artists in designing neurofeedback systems to promote positive sleep through the augmentation of pre-sleep.

4.4.3.1 Tactic 1: Facilitate Exploration

Through the study of the system, I have identified a set of mechanics that can facilitate playful exploration even in physically passive contexts, such as those of pre-sleep or sleep. This was arguably achieved through framing the subject of the exploration as none other than "the self", something that is perpetually dynamic in an otherwise static environment. It is through the lens of this concept that I propose neurofeedback or brain-computer interfacing as a powerful tool for bringing interactivity to a passive setting.

Furthermore, participant responses demonstrated a disposition of curiosity toward the depth of exploration the system allowed, stating their desire to take the system home, curate the experience, experiment with it, and use it to better understand themselves. With this considered, I propose it would be in the interest of designers developing interactive neurofeedback systems to expand on the level of variability and uniqueness that can be achieved with subsequent or prolonged use, to reward that exploration. I suggest this could be achieved by increasing the amount of biometric input the system is responsive to (more electrodes, or different biosensors), creatively using EEG feature extraction methods to produce unique output in specific circumstances or increasing the number of parameters that can be modulated through the brain-computer interface.

This concept builds upon the findings of Kitson et al. in their exploration of introspective VR as a tool for lucid dreaming (A Kitson, Schiphorst, & Riecke, 2018). The authors state that abstract spaces such as those experienced in lucid dreams provide an opportunity for the development of personal meaning, in turn exploring one's thoughts and feelings, whilst also being playful to encourage said exploration. However, while the authors state this is yet to be put into practice in interactive technologies (which are typically led by the designer), the present study demonstrates the capability of affording such experiences through the playful artistic abstraction of neurofeedback, within the context of presleep.

4.4.3.2 Tactic 2: Promote Neurocentric Agency

The prevalence of the theme of *neurocentric agency* suggested that in a multisensory neurofeedback or BCI driven system, individuals are more inclined to engage with and appreciate stimuli or components which they have agency over. Participants voiced opinions of feelings of disconnect or disparity between the components of the system not responsive to their thoughts. This also manifested as confusion as they attempted to manipulate non-responsive components, not understanding those stimuli were separate to the BCI. With these points considered, I propose that the future design of multisensory neurofeedback driven systems should consider avoiding the inclusion of non-reactive elements as core components of the experience.

Again, this resonates with the sentiment proposed by Kitson et al. who propose users should feel a sense of control in order to generate feelings of empowerment and confidence that can be carried into the real world when designing for lucid dreams (A Kitson et al., 2018). Through *neurocentric agency* I demonstrate that this can be achieved to the broader application of pre-sleep through the implementation of neurofeedback systems where the major parameters of the system can be controlled by the user's mind.

4.4.3.3 Tactic 3: Facilitate Self-expression

Furthermore, this appreciation of agency was often paired with appraisals of artistic creativity toward the system. This illustrated the notion that participants appreciated the degree to which they could fluidly create through expression of their private electrophysiological processes. As such, I recommend the exploration of means by which users can interpersonally express and share their creativity generated by electrophysiological output. This could be further fostered by, for example, designing toward the integration of multiple users in a neurofeedback driven system, thereby providing a means for sharing and mutually appreciating the individuality of mind.

4.4.4 Limitations

One limitation of the study, specifically when considering its situation within the broader context of sleep, was the design choices present due to the system's origin as a public interactive art installation. Accordingly, some components of the system, namely the use of VR, while suitable in the domain of pre-sleep, are not entirely compatible with sleep itself due to the unwieldy nature of the HMD. As such, while the use of VR assisted in demonstrating that neurofeedback driven artistic expression and creative exploration may promote positive pre-sleep states, the findings of the study cannot be generalized beyond pre-sleep.

Similarly, the study's research design did not directly measure the promotion of sleep quality directly but rather inferred the potential for interactive technologies to improve sleep through its positive influence on pre-sleep. With this considered, abstracting the findings of the present study beyond pre-sleep should be approached cautiously, as research directly assessing the influence of interactive technology on sleep quality must first be performed before it can be claimed with confidence that systems such as Inter-Dream can indeed promote sleep quality.

Finally, the interactivity of some of Inter-Dream's components (i.e. the bed and audio) were operated by the artists. With this considered, having a fully automated system driven completely by neurofeedback could potentially reveal more detailed or unique insights.

4.5 Informing the Framework

Considering the results and discussion of the first study ultimately lead to forming the foundation of the Brain-Computer Integration Framework. Namely, the insights gained from the exploration of this first case study primarily that feedback and agency are two critically influential factors of a BCI system when considering the user experience.

The themes of *passivity and self-exploration*, *mindfulness*, and *restorative restfulness* demonstrated that the way in which brain activity was translated into information accessible to the user greatly impacted the causal loops evoked by the system. These causal loops then ultimately went on to modulate the neurophysiology of the recipient, which in turn recursively influenced the system's translation of brain activity into accessible information yet again. Furthermore, these results highlighted that not all output is made equal, as participant responses varied in what kind of response they had to the output in relation to what they were feeling. This insight highlighted the need for future research to consider how different and more varied forms of communicating brain activity may influence the user experience.

Furthermore, the theme of *neurocentric agency* highlighted the importance of the user's sense of agency in determining the user experience. Specifically, participant responses indicated that different elements of the experience could be "felt" with varying degrees of cohesiveness to the experience and that the influence their brain activity had on these elements influenced this feeling. While I originally interpreted this finding to mean that all elements of a BCI system should be able to be influenced by brain activity, my later studies demonstrated this to not be entirely true, and that rather this only appeared to be true in the case of Inter-Dream because there was only a single user. Following this sentiment, the results of this case study indicated the need for the study of BCI systems in which brain activity information is exchanged between users, ultimately leading to the second case study, Neo-Noumena.

5 Case Study II: Neo-Noumena

This chapter details the second case study: Neo-Noumena, a system that employs BCI-driven procedural content generation (Freiknecht & Effelsberg, 2017), visualized using mixed-reality (Rokhsaritalemi, Sadeghi-Niaraki, & Choi, 2020), to augment interpersonal emotion communication (Guerrero, Andersen, & Trost, 1996) through dynamic, proxemic abstract representations of affect. With this case study, I explore my research question through the sub-question: *"How do we design integrated brain-computer interfaces for communicating brain activity?"*. The research question underlying this case study was informed by the directions for future work inspired by the findings of the first case study, Inter-Dream, which suggested the necessity to understand how the user experience of brain-computer integration changes when neurofeedback loops are directed outward to other users, and how this influences the experience of agency. Thus, in answering this research question I was able to explore the interpersonal aspect of the brain-computer integration design space and thus better understand the design of brain-computer integration as a whole. With the system being a BCI in the context of emotion communication, this case study allowed for the investigation of how BCIs can be designed to communicate brain activity by acknowledging emotional states as a set of information that can be transmitted. The rest of this chapter details the design and an evaluation of how this system interacts with the subjective experience of consciousness of the participants using it. I present findings around the use of the prototype in isolation and then generalise toward brain-computer integration. A video demonstrating Neo-Noumena can be found at: https://youtu.be/GbSzwxNmYz0

5.1 Associated Publications

The work detailed in the following section has been peer-reviewed and reported on in a full-length conference paper, titled "Neo-Noumena: Augmenting Emotion Communication", and a short paper titled "Neo-Noumena", presented at the ACM CHI Conference on Human Factors in Computing Systems (CHI) 2020, Honolulu, United States.

5.2 Prototype

Figure 12. Two participants observe fractal swarms representative of their emotional states through the Neo-Noumena system.

The following section details the technical implementation of Neo-Noumena.

5.2.1 EEG-Based Emotion Recognition

The system interprets EEG data to classify participants' subjective emotional experiences. To achieve this, eight channels of EEG data are collected via an electrode cap connected to an OpenBCI Cyton amplifier, relayed over to a HoloLens (a mixed-reality head-mounted display) through a "User Datagram Protocol" server. EEG electrode placement followed the 10-20 convention (Homan, Herman, & Purdy, 1987), with data recorded from electrodes: Fp2, F4, F7, F8, C4, P3, P4, O1, AFz (ground), and CPz (reference).

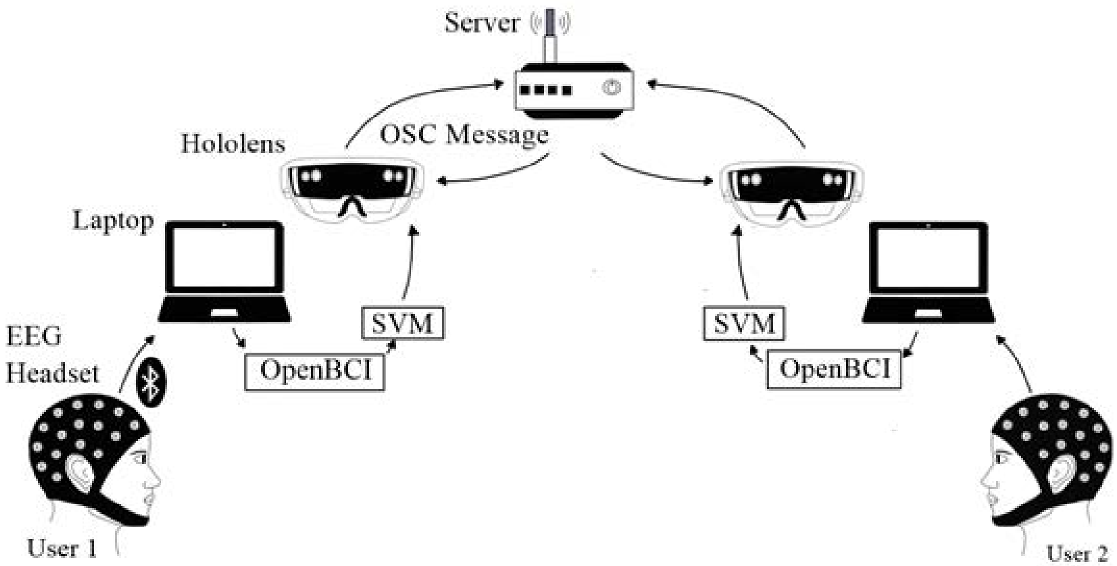

Figure 13. Neo-Noumena's system architecture.

The raw EEG signal is sampled at a rate of 250Hz, passed through a 50Hz notch filter, a 5-50Hz bandpass filter, and finally processed through the use of a mean smoothing filter to mitigate movement artefacts (Tarvainen, Hiltunen, Ranta-aho, & Karjalainen, 2004). Features from filtered data are then extracted, using the six statistical features identified in Picard et al. (Picard, Vyzas, & Healey, 2001). Features are then interpreted by a support vector machine classifier to infer the participants' emotional states. This support vector machine was implemented in Python with a radial basis function kernel for multi-class classification, with $\gamma = 1$ and penalty parameter C of the error term = 0, yielding classification accuracy of 58.33%. The classifier was trained using the DEAP dataset (Tripathi, Acharya, Sharma, Mittal, & Bhattacharya, 2017), fractally assessing emotion based on the dimensions of arousal and valence, following procedures previously identified (Liu et al., 2010). This approach binarily classifies EEG data for each dimension, leading to four possible classifications of affective category, these being: High-Arousal-High-Low, High-Arousal-High-Valance, Low-Arousal-High-Valance, and Low-Arousal-Low-Valance (figure 14).

5.2.2 Procedural Content Generation to Represent Emotion

Neo-Noumena utilises procedural content generation, employed in the form of a fractal generator, with the participants' concurrent classification of emotion being the "seed" for the generation of fractals. Thereby, each classification of emotion generates a fractal that differs across dimensions of node count, smoothness, angle size, rate of change and colour, which together create unique evolving patterns. These properties work to generate abstract representations of neurogenic affective signals which, as discussed above in related work, has been demonstrated to reflect subjective cognitive states in neurofeedback systems using similarly abstract representations. Considering this, I therefore argue they could be extended to reflect emotional states.

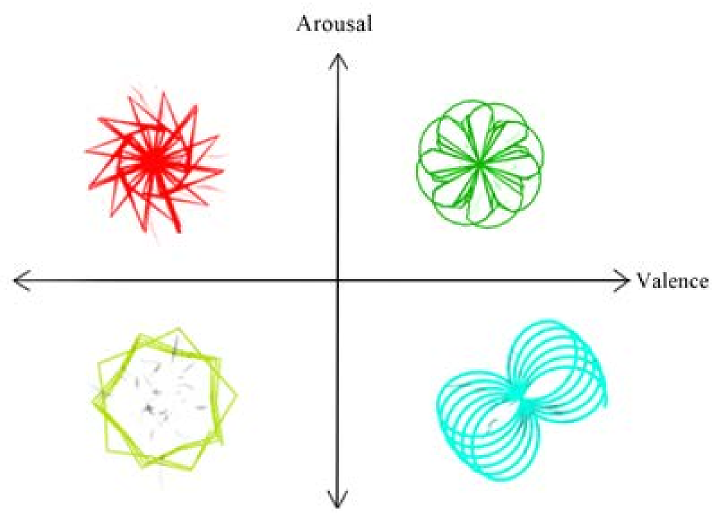

Figure 14. Example fractals based on classification of affect.

From the experiential perspective of the participant, Neo-Noumena renders their emotional state into AR as ambient swarms of fractals (with eight fractals per swarm) akin to an "aura" that surrounds and follows the participant (figure 15). This fractal swarm is generated in the participants' proximity at a circular range of ca. 1.2m, consistent with the proxemics definition of personal space (Hecht, Welsch, Viehoff, & Longo, 2019). The appearance and movement of the fractals change according to the participant's emotional state. Additionally, using the affective sound database Audio Metaphor (Fan, Thorogood, & Pasquier, 2016; Thorogood, Fan, & Pasquier, 2019), I generated sets of audio files which corresponded to each emotional state. This audio was then attached to the fractals, so that sonic representations of affect could be heard through the HoloLens when participants were in close proximity to them.

The decision to implement fractals to represent emotion was informed by a body of cognitive psychology literature documenting aesthetic appraisal of fractals (Bies, Blanc-Goldhammer, Boydston, Taylor, & Sereno, 2016; Spehar, Clifford, Newell, & Taylor, 2003; Street, Forsythe, Reilly, Taylor, & Helmy, 2016) as well as research identifying the efficacy of aesthetics as a potent medium for communicating emotion (Freedberg & Gallese, 2007; Pelowski, Markey, Forster, Gerger, & Leder, 2017; Pelowski, Markey, Lauring, & Leder, 2016; Ruiz, 2019; Springham & Huet, 2018; Street et al., 2016). Considering fractals specifically, it is noted that fractal properties such as complexity are associated with arousal, while smoothness and symmetry are associated with pleasure, and asymmetry being associated with displeasure (Bies et al., 2016).

Figure 15. A user wears Neo-Noumena, surrounded by their fractal sawm. The fractals here demonstrate low arousal and high valence, suggesting they are relaxed.

In utilising a boid swarm (Hartman & Bene, 2006), I intended to introduce an additional dimension of emotionality to the content being generated in the form of movement patterns of the fractals. Prior work examining emotion communication in drones and swarming behaviour has demonstrated how flight path, speed and algorithmic intelligence can be used to convey specific emotions (Cauchard, Zhai, Spadafora, & Landay, 2016; Delgado-Mata, Martinez, Bee, Ruiz-Rodarte, & Aylett, 2007; Ibáñez, 2011). As such, the fractal swarms communicate the affect of the participant through modulating the variables of the swarm's movement speed, cohesion, avoidance and alignment in accordance with the emotion they are representing.

Lastly, the decision to employ mixed-reality was enacted in accordance with Humanistic Intelligence (HI) (Mann, 2001) principles, which aim to design processing systems that are intertwined with the human body, such that enhanced intelligence arises from the synergy of human and computer. Mann argues that wearable computing embodies HI in that it offers an opportunity for enhanced intelligence to arise from the human-computer interface. I argue that AR embodies these principles due to its unrestrictive, attentive and communicative properties. Neo-Noumena intends to augment emotional communication, rather than replace it. Since AR allows for the placement of virtual objects in the real world, in contrast to VR that replaces the real world with a fully immersive virtual environment, I believe AR to be more suitable as a communication enhancing medium.

5.3 Results

In this section, I present both qualitative and quantitative results.

5.3.1 Emotional Competence

To assess the within-subject effect of Neo-Noumena on emotional competence, a series of paired-samples t-tests were conducted comparing pre and post-test scores for each scale. I found a statistically significant improvement between pre-test and post-test in participant measures of "emotion regulation of others" (t (1,9) = 3.24, p = .01, d = 2.13). There were no observed significant differences in measures of the other subscales of emotional competence.

5.3.2 Thematic Analysis

In analyzing the recounts of participant experiences through interviews and participant diaries, three major themes were revealed. Analysis of this material was performed inductively through thematic analysis (Clarke & Braun, 2014) in which myself and three co-researchers from the Exertion Games Lab independently reviewed transcripts and coded the data. Codes were iteratively clustered into high-level groupings agreed upon until they were consolidated into three final themes emerging from the data.

5.3.2.1 Spatiotemporal Actualization

The theme of *spatiotemporal actualization* regards how the experience was modulated by the way emotion interacted with physical space and time. Initially, the physical component of this theme was evident in the way participants described what the system does, with their use of language predominantly emphasizing that the system is "*projecting your emotions*" (P1 & P2). Participants explained that the system does this by "*taking your thoughts, your emotional cognitive activity and then translating it into something that's more spatial or in space so people can access it without necessarily having to give it to them*" (P4), that "*it's looking at 'how were you feeling over this past half a minute?'*[…] *and then manifesting that*" (P7), and that "*it feels like someone's actively interpreting things that you don't see to show you a depiction of it*" (P8).

Participants then appraised these projections as agents embodied by their emotions, reflected in statements such as: "*Sometimes it was like having a pet. It lands on your table, kind of like a cat […] but instead of a cat it's literally a piece of your emotion*" (P4). Participants also recognized that the behaviour of the representations was in correspondence with their emotions: "*I assumed red meant anger or frustration, and this seemed to make sense with the movement of the Noumena through space*"

(P8); “*I like the red. I think the movement was a really big one, looking at it was like 30 minutes after taking your ADHD medication*” (P7).

Through these emotionally embodied fractals, participants were purportedly made more aware of the interaction between emotion and time. This was typically first acknowledged as a realisation of how much emotions change i.e., “*I found it weird that the system showed that emotional state changes so frequently*” (P3). This sentiment was then built upon in their last entry of their journal: “*Still surprised about how frequently the system is suggesting these emotional states change. It is reassuring to know that these states can change and flow so quickly*” (P3). This initial awareness of the relationship between emotion and time was strengthened when participants explored how their emotions changed. This mostly took the form of recognizing patterns in the interaction between the environment and their emotional state, stating things such as “*[P2] noticed yesterday that when I was using my journal [...] that I had a lot of colours other than red*” (P1), and “*I can usually gauge ‘oh, it's red, it has shown up after this person would be agitated’, and similarly "oh this person is at a resting state, oh it's yellow*” (P5). However, participants later took to actively experimenting by subjecting themselves to different conditions to investigate how it would affect their emotions. This took many different forms, for example, P3 said: “*Listening to stupid music [...] was fun because if it was [...] enjoyable to listen to, you could tell. As in, the emotional content of the song, the valence and the arousal usually followed that*”, whereas P8 stated: “*I [wanted] to see if smoking a small joint would change how they reacted. I think it increased my stress levels, which seemed to be reflected in the Noumena activity, with them being far more active both in time and space afterwards than before*”. P7 described how “*last night we also watched a standup routine to see how that would interact with the system [...] I’m pretty sure the colours I saw were positive ones, green and blue*”. This taught the participants they can leverage control over their emotions to some degree by changing elements of their environment.

One participant demonstrated marked differences in emotional content across their three days. They recounted the first day by stating: “*On the first day my partner and I used it, it was after a long workday and we were pretty tired*” (P4). In contrast, they recounted that “*on the second day my partner and I drank a lot and listened to a lot of music. All that together produced a very noticeable difference in our mood from the day before for both of us. The whole night we were singing and dancing along with the music, and we were generating some pretty positive emotions. For me that made me even happier to see that she was happy. It felt like it was feeding back in on itself, like a nice big loop of happiness.*”

These accounts demonstrate that experiencing actualized emotion through time allowed participants to experiment with changes in their own emotions and their partner’s. Ultimately, this allowed participants to learn patterns, and build emotion profiles of themselves and their partners, often comparing them: "*[P4's Noumena] tended to be at least a lot more positive than mine was [...] more high arousal as well. Theirs were green and red a lot, whereas mine was yellow a lot*" (P3). Similarly, P8 stated "*[my partner was] generally more chill than me, and less likely to act on something when [the] red guys are there [...] it gave me an idea of maybe the emotional leeway that [they're] willing to give*".

As a result of using the system, participants were challenged to consider how emotions can be changed; actively by the individual or passively by the environment, in favour of more fatalistic notions of prescribed emotional predispositions. This is clearly demonstrated by the responses of one dyad in tandem: "*I know I'm a sad person, so it was interesting to see that actually [being] kind of true. But also, the fact that it wasn't just sad all the time. So that's interesting to see that it could very easily change in 30 seconds [...] It was quite nice to see you're not doomed to just be in one mood all the time*" (P3). This process of challenging the permanency of emotion was also mirrored in the participant's partner (P4) when considering what they learnt about P3 through the experience. "*The more negative side of the spectrum was very prevalent in my partner [...] which is kind of expected. But it was interesting to see it fluctuate from that a lot. It was very relieving to see [...] because sometimes I get worried that she's sad all the time*" (P4).

5.3.2.2 Objective Representation

This theme refers to how the system enabled participants to instantaneously experience emotion as a point of introspection or objective understanding about their own psychology. This was initially articulated by participants through the weighting they placed on the system's assignment of emotion, as opposed to their own self-appraisals. For example, participants stated that the categories they found their emotions fell into made them think: "*'Oh this makes a lot of sense', finally being able to test a hypothesis, finally, being like 'Ah yes! I thought so!'*" (P7) and describe the experience by saying "*it was more like a mirror; this feels more like it's a part of you*" (P4). Similarly, P4 described how their partner would say "*oh my god you're so happy, you actually love this band"* in response to their generation of positive emotions while listening to music, almost as if the visualisation of emotion was objective confirmation of a hypothesis held previously.

This also made participants realise they were previously less aware of their emotions than they thought they were, making statements such as "*maybe subconsciously my moods did change but I wasn't really aware of them*" (P2), and similarly "*getting something wrong [when playing piano] surprised me to see that it had such a big impact on, like, how I was feeling*" (P7), P8 stated, "*I would never have expected how big of a change could potentially be produced from all the little things* *that I think about in little moments [...] maybe I'm not as aware of it as I thought I was*". From this new foundation, participants found themselves in a position to perceive and more objectively understand emotion, stating: "*It's not about what you think you feel, it's about what's happening in the moment*" (P8). There were limits to this, however. For example, one participant reasoned that reducing emotion to four categories made it in times harder to interpret, stating: "*more than four of them, that obviously would be great [...] because there was little bits where I was just like 'Oh, I'm not quite sure what this is meant to mean' and they [emotions] can be quite a wide spectrum*" (P8).

Participants also found themselves able to objectively appreciate all dimensions of emotion, both positive and negative, with statements like: "*Even when it was a negative thing being generated, it was still really beautiful. It was like you could appreciate the negative moods just as much as you could appreciate the positive moods*" (P4). Considering the affordance of objectively understanding and appreciating emotions, participants suggested this allowed for Neo-Noumena to be used as a tool for reflecting on, navigating through, or challenging their own psyche, demonstrated by statements such as: "*I think I'm feeling pretty good, let's put on the Neo-Noumena's for a little and see if I'm actually feeling good or If I'm just tricking myself that I'm doing good*" (P7)..Or: "*it made me realise I have a pretty decent background level of stress all the time"* (P8). A few participants went so far as to say this would be useful in a psychotherapeutic context, stating: "*I can imagine for therapy, obvious usage there. I can only imagine it being a good thing, a boon*" (P5), and "*I think I would use it whenever I did my CBT homework, like, oh, when I challenge this particular idea how does it change how I'm feeling?*" (P7), and "*I think the idea of using it for CBT is really interesting [...] I think it could be a really useful tool to become aware of when I'm encountering [...] blockages and be like 'Okay, well you're like losing your shit a little bit, so why, what's going on? Can we interrupt this?'*" (P8).

This also translated interpersonally, with participants describing how the system served as a visual reminder to consider or reflect on the sentiment that other people hold their own emotional world. For example, one participant stated: "*The best part of it is, I think, maybe being made to think more consciously about my own emotions and also about other people*" (P8). Similarly, P4 stated: "*It was like a constant visual reminder to consider someone's mood [...] and just appreciate that other people have emotions as well*". This latter participant imagined a future where everyone was using Neo-Noumena: "*Everyone else is usually quiet, flat. But I'm sure that with all those flat expressions everyone's probably experiencing a massive difference in the dimension of their emotional state. [...] it would make a lot of future engagements with other people more humanistic*" (P4).

5.3.2.3 Preternatural Transmission

This theme refers to how the experience of the system was influenced by its capacity to hold and transmit information interpersonally beyond ordinary means. In reporting their experience with the system, participants often compared it to un-augmented human communication methods and identified how the system differs. In doing so, they acknowledged features of the system relevant to this theme, including automaticity, continuous flow of information, effortless communication, accurate communication, and examples of 'extrasensory' information where the system not only facilitated information exchanges but provided additional information that augmented communication between dyads.

For example, participants suggested that, unlike un-augmented communication, the system provided emotion information "*automatically*" (P3) and continuously, "*it was like you had an 'aura' you could always refer to, no matter what you were doing [...] it was always there*" (P4). The system provided information about emotion states, and P4 likened this process to "*asking someone 'how are you feeling right now?' But if you could do it at any point in time* (P4)", thereby distinguishing the system's automaticity through the notion that "*people can access it without necessarily having you have to give it to them*" (P4), as well as continuous information transmission. A few participants suggested that these qualities could even make the system's widespread usage controversial, voicing concerns such as: "*People would be worried if it got to the point of mind-reading*" (P5). Another feature participants identified, which differentiated the system from un-augmented communication, was that information was transmitted without effort from the communicator: "*It's cool because the whole thing technically takes no effort*" (P3). One participant explained how it made understanding their partner less effortful: *"It was like: 'Oh, you're feeling a bit frustrated at the moment' or: 'You're feeling a bit like you're feeling relaxed'. It took the guesswork out of trying to figure out, 'oh, what is this other person feeling?', 'What's happening with their brain?' and stuff like that*" (P8).

Participants were also interested in the accuracy of the information held and transmitted by the system. As identified by participants, the continuous and effortless nature of information transmission provided the opportunity to get "*a raw data feed* (P7)" of people's emotions. Unlike human's un-augmented emotion communication, like speech and body language which can usually be modulated, the system provided unbiased information, and "*could in a way potentially work to bypass the filtration system* (P7)". In fact, a participant described the system as being "*like a little window into their emotional state* (P4)". When queried whether the system is redundant considering we could just ask people how they feel, a participant responded: "*Nah, because you have to rely on what that person is saying, and they could be just making shit up [...] And also you have to rely on your own interpretation of how you're feeling* *as well, which might be biassed [...] so it's cool to just see it automatically* (P3)". Thus, the automatic and raw nature of the emotional information appeared to provide the opportunity for more accurate communication.

Participants realised that the system was not just facilitating communication, it was augmenting - providing more information - than un-augmented communication methods. For example, P5 and P6 played a card game while using the system, and P5 explained how the system suggested that their partner was "*generally mellow if it was a good hand*" and "*red towards the end of a round where it's determined who is going to win or lose*". They explained how the system provided an extra source of information, since "*this other person wearing the lens can see [...] my reaction to the [cards] that only I can see*", which they usually must keep hidden in the game. The participant explained that this was a team-based card game, with themselves and their partner on one team, and two others not using Neo-Noumena on the other, who "*were twins that can communicate telepathically*". Considering this, P5 mused that Neo-Noumena would "*even the playing field*".

Another example of the additional information the system can provide was in P7's experience of playing music while their partner worked on an essay, explaining how the system "*enabled me to monitor seemingly drastic changes in their emotions even as they affirmed to me it was, in fact, okay for me to keep playing [music]. They could say that everything was going okay, but whatever was happening with the AR made it apparent that at least in some instances it was not*". Similarly, participants recounted episodes of heightened levels of empathy, or "syncing up", for example, "*we seemed to 'sync up', where [P7's] playing worked well with my pop-esque ukulele strumming, I noticed all our Noumena's [...] hovering in the same corner of the room and acting mostly in the same way, with their colours and shapes shifting only slowly and gently*" (P8).

However, this sense of heightened communication was sometimes disrupted when participants held different preconceptions of what each classification meant. For example, P8 explained they interpreted the High-Arousal-Low-Valance Noumena to mean something less dire than what their partner thought, stating that "*they found them to be quite like 'oh no, what's wrong!', and I was just like 'oh, ok, I must be a little stressed out*". This was exemplified in P7's concerns that their partner might misinterpret how they were feeling, thinking "*oh no, don't think I'm angry at you please, I like hearing you singing, I just have a headache*" (P7). This demonstrates that individuals having differing perceptions of a Noumena's meaning might be a source of noise in the signal being communicated.

5.4 Discussion

In this section, I discuss the study's quantitative and qualitative results.

5.4.1 Psychometric Analysis

Measures of emotional competence showed no significant improvements in participants after their time with Neo-Noumena, save for the subscale measure of "emotion regulation of others". While this may be evidence for the absence of efficacy on the other subscales of emotional competence, this could be argued against when considering several factors. Firstly, that emotional competency or emotional intelligence has been argued to be relatively stable (Chamberlain et al., 2012). Second, interventions specifically designed to improve emotional competence are lengthy and very involved procedures, often being 15 hours in total (Hodzic, Ripoll, Lira, & Zenasni, 2015; Kotsou, Nelis, Grégoire, & Mikolajczak, 2011). In contrast, most participants engaged with Neo-Noumena 1 hour a day (the minimum I allowed), accumulating to an average of approximately 3 hours across their involvement in the study. All participants were apologetic about this while returning the system, stating they could not use NeoNoumena any longer because the HoloLens and EEG together were heavy on their head and the headset often pinched their nose. Nonetheless, with that considered, a significant improvement in a single subscale is a promising result.

5.4.2 Embodied Augmented Emotion Communication

Taken together, the results of the thematic analysis demonstrate that through *spatiotemporal actualization*, participants experienced emotion as something tangible that can be changed and interacted with. Through *objective representation*, participants experienced emotion as something that can be objectively appreciated and reflected on. Through *preternatural transmission*, participants experienced emotion as something that holds and transmits information, producing emergent, and novel opportunities for communication.

The validity of these themes is supported when considering their strong alignment with Grīnfelde's "four dimensions of embodiment" (Grīnfelde, 2018), which became evident following the establishment of the themes independently. These being: The body as 1) a bearer of sensations; 2) a seat of free movement, characterised by the faculty of "I can"; 3) a material thing in a causal relationship with the material world; 4) a material thing embedded in a social context. "The body as a bearer of sensations" most closely resonates with the theme of *objective representation*", which acknowledges that participants experienced representations of emotion through visually and auditorily "sensing" their manifestations, in turn prompting introspection. "The body as a material thing embedded in a social context" is most evidently aligned with the theme of *preternatural transmission* in which emotional information extracted from a participant's body was transmitted in a social context. Lastly, "the body as a seat of free movement" and "the body as a material thing in a causal relationship with the material world" is aligned with the theme of *spatiotemporal actualization*. The analysis presents these concepts as a singular theme due to the heavily dependent relationship between time and space, but nonetheless, participants experienced their emotion as a "physical thing" interacting with the "material world" through the head-mounted display, being a seat of "free movement" through its changes across time.

Furthermore, the findings contribute to ongoing debates within affective computing. Howell et al. sought to challenge the authority assigned to insights from biosensing systems for emotional reflection, by designing a system encouraging users to form their own interpretations (Howell, Devendorf, Vega Gálvez, Tian, & Ryokai, 2018). However, despite the design intention, participants still appraised the system's reflection of their feelings as authoritative, with little questioning of the congruence between the display and their feelings. This issue relates to the theme of *objective representation*. This theme describes how participants appreciated emotions as impartial observers without prescribing desirability to specific emotional states. Participants often weighted the system's classification of emotion over their own self-appraisal. Howell et al. provided three lenses through which to consider the design of biosensing systems for emotional reflection (Howell, Devendorf, et al., 2018). First, "affect-as-interaction" (Boehner, DePaula, Dourish, & Sengers, 2005, 2007) states that emotion systems should support interpretation and ambiguity, and that emotion is a dynamic, socially constructed experience. Second is a consideration of Verbeek's theory of technological mediation (Verbeek, 2015), which suggests that presentations of technology can mediate perceptual appraisals. Lastly, biopolitics, which considers societal discourses of biosensing technology, especially in matters of health and authority, which Howell later expands on, stating that "emotional biosensing products can be seen as modulating our emotions according to feedback systems and algorithms created by designers and technologists" (Howell, Chuang, De Kosnik, Niemeyer, & Ryokai, 2018). I retrospectively consider these lenses and how Neo-Noumena is situated within them.

Regarding "affect-as-interaction", Neo-Noumena was intentionally designed to support ambiguity and consider emotion as a dynamic, socially constructed experience. In fact, emotion classifications and corresponding procedural outputs were never revealed to the participants, so that participants could prescribe meaning to the representations through their own experimentation. This decision was also motivated by considerations of humanistic intelligence, which conceives of a computational-mediated reality similar to Verbeek's theory (Verbeek, 2015). For these reasons, I found it important to ground representations of emotion in theory while designing Neo-Noumena. However, where Boehner (Boehner et al., 2005, 2007) argues against any categorisation, as it may lead to treating affect as information rather than dynamic interactions, Neo-Noumena's focus on communication makes categorical representations difficult to avoid. Contemporary models of natural languages demonstrate that for human communication to be efficient, compression of meaning is necessary for communication to be informative and simple, as is accomplished by using categories (Kemp, Xu, & Regier, 2018). Lastly, in relation to biopolitics, the design of Neo-Noumena was intentionally ateleological (Introna, 1996), avoiding the designation of specific goals during use. Neo-Noumena could have been designed to facilitate the downregulation of negative emotions or upregulation of positive emotions. Instead, I acknowledge, as Howell stated (Howell, Chuang, et al., 2018), a need for affirmation over self-improvement. Nonetheless, the use of categories makes it difficult to assuage the "authority" of emotional biosensing systems and algorithms when designing for communicative efficiency.

5.4.3 Design Tactics

In considering the findings of the study and combining it with my craft knowledge of having designed Neo-Noumena, I propose a series of design strategies. These are intended to guide designers in designing systems for augmenting emotional communication.

5.4.3.1 Tactic 1. Emphasise Spatiotemporal Actualization if Facilitating Emotion Regulation

I have identified that the spatiotemporal mechanics of the system's interaction are instrumental in producing the experience of emotional control. Considering this, spacetime should be emphasised if the design aims to facilitate emotion regulation. In Neo-Noumena, this was achieved through designing the Noumena to appear as physical objects in the environment and dynamically avoiding or bumping into physical objects via HoloLens's spatial mapping, having them follow the person they were generated by through space, allowing their visual representation to change over time, and giving them simple swarm intelligence. These same properties, largely the ability to influence change over time, gave participants the ability to perform an action in physical space, and then observe the results in mixed-reality to better learn about how their emotions responded to the environment.

This extends the concept of *neurocentric agency*, which suggests that an expressive neuro-responsive system requires all components of the experience be controllable by the user's neural activity to avoid users feeling disconnected from the experience (Nathan Arthur Semertzidis et al., 2019). Neo-Noumena addressed this by ensuring all generated content is controlled by the user's brain and emphasising transience to the user through changing the spatiotemporal properties of the fractals. This level of control over the system across time ensures the user perceives a level of control over the content of the experience, theirs and others' emotions.

Therefore, when designing a system targeted toward emotion regulation, it is recommended that emotion: 1) be spatially embodied by a medium the user has *neurocentric agency* over, and 2) be temporally reactive to the user's emotion. This need not be carried out in AR. I believe other interaction paradigms, such as robotics, haptics, and many more, could also be effective. An example of this would be a drone whose movement is controlled by the emotion of one or even multiple users.

5.4.3.2 Tactic 2. Emphasise Objective Representation if Facilitating Introspection

The theme of *objective representation* was most evident when participants experienced perceptions of congruency between their brain's activity and what was being generated. It appeared that this congruency seemed to strengthen participants' faith in what they were experiencing as an accurate and *objective representation* of the reality of their emotional state. This provided the foundation for using the system as an introspective tool. I achieved this in Neo-Noumena by providing four broad emotion categories participants could prescribe meaning to, as well as making sure these categories would be reliably recalled whenever the participant exhibited the same physiological activity by ensuring a high degree of accuracy with the classification model. However, the experience of *objective representation* often broke down when participants felt like what they were experiencing did not fully encapsulate their lived experiences. In the study, this was apparent when participants thought themselves to be experiencing emotions that could not clearly be bound in one category.

Considering the tendency for individuals to place personal meaning to abstract stimuli [30], designers can emphasise *objective representation* in the design of a system by providing additional channels to interpret neurophysiological activity from. For example, I could have achieved this in Neo-Noumena by having the size of the fractals modulated by raw EEG amplitude, or have their colour modulated by frequency density while still having the geometric attributes of the fractal tied to the classification of emotion. These additional channels of information are typically fuzzy. Thus, they provide an opportunity for users to assign their own meaning to the generated representations, even when measures such as emotion classification fail to maintain congruence, thereby still facilitating introspection.

5.4.3.3 Tactic 3. Consider the Social Context of Preternatural Transmission for Facilitating Emergence

Communicative properties of Neo-Noumena are achieved as a result of its *spatiotemporal actualization* and *objective representation*. By improving these elements, one can ultimately improve the communicative properties of augmented emotion communication. However, it would be remiss not to consider the impact of the social context in which communicators are participating, which determines the constraints the system must operate within, and introduces new elements the system can interact with. These different contexts allow the emergence of context-dependent *preternatural transmission*, which refers to the extension of traditional forms of communication which, phenomenologically, approach the extrasensory.

I found that participants were most likely to experience preternatural communication when participants engaged in joint activities, like singing together, dancing together, playing games together, or purposely trying to influence each other's emotions. Neo-Noumena provided information that is not usually available in traditional communication. This gave participants the opportunity to participate in their contexts in enhanced ways and to better achieve the pre-defined goals of the social context, for example, informing the tactics used in a card game which capitalised on their partner's emotions, or anticipating their partner's needs while they completed a stressful task based on their emotional state.

This aligns with the finding that restrictive processes that constrain how elements interact with their environment can paradoxically produce new degrees of freedom, emergent tactics and behaviours (Leijnen & Van Veen, 2016). Similarly, I stipulate that social contexts can constrain how emotional information is interpreted and used, so that it is only relevant to goals relevant to the social context.

Therefore, I posit that understanding the context in which participants will use the system is important so that designers can leverage unique opportunities for *preternatural transmission* that the context may offer to empower them to better communicate and perform tasks within the social context.

5.4.4 Limitations

In the design of Neo-Noumena, I faced a tradeoff between the accuracy of the emotion detection model, the time it took to classify emotion, and the number of emotions that could be classified. Classification accuracy required large amounts of data, resulting in a latency of 30 seconds per classification. Training the model to each individual participant may have increased accuracy at the cost of increased setup time. This may have in turn produced a more dynamic experience with a greater potential for exploration or informationally rich communication. Future work would benefit from the exploration of such tradeoffs, possibly assessing the efficacy of different machine learning and BCI approaches geared toward a faster, more accurate and dynamic model.

A further limitation of this study was that participant dyads using Neo-Noumena were all already familiar with each other beforehand. While this gives insight into how couples and family members might experience BCI-augmented emotion communication, it remains to be seen whether the observed themes and dynamics carry over to contexts where users are unfamiliar with each other. For example, I anticipate that it would be less likely that users will try to regulate the emotion of others due to the questionable social acceptability of overtly provoking emotional responses in strangers. Future studies may address this gap by focusing on deploying BCI-augmented emotion communication in contexts where users are less likely to be comfortable with each other, such as campuses and offices, or through controlled grouping where dyads must be strangers.

A further limitation of the study was the presence of what could possibly be argued to be a confounding factor in that three of the 10 participants reported having been diagnosed with a psychopathology (one with ADHD and two with depression). As the study did not involve screening for psychopathologies as a prerequisite for participation, the presence of participants with psychopathologies was unknown until participant interviews (the end of the study). As the study that produced the original emotional dataset used in training the algorithm did not include a psychopathology screening procedure (to the best of my knowledge) it is unclear whether having a-neurotypical individuals using Neo-Noumena would have influenced the system's accuracy. As many psychopathologies, especially the ones presented by the participants in the present study, involve some disruption of emotion regulation, it may be possible that this was partially a factor in why emotion regulation was a common theme that participants discussed. Nonetheless, it is also worth considering that the Australian Bureau of statistics reported that 20% of Australians have some form of documented psychopathology. Considering that many cases of psychopathology also go unreported and untreated, this figure is likely even greater. With this in mind, it could be argued that a figure of 3 out of 10 participants in the study presenting with a psychopathology would be an accurate proportional representation of mental health issues in the general population (i.e., that mental health issues are not statistically uncommon enough to be considered a confounding variable because they are part of “normal”). Thus, I argue that we as a research community might want to further consider and re-evaluate whether the exclusion of participants presenting with psychopathologies hinders, rather than helps, the generalisability of our research.

Additionally, P8 complained of eye strain while using the HoloLens, and others complained that the apparatus was bulky. There is also a possibility that the device occluded the eyes and therefore decreased participants' ability to interpret emotions through facial expressions, though this was not brought up by participants. These points largely reflect the limitations of current technology, which will improve as the designs of wearable devices evolve, highlighting the need for continued work in this area.

5.5 Informing the Framework

Building on the understanding of Brain-Computer Integration yielded by the previous case study, the results of this case study furthered the formation of the framework.

Through Neo-Noumena, the framework was extended such that brain activity could not merely be conceptualised as "feedback" but rather as abstract information. This meant that the transmission of brain activity from one individual to another (or as feedback to themselves) could be articulated using canonical concepts in Shannon information theory (Verdu, 1998). This came with the insight that there are various ways information can be encoded and decoded, each with its own cost-benefit tradeoffs to both the sender and the recipient. This further came with the realisation that the information embedded in brain activity can be compressed, and lost through compression, during transmission. I found that these concepts could also better interface with the experience and phenomenology that these processes afforded through conceptualising this process within Verbeek's framework of technological mediation (Verbeek, 2015), in which they differentiate different ways in which technologies mediate information exchanges. Verbeek differentiates between hermeneutic relations and embodied relations (Rosenberger & Verbeek, 2015; Verbeek, 2005; Verbeek, 2015). In hermeneutic relations technology represents a certain aspect of the world (i.e. representing brain activity) while in embodiment relations, the technology does not call attention to itself but to aspects of the world given through (i.e. directly influencing brain activity). With this considered, it was evident that these first two case studies were examples of hermeneutic relations, and that the next step in understanding brain-computer integration lay in understanding BCI-based embodiment relations. This insight thereby inspired the third case study, PsiNet.

Furthermore, the findings of Neo-Noumena provided a more nuanced understanding of how agency can be experienced when using brain-computer integration systems. Namely, that agency can be described as having a variable distribution between agents or actors participating in the flows of information mediated by the system. This highlighted that agency was not only something possessed by users' brains, but also by other agents acting on or within the system, such as the environment, or the codings of brain activity themselves (e.g., the fractals had their own agency with limited independence from the brain they were generated from). Thus, I was motivated to use the third case study of this thesis to further understand how different distributions of agency could influence the experience of Brain-Computer Integration.

6 Case Study III: PsiNet

This chapter details the third case study: PsiNet, a network of systems that combines EEG and tDCS to synchronise the brain activity of a group of users (figure 16). With this case study, I explore my research question through the sub-question: *"How do we design integrated brain-computer interfaces for synchronising brain activity interpersonally?"*. The sub-question was informed by the insights gained from the previous case study, which ultimately suggested that to further understand the design of brain-computer integration, I would need to design and evaluate an integration BCI system that affords "embodied" human-technology relations in contrast to my previous case studies which afforded "hermeneutic" relations. Furthermore, the insights gained from the previous case study suggested the necessity to further explore integration BCI systems that afforded a more even distribution of agency across the users and the system.

With these considerations in mind, I designed PsiNet, through which I aimed to achieve embodiment relations both technologically, through the use of transcranial electrical stimulation (tES); and experientially, through the facilitation of inter-brain synchrony. The motivation of using tES what that stimulating the user's brain to invoke an experience of another's brain activity rather than have them interpret symbiotic representations of another's brain activity (like in Neo-Noumena) would afford an embodied relation in that the user experience through the technology, rather than experiencing the technology itself (Rosenberger & Verbeek, 2015; P.-P. Verbeek, 2005). Furthermore, I also considered that using brain stimulation alone was not sufficient grounds for claiming embodied relations were achieved, as brain stimulation also possessed the potential to be used hermeneutically (e.g. using phosphenes to symbolically indicate "yes" or "no", as was done in previous brain-to-brain interface studies (Jiang et al., 2019)). With that in mind, PsiNet was designed toward the application of amplifying inter-brain synchrony in groups, with inter-brain synchrony being the tendency for brain activity to synchronise between people when they interact (Hu et al., 2018; Shehata et al., 2020; Valencia & Froese, 2020). As brain inter-brain synchrony can be interpreted to be indicative of a shared embodied experience between people, I reasoned the amplification of inter-brain synchrony through tES would ultimately allow for interpersonal embodied human-technology relations. Furthermore, in designing the system toward the synchronisation of the group as a whole, the brain activity of each user had equal influence over the functioning of the system, thus allowing for an even distribution of agency between users. Through these features, I was able to complete my exploration of the brain-computer integration design space.

The rest of this chapter details the design of this prototype and the subsequent study of how this system interacts with the subjective experiences of the participants using it. Finally, I present the findings from the study, reporting them first in the immediate context of the prototype in isolation, and then generalising toward the brain-computer integration framework. A video demonstrating PsiNet can be found at: https://youtu.be/Nv9PtTr03vc

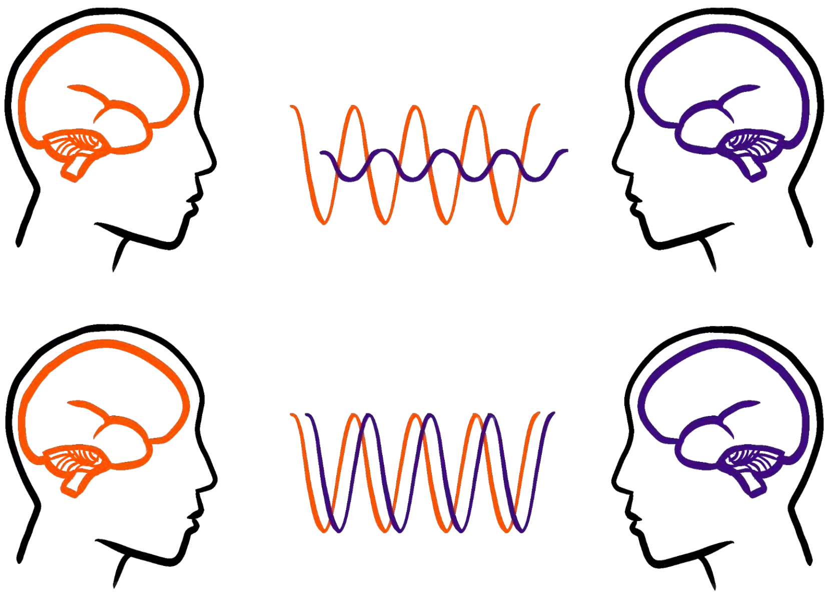

Figure 16. Comparison of two desynchronised brains (top) with different phase and amplitude, to two highly synchronised brains, with similar phase and amplitude.

6.1 Associated Publications

The work detailed in the following section is a manuscript currently submitted to the 2022 "Designing Interactive Systems" (DIS) conference.

6.2 Prototype

PsiNet is composed of three wearable units and an offsite server hosting a reinforcement learning agent that supervises the system. The following sections describe the design of PsiNet and provide an overview of the system architecture and a description of the algorithm aimed to support inter-brain synchrony (figure 17).

Figure 17. PsiNet, a network of wearable brain-to-brain interfaces that synchronises brain activity between its users to strengthen interpersonal connections.

6.2.1 System Architecture

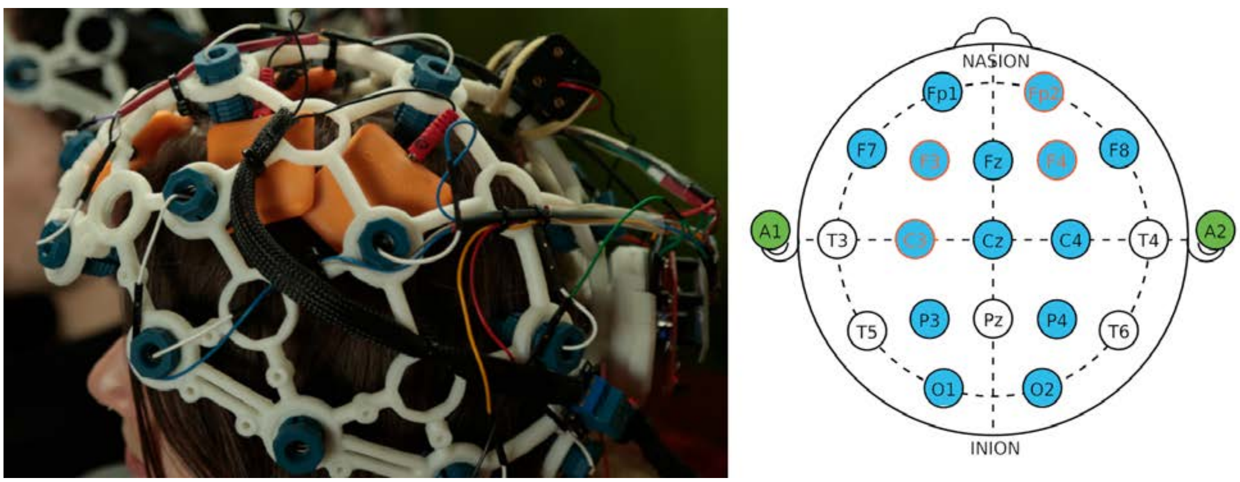

Figure 18. A closeup of one PsiNet unit (left) and the positions of electrodes superimposed over the 10-20 electrode positions (right). Blue signifies the presence of an EEG electrode at that position, orange outline indicates the presence of a tES sponge, and green represents reference and ground electrodes (for which I used electrode ear clips).

Each wearable unit consists of an OpenBCI 16 channel Cyton EEG board, mounted onto an OpenBCI Ultracortex Mark IV headset, which houses 16 Ag/AgCI dry EEG electrodes. Electrodes were configured following the international 10-20 electrode configuration (figure 18). Each headset was modified to house an additional four 5cm x 5cm sponge tES electrodes situated at the positions of F2, F3, F4, and C3, stimulated by an onboard "foc.us V3" tES device. Participants were also fitted with a small carry bag that contained a battery-powered Raspberry Pi 4, connected to the headset via

Bluetooth, with a tether from the Pi to the headset to power tES stimulation (figure 19). The Raspberry Pi was also connected through participants' home Wi-Fi to a server hosted by the researchers where de-identified data was saved securely.

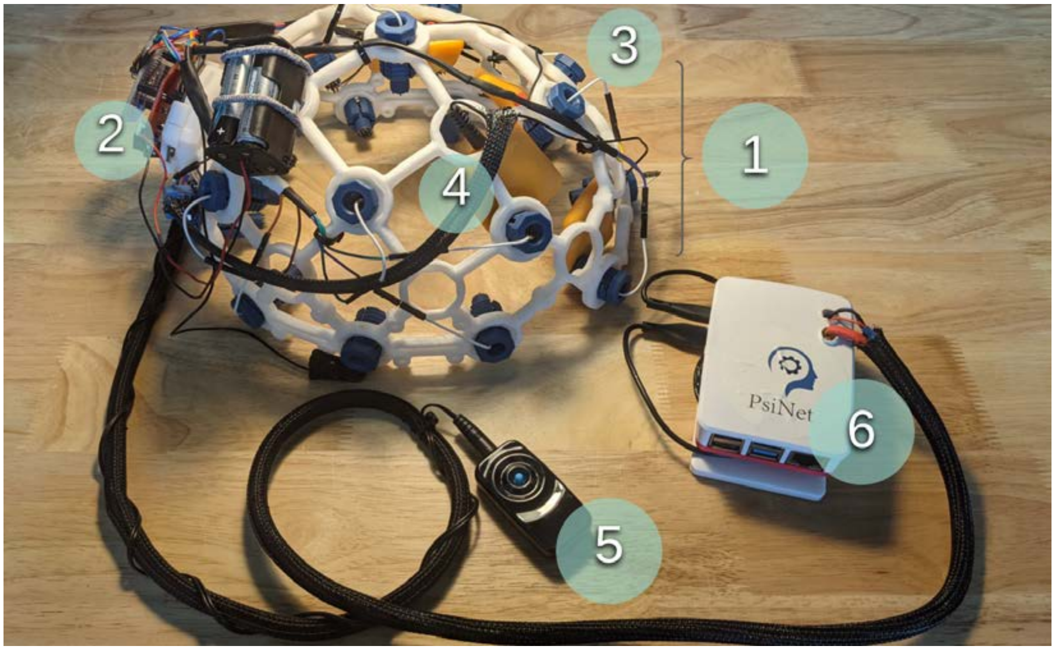

Figure 19. The components of PsiNet: 1 - Ultracortex, 2 - OpenBCI Cyton Board, 3 - EEG Electrodes (blue bolts), 4 - tES Electrodes (orange squares), 5 - tES Device, 6 - Raspberry Pi

The headset sensed the electrical activity of each participant's brain and sent data to their Raspberry Pi for processing. This processing resulted in the classification of the participant's brain activity as interpreted by the algorithm. Data was sent in 10-second epochs since the system requires a window of time on which to base its classification of the user's state. Ten seconds was chosen as it allows classification to be robust to noise, movement, and eye-blink artefacts while being short enough to respond quickly to changes in the user's brain activity (Klimesch et al., 1996).

In describing the flow of information through PsiNet at a high level, the pipeline underlying PsiNet can be described as having four major components. First is the EEG pre-processing and subsequent classification of the brain activity of each member in the group through measuring individual event-related desynchronisation/synchronisation. Second is a weight matrix, which considers what brain state each user is in, and then uses this information to decide who in the group receives a stimulation, and what stimulation they will receive, with the aim of increasing inter-brain synchrony. Third is the tES stimulation itself. Finally, fourth is the calculation of the inter-brain synchrony of the group before and after being stimulated, with the result of this calculation being used to reinforce the weight matrix such that it better learns how to increase inter-brain synchrony in the next stimulation.

6.2.2 EEG Preprocessing and Denoising

Before interpreting the brain activity, PsiNet first undergoes a series of processes to filter the EEG signal, remove noise, and extract relevant features. To do this, raw EEG data is received in real-time and passed, in 10-second epochs, through a fourth-order Bessel bandpass filter between 0.5-48Hz; this being the standard relevant frequency range in EEG signal processing (Hiltunen et al., 2014; Vanhatalo, Voipio, & Kaila, 2005). To correct for noise, including ambient signal, eye blinks, and muscle artifacts, I applied a wavelet-based denoising filter called 'coif3' that efficiently improves signal-to-noise ratios compared to other wavelet-based filters (Alyasseri, Khader, & Al-Betar, 2017; Khatun, Mahajan, & Morshed, 2015). A mean smoothing filter was also applied to complement the denoising filter (Azami, Mohammadi, & Bozorgtabar, 2012). Finally, I calculated Welch Power Spectrum values using a Blackman-Harris window for alpha (8-12.5Hz), beta (12.5-30Hz), theta (4-8Hz), and mu (9-11Hz) bands (Kivinukk & Tamberg, 2007).

6.2.3 Classifying Brain Activity

PsiNet classifies seven different brain activity states: concentration, focus, stress, excitement, relaxation, boredom, and motor activity/imagery. Table 6 provides the theoretical basis underlying the classification of each state of brain activity, as well as the methodological details of its execution. The rationale for this classification is to accommodate a variety of different states that may arise during an average user's daily routine. While future BCI's may be able to capture a broader range and nuance of the subjective human experience, we are currently constrained by both our computational and neuroscientific knowledge. Consequently, I have attempted to approximate this range through the selection of broad yet common brain states that have each been verified as reliable (Antonenko, Paas, Grabner, & van Gog, 2010; Hobson & Bishop, 2017; Mazher, Abd Aziz, Malik, & Ullah Amin, 2017).

6.2.4 Event-Related Desynchronisation/Synchronisation

To interpret brain activity, PsiNet employs an "event-related desynchronization/synchronisation" (ERD) approach (Antonenko et al., 2010; Albuquerque, Viana, Da-Silva, & Cagy, 2019; Kato, Kadokura, Kuroki, & Ishikawa, 2019; Lee, Lindquist, & Nam, 2017). I note that ERDs are distinct from inter-brain synchrony in that ERDs consider synchronisation within the brain of a single individual, rather than between individuals. For instance, it is understood that short-lasting amplitude changes of neural oscillatory rhythms within a predefined feature space in an EEG's spectra correspond to cortical activity (Pfurtscheller, 1991). Combining knowledge of where this cortical activity is taking place with the observation of an increase or decrease of amplitude in that specific feature space, we are able to deduce the underlying brain activity responsible for that shift in spectral amplitude (Albuquerque et al., 2019; Kato et al., 2019; Lee et al., 2017). Therefore, if we have the foreknowledge of which EEG channels and spectral power density bands are associated with a specific state of brain activity, we can detect that brain activity by observing changes in those features. Table 6 provides more details for each individual classification.

Table 6. The brain states that are measured by PsiNet's algorithm, the theoretical basis for making a given classification, and the conditions that must be met for that state's classification.

Brain State	**Theoretical Basis**	**Classification Conditions**
Concentrating	Increased theta band power over the frontal midline was found to be associated with high cognitive load, possibly reflecting anterior cingulate cortex activity (Mazher et al., 2017). Decreased alpha band power over parietal and occipital regions have also been found to be associated with high cognitive load (Antonenko et al., 2010).	Negative theta and alpha ERD% (equation 1) in F1, F2, F3, F4, F7, F8. Positive theta and alpha ERD% in O1, O2, P3, P4.
Focused	Increased beta and theta band power in Fp1 and Fp2 have been found to be associated with higher concentration indices, a measure of concentration (Lim, Yeo, & Yoon, 2019). Significant decreases in beta and theta band power were also found over C3, C4, and O2.	Negative Beta and theta ERD% in F1, F2. Positive beta and theta ERD% in C3, C4, O2.
Motor Activity	Decreased mu band power in electrodes placed over the motor cortex is observed when moving, imagining, or watching motor movement (Freitas, Inocêncio, Lins, Santos, & Benedetti, 2019; Hobson & Bishop, 2017).	Positive mu ERD% in C3, C4, Cz.
Stressed	Asymmetry of frontal alpha-beta activity between brain hemispheres has been demonstrated to correlate with valence (Blaiech, Neji, Wali, & Alimi, 2013; Kirke & Miranda, 2011; Looi et al., 2016). An increase in the alpha beta ratio on the mid-frontal cortex has been shown to correlate with arousal (Blaiech et al., 2013; Kirke & Miranda, 2011; Looi et al., 2016; Ramirez & Vamvakousis, 2012).	Positive Log2 of alpha/beta ratio ERD% in Fz. Negative difference between alpha/beta ratio ERD% in F4 and alpha/beta ratio in F3.

Excited	As above.	Positive Log2 of alpha/beta ratio ERD% in Fz.
Relaxed	As above.	Negative Log2 of alpha/beta ratio ERD% in Fz.
Bored	As above.	Negative Log2 of alpha/beta ratio ERD\% in Fz.

I acknowledge that other approaches to interpreting brain states through EEG could have been adopted. Specifically, machine learning (ML) has become almost standard (Lotte et al., 2018). Whilst I adopt a reinforcement learning system for guiding the distribution of stimulation across participants (later described in 3.4), I opted to classify brain states using a rule-based system rather than an ML system. Using a rule-based approach (ERD) inferences of the users' brain states can be made based on differences between their current EEG activity, and values derived from a resting baseline, with the baseline accounting for unique biometric properties of the user at rest. When compared to building a machine learning model, a baseline of averages would require a significantly shorter time to establish (seconds) as demonstrated in many past studies (Cannon et al., 2016; Daly et al., 2014; Orgs, Dombrowski, Heil, & Jansen-Osmann, 2008; Gert Pfurtscheller et al., 2010; Schubring & Schupp, 2019; Severens, Nienhuis, Desain, & Duysens, 2012; Tangwiriyasakul, Verhagen, van Putten, & Rutten, 2013; Tariq, Trivailo, & Simic, 2020). This is in contrast to personalised machine learning models, which for tasks involving the detection of cognitive states, often require hours per participant and unique training tasks and sessions dedicated to training the classification of the different classification classes of interest, which may even necessitate multiple sessions over multiple days before the participant can begin to use the system (Alarcao & Fonseca, 2017; Lotte et al., 2018; Noh, Kim, Jang, & Yoon, 2021).

I also acknowledge that my approach of interpreting brain activity from EEG as "states" embeds my work in a larger ongoing contention regarding the interpretation of biodata as stateful (Howell, Devendorf, et al., 2018; Stark & Crawford, 2015; Stark, 2018). For example, some have warned that the entanglement of psychology and computer science has led to the "calculability of human subjectivity," quantizing the individual into information for psychographic models through which individuals can be digitally categorised (Stark & Crawford, 2015; Stark, 2018). Furthermore, some have argued that rather than designing for discretely classified presentations of physiological or psychological activity, designers should instead consider ambiguous displays that allow for the user to form their own meaning (Howell, Devendorf, et al., 2018). I nonetheless maintain my stance in applying a stateful approach to the interpretation of EEG, grounding the system in neuroscience's paradigmatic conceptualization of brain activity as dynamically stateful (Gautam, Hoang, McClanahan, Grady, & Shew, 2015; Meisel, Klaus, Kuehn, & Plenz, 2015; van de Leemput et al., 2014). The functional neuroanatomical representations of brain states like affect are robust, generalizable, and produce predictable reactions in response to corresponding stimuli (Bush, Privratsky, Gardner, Zielinski, & Kilts, 2018). Also, considering PsiNet employs neurostimulation, it would be unsafe to employ a stimulation paradigm that is not categorical, as neurostimulation research to date has mostly been focused on discrete simulations for categorical brain functions.

6.2.5 Establishing a Baseline for Calculating ERDs

To calculate ERDs, an individualized baseline recording is required for each participant, which quantitatively describes their brain in a normal resting state. Since EEG signals can differ between individuals due to age, head shape, hair density, and so on, comparing absolute powers of frequency bands is not advisable (Antonenko et al., 2010). Instead, I calculated ERD's as a percentage divided by the baseline (Antonenko et al., 2010).

$$ERD\% = 100 \times \frac{baselinebandpower - presentbandpower}{baselinebandpower} \quad (1)$$

Each day of system use, the first 10 seconds were considered for calculating baseline values for ERD classifications (again, I stress that this is separate to the calculation of inter-brain synchrony). The choice of a 10 second baseline was informed by previous studies also employing ERD BCI paradigms. I found that previous works employed baselines ranging from less than 1 second to 10 seconds. Specifically, I found studies to report adopting ERD baselines of: 0.1 second (Schubring & Schupp, 2019), 1.5 seconds (Daly et al., 2014), 3 seconds (Cannon et al., 2016; Orgs et al., 2008; Tariq et al., 2020), 4 seconds (Pfurtscheller et al., 2010), and 10 seconds (Severens et al., 2012; Tangwiriyasakul et al., 2013). Considering this, I decided to implement a baseline of 10 seconds to err on the side of caution. Participants were informed that the first 10 seconds of use would form a baseline that would be important for the system to function correctly. Participants were instructed to get into a comfortable and unoccupied state, only turning on the system when they felt they were ready.

6.2.6 Weight Matrix Calculations

Once the concurrent brain activity of each user was classified, classifications were sent to the central server. The server hosts a reinforcement learning agent (a weight matrix) that decides which group member receives what kind of neurostimulation based on the brain activity of other members of the group, with the agent motivated to ultimately increase the group's inter-brain synchrony. After classifications were made, a binary state vector was generated for each group member, in which a "1" signifies that the user met the conditions for that state, and a "0" indicates they did not. Concatenating these into one state matrix *S*, we get, for instance:

$S =$

	concentrating	focused	motor	stressed	excited	relaxed	bored
Participant 1	1	0	1	0	1	0	0
Participant 2	1	1	0	1	0	0	0
Participant 3	0	1	0	0	0	0	1

(2)

The state matrix is then multiplied by a weight matrix $W_{i,j}$, where entry *i,j* represents the probability that a user's state *i* will trigger stimulation *j* in the rest of the group. The weightings themselves were initially set to favour intuitive outcomes while remaining close to chance value, but as the system was reinforced by changes in the group and weightings were updated according to favourable pairings. The exact initial starting values of the matrix were made as a design decision based on trial-and-error experience gained through prototyping the system. The initial $W_{i,j}$ matrix was:

$W_{i,j} =$

	motor	concentrate	relax	phosphene
concentrating	0.5	0.6	0.5	0.5
focused	0.5	0.6	0.5	0.5
motor-imagery	0.62	0.5	0.5	0.5
stressed	0.5	0.5	0.5	0.59
excited	0.5	0.5	0.5	0.5
relaxed	0.5	0.5	0.5	0.5
bored	0.5	0.5	0.5	0.5

(3)

We then multiply these matrices:

$S * W_{i,j} =$

	motor	concentrate	relax	phosphene
Participant 1	1	0	1	0
Participant 2	0	1	0	0
Participant 3	0	0	0	0

(4)

Each person then receives the stimulation type with the highest magnitude, which does not belong to their row. In this case, we get:

	Candidate stimulation	Received stimulation
Participant 1	motor	concentrate
Participant 2	concentrate	motor
Participant 3	concentrate	motor

(5)

If group neural synchrony increases, the system rewards each *i,j* weighting that was not zeroed by the S matrix from the corresponding column in the $W_{i,j}$ matrix by 0.05, or reduces it by 0.05 if synchrony did not increase. In the above example, if the "motor" synchrony stimulation from participant 1 was run on the other participants and an increased inter-brain synchrony is observed within the group, the "concentrating", "motor-imagery" and "excited" entries under the "motor" column of $W_{i,j}$ would each increase by 0.05, increasing the likelihood that these pairings result in motor stimulation in the future.

6.2.7 tES Stimulation

After the weight matrix decides who to stimulate and which type of stimulation to use, PsiNet then delivers said stimulation through the use of transcranial electrical stimulation (tES). The decision to use tES was multifaceted. My primary motivation was due to the technology's portability, with the model that I used being under 5 cm cubed, battery-powered, and Bluetooth compatible.

6.2.8 tES with EEG

I acknowledge that tES produces electrical activity and introduces exogenous current to the brain. Hence, there is the potential for the stimulation to introduce noise to EEG readings. In anticipation of this, I designed the system such that the EEG of a given participant would not be read whilst they were being stimulated. This absence in the data stream did not interfere with assessing inter-brain synchrony, as measures of inter-brain synchrony were taken just before stimulations and 30 seconds after stimulation. Thus, EEG data during stimulation was not needed for the calculation of post-stimulation change in inter-brain synchrony. Furthermore, as classifications could not be made during stimulations due to the absence of data, this simply meant that participants could not stimulate others while they themselves were being stimulated.

6.2.9 Stimulations and Electrode Positions

The electrode positions chosen for tES stimulation are described in Table 7 and expressed using anatomical features and international standard 10-20 electrode positioning, based on their validity from past research (Raco, Bauer, Olenik, Brkic, & Gharabaghi, 2014; Utz, Dimova, Oppenländer, & Kerkhoff, 2010). I considered these choices of stimulation types to be acceptable because they appear consistently across tES reviews, and their efficacy is validated in that they produce consistent results (Raco et al., 2014; Utz et al., 2010). I note that I employed the lower limit of the recommended time for each stimulation to prevent over-stimulation (Nitsche et al., 2003; Woods et al., 2016) (table 7).

Table 7. tES stimulation names, electrode stimulation locations and parameters, and duration of each stimulation.

Stimulation Name	Electrode Stimulation Locations and Parameters	Duration
Motor	tDCS stimulation between C3 and rSupraOrbital; 1.5mA; anodal	2 minutes
Relaxation	tDCS stimulation between F3 and F4; 2mA; anodal	2 minutes
Cognition	tDCS stimulation between F3 and rSupraOrbital; 2mA; anodal	5 minutes
Phosphene	tACS stimulation between F3 and F4; 1.5mA; 12Hz; bipolar	10 second

6.2.10 Classification-stimulation Pairings and the Experiences of Stimulation

I found that the chosen tES stimulations could coincidentally be easily paired with the EEG classifications I employed, with all EEG classifications having a thematically corresponding stimulation. To further understand how these classifications and stimulations relate to each other, four researchers trialed the stimulation on themselves and individually took notes describing their experience as soon as the simulation was complete. Each researcher then compared notes and coded each experience. Experiences with common codings across each researcher were then described generally and compared to descriptions in the literature. A summary of descriptions is provided in table 8:

Table 8. Comparisons of experiences of tES stimulation documented in the literature with my own documented experiences.

Stimulation Name	**Literature Description**	**My Experience**
Motor	Experiences of heightened reflexes and reaction times, a heightened desire to move, and a predisposition toward thinking about moving (Utz et al., 2010).	Feelings of restlessness and strong mental imagery of performing movements such as "hoisting a flag" while eyes were closed.
Relaxation	Drops in physiological activity indicative of arousal, such as a decrease in heart rate and with reported experiences also indicating a lowering of self-perceived arousal (Utz et al., 2010).	Mild feelings of heaviness.
Cognition	Experiences of heightened mental acuity, including improvements in focus and concentration and improvements in the performance of tasks designed for testing cognitive abilities such as recall and cognitive load (Utz et al., 2010).	Feelings of heightened arousal, with intensity ranging between a feeling of increased energy, to feeling agitated or hyper-vigilant.
Phosphene	Perceptions of flashing lights in the periphery of the visual field, which blink at the speed of the simulation's frequency (e.g., a stimulation at 12 Hz will result in seeing twelve blinks per second) (Raco et al., 2014)	My own experiences corroborated this experience.

6.2.11 Classification-stimulation Pairings and the Experiences of Stimulation

I followed safety recommendations from the device's user guide and the literature. With respect to use of tES stimulation in a non-clinical setting, I tailored the stimulation to be well below the safe maximum (Nitsche et al., 2003; Woods et al., 2016). Considering the sources in table 8, I implemented a number of steps to ensure that parameters were well below that of what is recommended. This included long "cooldown" periods between simulations to allow for endogenous neural activity to return to normal before a sequential stimulation and amperage limits that did not exceed 2mA. I also maintained an exclusion criteria during recruitment to avoid populations that might be at risk of harm when using PsiNet. This included the following conditions: a history of brain surgery, head trauma, and/or cognitive deficit; a history of tumor, stroke, seizures, epilepsy, or other intracranial diseases; the implantation of intracranial metal; the wearing of a pacemaker; and pregnancy.

6.2.12 Measuring Inter-Brain Neural Synchrony

Once the system administered neurostimulation, the system calculated whether that round of stimulations increased the group's inter-brain synchrony. If the system was successful in increasing inter-brain synchrony, the agent was rewarded, strengthening the connections between inputs and outputs that lead to that result. In related works, measures of inter-brain synchrony are most often measured using Phase Lock Value (PLV) and Phase Lock Index (PLI) (Barde et al., 2019). However, Burgess et al. (Burgess, 2013) found that PLV and PLI can result in spurious hyper-connections when study conditions are not well-controlled. Considering this, I chose the circular correlation coefficient (CCorr) (Jammalamadaka & SenGupta, 2001) as a measure of neural synchrony, as it has been shown to be more robust (Burgess, 2013).

CCorr is defined as:

$$CCorr_{\phi,\psi} = \frac{\Sigma_t sin(\phi-\overline{\phi})sin(\psi-\overline{\psi})}{\sqrt{\Sigma_t sin^2(\phi-\overline{\phi})sin^2(\psi-\overline{\psi})}} \qquad (6)$$

Where ϕ is one user's phase angle at time i, ψ is another user's phase angle at time i, and $\overline{\phi}$ and $\overline{\psi}$ are the mean phase angles over that epoch. High covariance and CCorr values closer to 1 indicate synchrony, while low covariance and CCorr values closer to 0 indicate little synchrony (Honari, Choe, & Lindquist, 2021).

Pairwise CCorr values for all participants were calculated, and transformed to Fisher's z; letting CCorr equal r:

$$z = \frac{1}{2}log_e(\frac{1+r}{1-r}) \qquad (7)$$

These z values were averaged over, and this average was then transformed using the inverse of (7). These transforms were done to circumvent the bias introduced from averaging over multiple correlation coefficients (Silver & Dunlap, 1987).

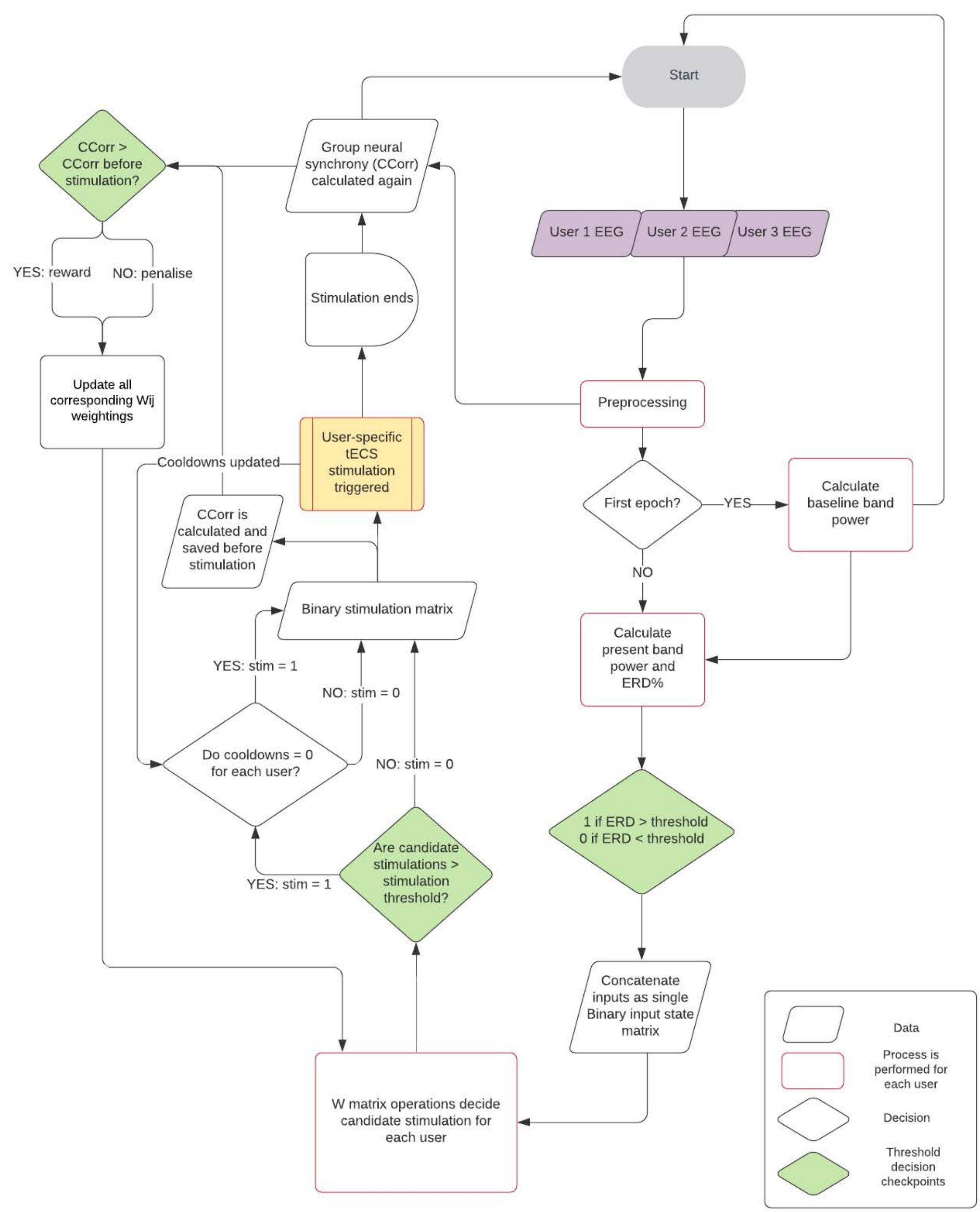

Figure 20. The algorithm driving PsiNet

In regard to how and when group inter-brain synchrony was measured, I assed group inter-brain synchrony though taking readings of CCorr just before each stimulation, and 30 seconds after each stimulation. To measure changes in inter-brain synchrony resulting from the presented stimulation, I made comparisons between CCorr just before the initiation of stimulation and 30 seconds after stimulation was completed. This time window was chosen to mitigate the chances that readings of increased synchrony were due to participants cognitively attenuating toward the sensations associated with the stimulation, rather than the neuronal activity resulting from the stimulation, by providing a time window for their brain activity to normalise and habituate to the introduction and subsequent removal of the sensation of stimulation. I believe this time window was short enough to prevent measures of change in synchrony that might have resulted from participant activities or interpersonal interaction. Therefore, any increase identified after stimulation was most likely due to the tES stimulation itself and not caused by situational factors or other stimuli.

Finally, the system rewards the relevant weights in $W_{i,j}$ if this final value is greater than the CCorr value measured just before stimulation occurred. A diagram depicting the algorithms dictating this entire procedure is shown above in figure 20.

6.3 Results

In this section, I present both the qualitative and quantitative results.

6.3.1 Quantitative Analysis of Inter-Brain Synchrony

To evaluate whether the group's inter-brain synchrony increased after stimulation, I measured group inter-brain synchrony before and after each stimulation, as given by the metrics $CCorr_{before}$, and $CCorr_{after}$, respectively. As discussed in 3.6, I transform these values using Fisher's z-transform (equation 4), since z becomes normal with increased sample size and can thus be used to conduct tests of significance and calculate confidence intervals. Hereafter, references to CCorr values are to their z-transformed values.

On average, the system was used for 3.81 hours per group total, with each usage session lasting for an average of 1.27 hours. During each use session, participants received on average 5.56 stimulations, with an average stimulation frequency of 4.38 per hour. The total number of inter-brain synchrony change measurements across all groups and participants given by CCorr was 48.

I removed two outliers where the CCorr $_{before}$ value was 0.035, likely due to signal artifacts like movement or sensor interruption. Descriptive statistics for the remaining data are summarised in Table 9.

Table 9. Descriptive statistics for z-transformed circular correlation values before and after stimulation.

	CCorr$_{before}$	**CCorr$_{after}$**
Valid Cases	48	48
Mean	0.88	0.92
Standard Deviation	0.16	0.14
Minimum	0.68	0.63
Maximum	1.34	1.26

The difference in CCorr $_{after}$ and CCorr $_{before}$ was evaluated, with this value ranging from -23.26%, and 38.92%, with an average of 3.78% and standard deviation of 10.74%. Thus, on average, group inter-brain synchrony increased after stimulations as given by the metric CCorr.

A Shapiro-Wilk test found evidence that CCorr $_{before}$ was not normally distributed ($p < .001$) and no evidence that CCorr $_{after}$ was not normally distributed ($p = 0.54$). Thus, to investigate whether the increase in group synchrony after stimulation was statistically significant, I performed a two-tailed, paired-samples, Wilcoxon signed-rank test. I found that CCorr $_{after}$ is significantly greater than CCorr $_{before}$, with $Z = 794.00$, $p = 0.035$, indicating that the increase in group inter-brain synchrony was of statistical significance. This result had an effect size, calculated by the matched rank biserial correlation, of 0.35. These results will be discussed in 6.1.

6.3.2 Qualitative Analysis of User Experience

In analyzing the interviews, three major themes were revealed. Analysis of the collected data was performed inductively through thematic analysis (Clarke & Braun, 2014) in which six researchers independently reviewed transcripts and coded the data. Each unit of data represents a completed sentence from the data. Codes were iteratively clustered into high level groupings agreed upon between researchers until they were consolidated into three final themes emerging from the data, each with three sub-themes. The following sections investigate these results further by articulating three themes: *dissolution of self*, *hyper-awareness*, and *relational interaction*.

6.3.2.1 Dissolution of Self

This theme describes 40 units of data in which participant recounts implied a blending between the subjective selves of those using the system. The theme is composed of three sub-themes, *ambiguous experience* (12 data units), *uncertainty over ownership of experience* (8 units) and *equal distribution of agency* (10 units).

Ambiguous Experience. Eight participants described feelings of uncertainty regarding what stimulation they were receiving, and from whom they were receiving it. Participant 6 said: *"you kind of don't know why you are doing things or to what degree you're doing things or influencing each other. You don't really know where things are coming from anymore."* This was compounded by the observation that participants often did not directly interact with the system but often allowed it to operate passively, noting that at times they were unaware of whether a stimulation was taking place. Participant 1 said: *"sometimes it did feel a little bit arbitrary because even when we were doing the same task, some of us got different types of stimulation."* I note that this group asked for more information about what kinds of stimulations there were.

Uncertainty of Ownership of the Experience. Five participants noted that it was difficult to appraise whether their feelings, affects and behaviors were purely endogenous, or under exogenous influence. Participant 8 described: *"feelings of connection and being able to affect each other without having to really act and do something. It just automatically sent stuff out. So yeah, it was like a phone picking up on your emotions and brain states and sending a message for you."* Participant 6, who tried to understand where the stimulation was coming from, said: *"you acknowledge that from the physiological sensations of feeling the stimulation, but also from other people's reactions as well."* In the pursuit of trying to understand the source of the stimulation, participants found themselves empathizing with their group. Participant 2 said: *"the phosphene was really interesting because a flashing light I'd kind of associate that to something very high energy. And I think maybe if someone was quite agitated or aggravated by the work that they were doing or whatever the topic was, and maybe they were concerned or annoyed about something, that might explain why our housemate got a phosphene."*

Equal Distribution of Agency. Six participants stated that their thoughts contributed equally to the function of the system, believing they controlled the system together. When participants were asked where they felt the power lay in directing the flow of information across the system and its users, participant 2 said: *"it seemed pretty equally distributed."* This idea of the equal distribution of agency was shared by other participants, including participant 1, who said: *"we had control via our inputs and how we responded to the outputs of the system as well. So it was everyone", "I think it was evenly distributed"* (P3) and: *"I'd love to say it was with us" (P9).* Other participants stated there was no absolute power to control the system, like: *"It was just totally random"* (P5) and: *"I didn't notice a pattern"* (P4). Ultimately, these elements together describe the overall experience of how participants experienced some dissolution of the "self" with the use of PsiNet.

6.3.2.2 Hyper-Awareness

This theme describes 48 units about participants' descriptions of how the system promoted a heightened level of awareness individually and as a group, labeled *"hyper-awareness"*. The theme is composed of three sub-themes, *heightened bodily awareness* (18 data units), *group cohesiveness through shared sensations* (14 units), and *away, but neurally together* (16 units).

Heightened Bodily Awareness. Seven participants discussed the way their body was feeling when they were receiving stimulations and how it made them reflect on what they were doing at the time when the stimulation occurred. For example, participant 2 spoke about how they felt as the stimulation began: *"It was often quite noticeable. It feels hot, it feels itchy, tingly."* While this comment refers to external bodily sensations, this participant also mentioned how they felt internally: *"Oftentimes I'd feel like I just had heaps of caffeine or coffee or energy drink."* Participant 3 spoke about how their state of bodily awareness was brought to the fore by the unintended audio design feature of the headset: *"I felt the buzz of the tDCS thing and a click sound at the back of the headset. So I knew that the stimulation was happening"*.

Group Cohesiveness Through Shared Sensations. Participants experimented with different activities while using PsiNet in order to understand how the system reacted. As participants began experiencing the stimulation and discussed the resulting sensations, they became more aware of their shared experience. Participant 5 spoke about how they felt connected to the other people in their group: *"I heard the click and I remember I was kind of in the flow of my work [...] I knew everybody else was doing work, I was wondering if everyone else was also in their own flows and it made me think of them and kind of feel like I was connected to them while I was in my own flow, which is quite weird because usually a flow is where you don't think of others, you're just in your flow."* More than half of the participants played games while using PsiNet, with participant 1 reporting: *"it might have made us focus more while we were working, or might've made us like faster to hit the buttons on the controller when we were playing a game together"*. As a result, participants reported experiences of increased team cohesiveness, connectedness, and feelings of closeness even when in separate rooms.

Apart But Neurally Together. Five participants commented about how they experienced a sense of connectedness with the other participants even when they were in different locations within their home. Participant 1 mentioned how they felt PsiNet influenced them, *"you kind of acknowledged that from the physiological sensations of feeling the stimulation"* (P2), and how it allowed them to influence their group, *"that was a very different experience when we were all together and doing a cooperative or playful experience, the system added to that"* (P1). Participants' discussed their group having a similar state of consciousness, describing how they were not certain if the shared sensations put them in a flow state. However, they chose to *"believe"* this was the case, stating, *"I'm thinking of actually, we were all working, but doing our separate thing, just doing work and there was the stimulation. I noticed I started to feel a bit like I had a coffee shot. And then I think my partner got stimulation as well, and then a housemate in the other room messaged us saying that they got a phosphene."*

6.3.2.3 Relational Interaction

This theme describes 36 units about participants' descriptions of how the system was influenced by the relations between elements within its context of use. The theme is composed of three sub-themes, *exploration with environmental activities* (14 data units), *group contexts* (13 units), and *isolated contexts* (9 units).

Exploration With Environmental Activities. Participants experimented with different social activities while using PsiNet, such as playing cards (P4, P6), playing video-games (P1, P2, P3, P6), and watching TV (P8). Some participants reported feeling as though PsiNet improved the group's performance in the tasks they were jointly engaged with, with P1 saying, *"we thought, 'are our collective thoughts and the stimulations making us really good at everything'?"* In contrast, one participant felt as though the presence of the system produced no noticeable change in their group's social interaction, stating, *"No, I don't think it changed anything"* (P9). This participant further explained why they thought this might be the case, stating, *"I think we're like any other group or family, most of the time you're pretty much synchronized already"*.

Five participants described their attitudes toward PsiNet positively using words like, *"curious," "excited,"* and *"new"*. Participant 4 said, *"Yeah, I was probably more excited than worried. I mean you're just wondering what's going to happen,"* while P1 said, *"I think we were just curious,"* and P7 said, *"But yeah, the stimulation is the exciting part."* Such curiosities drove participants to play and explore with PsiNet. They consciously strove to adjust their brain activity or the task they were doing to see what kind of social interaction could be triggered by PsiNet. Participant 8 said, *"Hmm, maybe I'll sit down and watch Netflix and see how it differs"* and P1 said, *"We were just hanging out and being silly, trying to influence each other."*

Group Contexts. In the context of group activities, participants reported more *"playful"* experiences (P1). The presence of PsiNet in these group activities also contributed toward a feeling of combined ability, with participant 2 stating, *"that because we've all* *combined our collective thoughts together and the stimulations have made us really good at everything, and now we're just some kind of superhuman group."* Similarly, P2 recalled that *"one time we were trying to do a puzzle in a game and I worked it out and we all were like, oh, it's totally because I must've gotten stimulation."* Participants also believed that the system might have changed how their group interacted. Participant 8 said, *"we were all kind of on the same level,"* as they used the system, believing that it could *"amplify"* (P8) how someone was feeling by stimulating the others in the group.

Isolated Contexts. Some participants noted that they were able to get into solid workflow states while doing work individually. A participant reported that they were able to *"concentrate intensely"* (P8) on their work, another stated *"the time is passing really quick"* (P7) as they worked, and another stated that they *"almost forgot entirely about the study"* (P5). Participant 3 suggested that they felt *"a silent motivation"* when working by themselves because they still felt connected to others in the group through PsiNet: *"it was just knowing that they're also working and being in a similar state to me [...] that was sort of even motivating for me to concentrate more and stay in my flow"*.

6.4 Discussion

In this section, I discuss the study's quantitative and qualitative results.

6.4.1 Discussion of Quantitative Results

The results showed that neural synchrony increased in the period after stimulation, compared to the period just before stimulation. While this result could indicate that PsiNet was able to increase neural synchrony in the group, as was intended, I proceed cautiously in drawing such a conclusion. I acknowledge that the epoch period could have been designed to be shorter or larger, as there is currently no research indicating what an optimal epoch period would be for measuring neurostimulation-triggered increases in inter-brain synchrony (Wan, Vi, Subramanian, & Martinez Plasencia, 2016). Furthermore, it is difficult to infer exactly how the stimulations may have increased group neural synchrony. Considering how conscious experiences can be considered as integrated (Tononi, Boly, Massimini, & Koch, 2016), it would be impossible to separate what contribution the stimulations were having to the individual's conscious experience from other causal factors. This uncertainty is consistent with participant's experiences, with P2 stating that *"It was very difficult to tell what stimulation you were getting and [...any] change in your mental state"*, and P3 similarly stating, *"there was no way to tell which stimulation you were getting and hard to correlate that with what people were doing"*. Nonetheless, the significant effect measured in the quantitative analysis of CCorr suggests that brain-to-brain interfaces can indeed increase inter-brain synchrony. This effect suggests some validation of participants' experiences and beliefs that the system was influencing them and their group. This effect also illustrates the strong potential for future iterations of brain-to-brain interfaces to be powerful tools in the amplification of inter-brain synchrony, which will no doubt become more effective and efficient as technology improves. The research, therefore, frames the future development of BBI's as an important technological instrument in the design of systems for strengthening interpersonal relationships and group dynamics.

6.4.2 Discussion of Qualitative Results

Here I discuss the themes from section 5.2 in the broader context of the literature.

Regarding the theme, *dissolution of self*, participants reported feelings of ambiguity as to whether their conscious experience resulted from endogenous or exogenous causes, from their "selves" or from the system. This experience could suggest that as humans integrate with technology, we may trend towards the experience of a seamless blend of the self with technology, and thus the dissolution of the old self into something "other". This notion speaks for the "bodily integration framework," Mueller et al. (Mueller et al., 2021), which as I explained earlier, describes the user experience of bodily integration systems—systems in which the human body and computational machinery are tightly coupled in a way that allows for bidirectional actuation—and acknowledge that both human and machine can possess agency and enact on each other. Here, I refer specifically to the frameworks axes of "bodily agency," (the feeling that the user has control over their body or the machinery acting upon it); and "sense of ownership," (the degree to which the user feels they are the owner of their body, or that the system is part of their body). In the case of PsiNet, the ambiguity of the system's stimulation and its ability to modulate the user's brain activity without their attenuation ultimately allowed the output of other brains to be experienced with a high sense of ownership, meaning these individuals feel their modified cognitive experience to be their own. Users can find it difficult to separate their own unique cognitions from the collective cognitions of the group, suggesting they can at times experience exogenous feelings, which come from the stimulation of the system as their own naturally occurring endogenous feelings. This high sense of ownership is complimented by the notion that participants felt that agency within the system was homogeneously distributed across all users. This allows PsiNet to facilitate experiences of collective agency, characterised by the feeling of "we did that" rather than "I did that". Thus, it can be said that the PsiNet users experienced the output of other brains with a high sense of ownership and agency, ultimately extending the theory of bodily integration by demonstrating that bodily integration can also take place between human and human, rather than just between human and machine.

In the second theme, *hyper-awareness*, users initially experienced increased bodily awareness while adjusting to the headset. But as participants became accustomed to the sensation of wearing the headset, their increased awareness arose from anticipating the next stimulation and observing other group members having similar experiences. As a result, participants reported experiences of increased team cohesiveness, connectedness, and feelings of closeness even over a distance. This increased awareness is consistent with the findings of Andres et al. (Andres et al., 2020). In relation to the authors' theme, "The User Experience of Peripheral Awareness as a Mechanism for Integration," participants recalled actively attempting to reach higher levels of peripheral awareness because their context was one in which they interacted with the system. With respect to the theme "Internal Bodily Signals Observed by Users", participants reported feeling greater awareness of their internal states as a result. Since it is understood that PsiNet could alter participants' conscious experiences by changing how they interact with their environment, I reason that it may lead to participants feeling greater awareness of their internal or external states. This does not mean that PsiNet stimulations directly cause this heightened awareness. It is possible that simply knowing that the system could lead to changes in awareness may have caused users to act in accordance with this knowledge and fulfil a kind of placebo effect. In interviews, participants reported that, while using PsiNet, they discussed how they were feeling more than they usually would. It may be that simply knowing that other users were sharing a similar experience and exhibiting heightened awareness may have produced a feedback loop in which all users felt drawn to participate in this heightened awareness.

The theme of *relational interaction* is similar to the theme of *passivity and self-exploration* from case study 1, Participants reported alternating between feelings of passivity and playful exploration. In a similar way, participants who used PsiNet sometimes reported feeling as though the system operated passively in the background, particularly when the participant was alone or focusing on a particular task. In contrast, participants also reported experiencing feelings of engagement, play, and silliness, particularly when operating PsiNet in proximity with other users. Clearly, context impacted how participants experienced PsiNet, whether it was a context appropriate for play, for social interaction, for solitude, or for work. In each context, PsiNet serves different purposes, which include but are not limited to: helping to improve group performance in shared tasks; promoting individuals to be mindful of the presence of others when interacting in a group; or providing a feeling of connectedness with others even when alone.

6.4.3 Design Tactics

After reflecting upon the discussion of the results, I translated the knowledge contributed by each theme into actionable advice. Specifically, each theme yielded a corresponding design tactic, with themes and tactics being presented in the same order. I contribute these design tactics to HCI practitioners, developers of wearable BBI systems, and designers of inter-brain synchrony experiences, to better guide their own forays into research.

6.4.3.1 Tactic 1. Consider Designing Technologies Favouring Implicit Interactions for Inter-Brain Synchrony

I recommend that designers consider designing brain-to-brain interfaces that avoid direct human input and instead favour implicit interactions (Mueller et al., 2020; Zander, Brönstrup, Lorenz, & Krol, 2014). This could involve ensuring that systems do not require users' direct attention or cognitive capacities. For example, the system did not require responses to notifications. Instead, the system acted autonomously; automatically taking in electrical activity as input and adapting to the users through reinforcement learning. This tactic is congruent with the idea of "mindless computing" (Adams, Costa, Jung, & Choudhury, 2015), referencing technologies that do not require explicit user attention. Studies found that such technologies can still result in subtle changes in behaviour, of which the user is unaware, while potentially overcoming the limitations of technologies that require their users to divide cognitive capacities and attention through controlling the system (Costa, Adams, Jung, Guimbetière, & Choudhury, 2016).

6.4.3.2 Tactic 2. Consider Developing Seamless Bodily Integration for Unobtrusive Operation

I recommend aiming toward designing wearable BCI technologies to conform and overlap with the user's unique physiology so that they might be used in more contexts and for longer periods of time. This design tactic will also improve the temporal resolution of data for researchers and industry. Previous studies (Li et al., 2019) have suggested that unobtrusive systems—those that can be operated without the user's attention and employed when the user is not focused on the interactive device—can facilitate experiences of inter-brain synchrony. Applying this design approach to brain-to-brain interfaces, it can be argued that inter-brain synchrony promoted by an unobtrusive interface may allow users to experience their contribution to group synchrony as something generated by themselves, not something mediated through technology. This experience would ultimately allow for an empowering experience of user agency, where amplified inter-brain synchrony may be perceived as a natural process of their body (Mueller et al., 2020).

6.4.3.3 Tactic 3. Consider Designing User-controllable System Adaptability for Transparency and Consent

PsiNet provided different uses in different contexts, including facilitating play and stimulating curiosity, enabling connectedness with others, increasing awareness of self and the environment, and possibly assisting work. However, P1 stated that they felt the system could be intrusive when they were trying to concentrate and *"you're not really open to disruptive inputs"*. Indeed, trying to force a playful experience within a work context seems inappropriate. It may, therefore, be beneficial to provide users with options that allow them to tailor the system for appropriate use in different contexts such as play, social interaction, and work. For example, this could mean allowing users performing a similar activity to set agreed-upon stimulation settings in accordance with what they think may be appropriate (e.g., disabling stimulations that may hinder someone's ability to concentrate while they are working). Another suggestion would be allowing users to set times in the day when they are open to receiving stimulations (and times when they are not). This capacity to limit is important as it gives users the power to consent to the experience (or not), including defining what consent means for them in different contexts and them having discretion to change that definition.

6.4.4 Limitations and Future Work

I believe this work could be complemented by further studies that might focus on more controlled experimental approaches focusing on statistical power and efficacy, contrasting my longitudinal and experientially focused exploration. Due to the in-the-wild approach adopted, the presence of experimental control or a placebo group was sacrificed to allow for real-world, naturalistic, and authentic interactions between the participants and PsiNet. I do this following a well-established HCI research methodology employed in many similar studies, in which qualitatively analyses human interactions with technologies, and the experiences they afford, in their naturalistic setting (Boldu et al., 2018; Hauser et al., 2018; Koelle, Ananthanarayan, & Boll, 2020; Odom et al., 2020; Odom et al., 2018). While this approach imposed a limitation on how precisely I could evaluate the degree of PsiNet's efficacy in promoting inter-brain synchrony, I gained access to detailed first-person accounts and insights into the user experience of brain-to-brain interfaces, specifically those focused on inter-brain synchrony, which has helped to understand this emerging technology from a subjective experiential perspective.

An additional direction future work would be the consideration of alternative tES stimulations. While much of the stimulation in this study was tDCS, there has been many recent developments in the use of tACS stimulations to induce neural entrainment (Vosskuhl, Strüber & Herrmann, 2015). While less researched than tDCS, neural entrainment from tACS will allow for generating more varied and pronounced neurodynamic effects, such as the induction of slow wave oscillations associated with sleep and meditative states of consciousness (Wilckens, Ferrarelli, Walker, & Buysee, 2018). Furthermore, tACS could also be used non-categorically if a stimulation paradigm were adopted in which stimulatory oscillation in one user matched endogenous brain oscillations in another, hypothetically allowing for dynamic brainwave synchronisation without needing to pre-emptively categorise mental states for classification. In addition, while the circular correlation coefficient was the metric chosen for measuring inter-brain synchrony in the present study, future studies may consider alternative measures of inter-brain synchrony, for example, phase lock value, which has also been used to measure inter-brain synchrony in the past (Burgess, 2013).

6.5 Case Study III: Informing the Framework

Building on the understanding of Brain-Computer Integration yielded by the previous case studies, the results of this case study furthered the formation of the framework.

Regarding the technologically mediated transmission of brain activity afforded by brain-computer integration, the findings of PsiNet demonstrate that neuromodulation represents a way in which to achieve what Verbeek identifies as embodiment relations (Rosenberger & Verbeek, 2015; Verbeek, 2005; Verbeek, 2015). Furthemore, the findings indicate that such relations can be experienced without the attention of the signal recipient, in effect integration into the endogenous background cognitive processing and brain activity of the recipient without their awareness. This allows brain signals to be received without the need for interpretation permitting the user to experience them as if they were generated by their own body, ultimately producing a high fidelity recreation of the experience the signal is trying to convey. This is in contrast to hermeneutic relations mediated by symbols, which require attention, interpretation, cognitive effort, and resultantly are subject to lossy compression and information bottlenecks, yet benefit from ease of understanding. This distinction ultimately informed one of the axes of the final framework, titled *Neural Congruence*.

Regarding agency, the findings of PsiNet demonstrate that sense of agency and sense of ownership are things that can be distributed between brains. People can have shared agency and resultantly experience a shared sense of ownership over their brain activity. Specifically, BCI systems characterised by embodiment relations can allow people to experience the brain activities of other people as their own when brain activity is transmitted from one person to another (shared sense of ownership). When a group of users has an equal ability to influence the brain activity of other users with their own brain activity, this ultimately amounts to a sense of shared agency, where the self is dissolved and a new collective ontology begins to arise. This insight in tandem with the insights of the previous case studies regarding agency ultimately culminated to form the framework axes titled *Distribution of Agency*.

7 The Brain-Computer Integration Framework

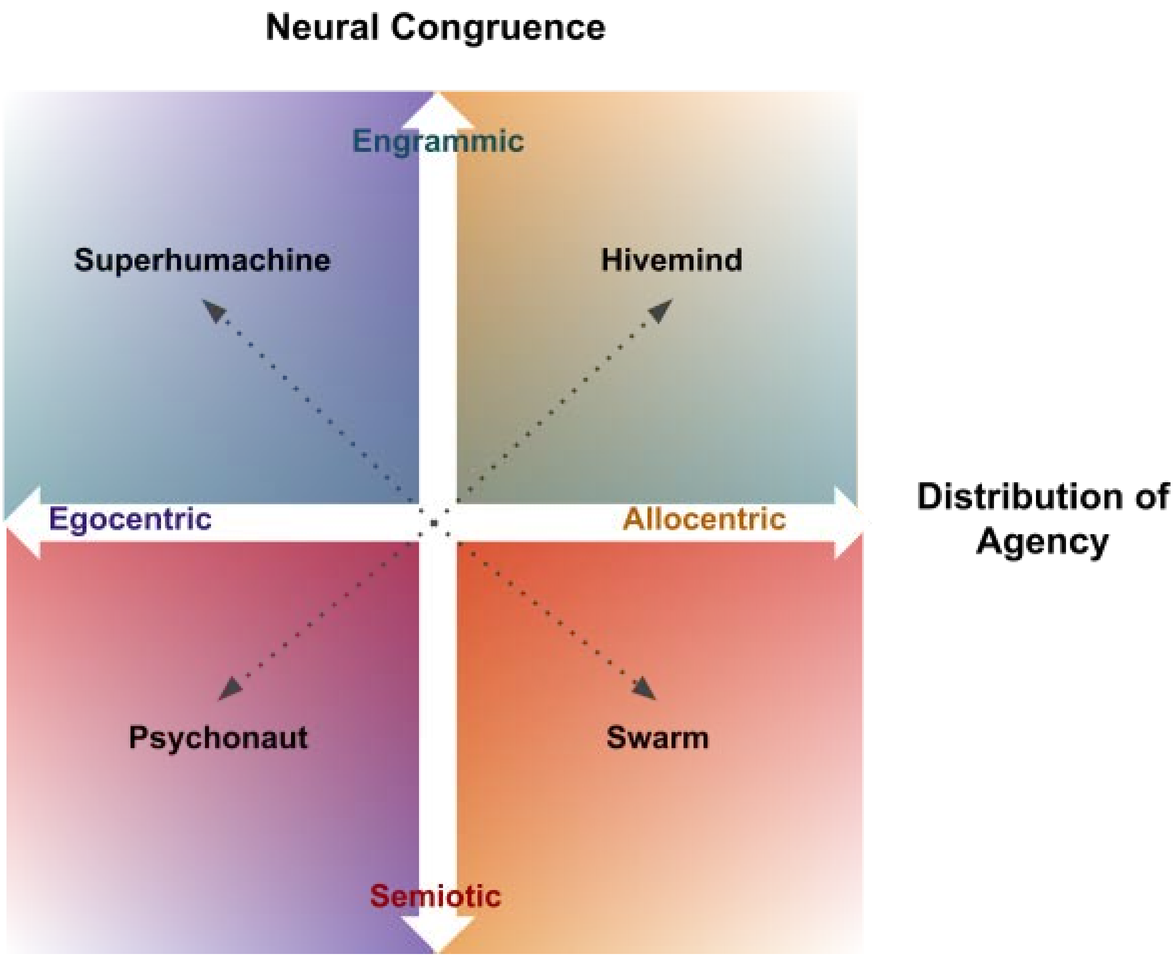

Figure 21. The Brain-Computer Integration Framework

This chapter introduces the brain-computer integration framework (figure 21). The proposed framework depicts a design space of Brain-computer Integration as a two dimensional cartesian plane. Each axis of the framework represents a dimension of the user experience of integrated brain-computer interfaces. Note that, as the design space qualitatively describes the experience of brain-computer integration from a subjective phenomenological perspective, the positions of systems mapped onto the design space relative to each axis are not intended to represent or denote discrete, concrete, specific or measurable quantities of each dimension, but rather the position of an experience in the design space is intended to provide a qualitative approximation of how a system is "felt" or experienced by the user relative to other systems from the subjective perspective of the user. It is intended that this qualitative articulation of the dimensions of brain-computer integration serves as an initial tool to qualitatively conceptualise brain-computer integration such that future work may begin to operationalise these dimensions for quantitative analysis and measurement, which will be discussed further in section 10.3 . This framework is a synthesis of the knowledge gained through reflecting on the design of the three prototypes, in conjunction with their results. The framework has emerged describing the design space of integrated neural interfaces, in addition to prescriptive design strategies. It is intended this will ultimately help designers and practitioners navigate this design space to generate the desired user experience when designing future integrated BCI's. This was inspired by previous works in HCI that have used two dimensions to describe design spaces, prescribing names to each quadrant which resultantly represent unique types of user experiences (Andres, 2021; Byrne, Marshall, & Mueller, 2020b; Byrne, 2016; Mueller, Byrne, Andres, & Patibanda, 2018; Mueller et al., 2020; Mueller et al., 2021).

7.1. The Framework Axes

The first dimension concerns "distribution of agency", spanning from an egocentric to an allocentric distribution. The second dimension concerns the "neural congruence", spanning from semiotic to engrammic. The following chapter defines, describes and differentiates these dimensions and the quadrants that result from their interaction.

7.1.1 Distribution of Agency

The first dimension of the design space is "Distribution of Agency". This dimension is concerned with causal influence distribution amongst agents participating in the system, and by extension, the user experience. In other words, how agency is distributed. This dimension represents how the brains of users of the systems control their processes, how equally that control is distributed amongst users, and how much other causal factors such as situational context, influence the user experience. Through applying Latour's Actor Network Theory (ANT), we can conceive of systems as a human-machine assemblage, or humanchince (Mann, 2020) in which agential actors within the system, either human, machine or environmental, form nodes in a network where the graphs edges denote afferent causal connections. Here, I describe highly centralised networks (left side of the dimension) as egocentric, as causal influence within the network is relegated to one or a small number of actors (human or artificial agencies). At the opposite end of the dimension sit decentralised networks in which causal influence can be exerted or injected into the system from many actants relatively equally (again being both human or artificial agencies), which I describe as allocentric. While the use of "egocentric" carries with it negative connotation in colloquial usage, such as indicating "selfish" or "self-centred" sentiment, the present use of the terms "egocentric" and "allocentric" was inspired by Georg Northoff's "lessons from astronomy and biology for the mind-Copernican revolution in neuroscience" (2019). In this work, the author articulates a distinction between "egocentric" and "allocentric" vantage points for considering the origin of consciousness and mental feature in neuroscience, where an egocentric vantage point describes mental features emerging from the brain dynamics of the individual, an allocentric vantage point considers mental features to be emergent of brain-world relations with emphasis of what happens beyond the brain when considering the aetiology of mental features. This dimension considers interactions between causal agents within the system holistically, imagining them as a network which can be described as a whole. For example, imagine a user is part of a BCI experience in which the neurocognitive activity of themselves and a group of other users are controlling a swarm of drones. In analysing this experience, this axis would pose the questions "how equally is control distributed across users' brains?" and "how much does situational context influence the experience?", e.g., nearby drafts and airflow, or the social norms around using drones (such as air traffic laws). Furthermore, the formation of this network of users, technologies, environmental conditions and abstracted socio-semiotic factors can then be taken together to be described as a singular agent in itself through conceptualising it as a network, as I will explain.

While it may be easy to quickly assume this axis refers to how "social" a system is, this is not entirely correct. The distribution of agency within a BCI system is not merely a measure of how many users are in the system, but rather a description of the distribution of the causal agents acting within the system. For example, a neurofeedback system in which a single user's brain drives the experience (i.e., the system completely stops if the user removes the BCI) is highly egocentric, even if other people were involved in this experience. Furthermore, this axis does not just concern how many people are wearing BCIs. For example, a system in which a group of users' brains are stimulated in accordance with the activity of a single user's brain would be considered highly egocentric. Thus, the motivation for generalising this axis as distribution of agency rather than simply the number of users in the system, is to allow for a flat agential ontology that allows for more complex systems rather than the traditional human-as-master, machine-as-tool dichotomy. Rather, this ambiguity allows for the human-computer integration framework to consider assemblages in which human agency is sacrificed to a machine agent for the sake of supporting the functioning of the assemblage as a gestalt. An example of this would include the slave gally analogy made by Mann (2021), EMS games which take over your bodily processes to allow you to play hand games akin to rock-paper-scissors against oneself (Patibanda et al., 2022), and Machine_in_the_middle, which hijacks physiological processes intended for the expression of human emotion to eliminate deception (Dickinson & Semertzidis, 2022). Furthermore, this flat agential ontology also leaves room for the considerations of "posthuman" BCI assemblages which may not have humans in the loop, including BCI systems using animal brains (Zhang et al., 2019), BCI systems using cultured human neurons (DeMarse et al., 2005) and BCI systems using neuromorphic computers or synthetic brains (Schuller et al., 2015; Thomas et al., 2014), all of which can be considered agents. Thus again, it is helpful to think of this axis not as the number of users the system supports, but as the number of agents influencing change in the system's processes. An analogous quantitative measure would include analyses such as Dynamic Causal Modelling, which is used in neuroscience to infer the causal architecture of coupled or distributed dynamical systems (i.e., causal hubs within the brain) (Marreiros, Stephan & Friston, 2010). Nonetheless, alternative or additional axes such as number of users or "crowd size" are also valid variations of the illustrated design space and future work looking to expand the brain-computer integration framework would do well to consider crowd size as a candidate for a third axis following further research focusing specifically on how number of participants influence the experience of brain-computer integration.

The dimension of distribution of agency speaks to Latour's "Actor-Network Theory" (ANT) (Latour, 1996), which seeks to define and describe the relational ties between human and non-human actors by describing them as nodes within a network, with each node being called an "actant". This network is placed on a "flat ontology", meaning that all actants within the network can equally be assumed to have implicit value or agency. This is the case regardless of what the actant is, be it human or not, and as such it treats humans and technology equally in terms of possessing agency and value within the network, thus favouring neither social nor technological determinism. Taken together, the amalgamation of actants within a given network can be conceptualised as an "assemblage", the sum total of individual actants forming the whole. With these points considered, I can thus state that ANT explains how material–semiotic networks (networks of physical artefacts and living organisms (material) and transmissible information (semiotic)) come together to act as a whole.

For example, consider the network of PsiNet. The actants in this network include not just the users, but also the algorithms driving the system, the hardware mediating the exchange of information between the system and its users, and the contextual factors present around the users. Together, these actants connect to create a joint agency from which a brain of brains emerges, imbued with its own novel ontological experience. Furthermore, in describing the actants within this brain of brains as networked nodes, its composition can be further described through "node centrality", which will ultimately allow us to determine the distribution of agency of this brain assemblage (Borgatti, 2005).

Node centrality (Borgatti, 2005) is a descriptor of the importance of a given node in a network (i.e., how central it is to the network). This importance can be established in various ways, such as considering the number of connections to a given actant, or also the number of important actants connected to a given actant. Important nodes are integral to the identity of the network, and have the most agency over the flow of information throughout the network; thus dictating its ontology. Highly centralised networks would tend to have a single or small number of important nodes which boast a disproportionately large number of connections relative to other nodes. Conversely, the connectivity of nodes in decentralised networks would tend to be homogenous, with many nodes sharing a similar number of connections resulting in no nodes being of particular importance.

Returning to BCI's, results from the case studies of the present thesis suggest that human-system assemblages with an egocentric distribution of agency can be described as centralised networks. In such assemblages, a small number of important nodes, or actants, exist, most often a single user and the interface itself, with all other actants (e.g. observers, other participants, etc.) participating in the network through connections to these actants (e.g., rather than to each other). As such, the experience is highly contingent on these specific actants and their actions, giving them a disproportionate amount of agency over the experience. In turn, other factors such as context and situatedness present little influence over the system. Consequently, the removal of said important highly connected central actants would ultimately destroy the assemblage, in turn ending the experience.

Conversely, results from the case studies of the present thesis suggest that human-system assemblages with an allocentric distribution of agency can be described as decentralised networks. In such assemblages, there are no "important" actants but rather all actants have homogenous degrees of connectivity within the assemblage, resultantly supplying similar amounts of influence over the network. As a result, this creates a joint agency in which agency is not centralised within a given actant but rather in the gestalt of the assemblage. As such, the system is not contringent on a single actant. This comes with the benefit of rendering such systems scalable, specifically in that actants can be added and removed from the assemblage (e.g., more and more users can join) without disrupting the experience or needing to re-engineer the system. Furthermore, such distributions place a larger emphasis on situational factors, as each actant is not more or less connected to their semiotic (informational) or material (physical) space.

With the assumption that in a BCI system, important nodes will tend to be brains considering they are the system's subject of interest, a system's distribution of agency can simply be summarised in the notion of "weather there is a central brain or not", with this outcome being resultant on weather the designer configures flows of agency within the system to be either allocentric, or egocentric.

7.1.2 Neural Congruence

The second dimension of the design space is “neural congruence”. A term I introduce to HCI research discourse to articulate the phenomenological congruence between the source experience the BCI is encoding from neurocognitive activity, and the resulting user experience of the recipient when decoding BCI data. For example, if a user feels sad, and the underlying neurocognitive processes behind this feeling are encoded and represented on a screen as a sad face, what is the similarity between the feeling that generated that sad face, and the feeling one would get when looking at it? That extent of similarity, or *neural congruence* is the focus of this axis. Here, the term congruence is chosen specifically to refer to the phenomenological agreement, harmony, and consonance between the source experience that give rise to the brain activity the BCI sense and codifies into digital data, and the resulting experience the user at the end of the feedback loop phenomenologically receives from BCI output (or human input). The dimension is qualitative and subjective, meaning that the denotation of a system’s user experience on the framework's design space is a representation of the approximate “felt” quality of congruence associated with that given system. An analogous objective and qualitative measure would be “mutual information”, which in information theory denotes the mutual dependence or amount of information obtained from one variable by observing another (e.g., the experience of receiving BCI output, and the preceding source experience). The quantitative articulation and analysis of this dimension, however, is beyond the scope of the present thesis, and is suggested as future work later in section 10.3.

Systems which exhibit a low extent of congruence generally encode brain data via semiosis, meaning that they translate the source experience into abstracted signs, symbols, or representative metaphors (Eco, 1976; Peirce, 1991). Recipients of such signals decode the signal by engaging in the more active cognitive processes of perceiving and schematising these symbols in order to extract meaning. This process ultimately renders the user responsible for sense-making, as they are required to consciously act as a decoder.

Conversely, in analysing the user experiences generated throughout the three case studies of this thesis, it was observed that systems which exhibit a high extent of neural congruence generally encode brain data as an “engram”, meaning that they relay the source experience through stimulating neural activity in the recipient which is congruent with neural activity that was previously encoded (Josselyn, Köhler, & Frankland, 2015). Recipients of signals with a high extent of neural congruence decode these signals more passively, as their brain is entrained to produce a distribution of neural activity similar to that underlying the source experience. This process ultimately distances the user from being involved in sense-making, as information is instead decoded unconsciously by the user's brain as the system's output merges with the user's neural activity.

The dimension of neural congruence speaks to post-phenomenological conceptualizations of human-computer relations. Specifically, Verbeek's "theory of technological mediation" (Verbeek, 2005), which was formulated to analyse how different technologies can mediate the relations between users and the external world. In applying Verbreek's theory of mediation to the context of a brain-computer integration framework, my thesis supports this previous work by demonstrating how different forms of Verbreek's human-technology relations are manifested by systems at different points of the neural congruence spectrum. Furthermore, my thesis extends this work by describing how Verbeek's human-technology relations are mutated into modified variants of the theory's original relations due to unique properties of BCI systems, as I will discuss in the following paragraphs.

Verbeek uses the term "hermeneutic relations" (Rosenberger & Verbeek, 2015; Verbeek, 2005) to refer to human-technology relations in which a system is used via the act of perceiving and interpreting a system's semiotic output. Through this process, the user experience is a transformed encounter of what is being represented through the direct experience and interpretation of the technology itself. An example of this in the context of BCI would be a representation of brain activity through a graphical visualisation. In this example, the user experiences symbolically translated access to the cognitive processes of the brain being encoded. This resulting experience can be considered to have a low extent of neural congruence, as the human decoder is perceiving and actively interpreting the semiotics of the technology itself, rather than the source experience it is translating. Thus, it can be said that BCIs transmit semiotic signals through hermeneutic relations. However, due to the nature of BCI, the subject that is being hermeneutically related as semiotic information via technology is itself the subject (i.e. a user) which interprets it. Specifically, neurocognitive activity is what is both being represented via hermeneutic relation, but also, what is being used to interpret the hermeneutic relation. This process creates a hermeneutic feedback of semiotic brain data which ultimately puts the user's conscious cognitive processes at the centre of sense-making in the experience, both in terms of encoding and decoding information.

Alternatively, "embodiment relations" (Rosenberger & Verbeek, 2015; P.-P. Verbeek, 2005) are human-technology relations which transform a user's behaviour and perception of the world. In the context of BCI, embodiment relations facilitate experiences in which the user's neurocognitive processes are mediated through the system, rather than being represented by the system. That is, the user's experience of reality is modulated through the device, with the device in some ways taken into the user’s bodily awareness. An example of this is a system which modulates the user's brain to produce an altered state of consciousness, like how PsiNet was able to modulate users' brains to have them enter a state of focus. This thereby changes the way the user perceives the world. Such systems are able to facilitate a high extent of neural congruence as they are able to shift a decoder's experience of the world to resemble that of the encoder. However, while Verbeek describes embodied relations as relations in which the human uses a system as a mediational lens to see the world through, embodiment relations in the context of BCI are unique in that the mediational lens through which the human interacts with the world is their own brain. That is, while the human sees the world *through technology* in typical embodiment relations, the human sees the world through *their technologically altered brain* in BCI embodiment relations. Here, humans are not perceiving through the technology, but rather the technology is part of the perception process itself. Through this insight it can thus be see that in the context of BCI embodiment relations, the separation of human and technology becomes incredibly difficult, suggesting that embodiment relations align closer to what Verbreek described as “fusion” or “cyborg” relations (Rosenberger & Verbeek, 2015).

Fusion relations describe embodiment relations taken to a deeper form in which it is no longer enough to say that the user experiences *through* the device, as no clear distinction can be made between the human and nonhuman elements in these relations, referring to neural-implants for deep-brain and cochlear stimulation as examples of technologies enabling fusion relations (Rosenberger & Verbeek, 2015). The experiences afforded by fusion relations can be considered to possess a higher extent of neural congruence than embodied relations, as they enable the activation of specific neural distributions necessary to reproduce the originally encoded source experience in the decoder. That is, the signal takes the form of an engram. With this considered, such systems find themselves at the highest end of the neural congruence spectrum.

To illustrate the distinction between semiotic and engrammic codings, which produce hermeneutic and embodied relations respectively, let us consider the example of a BCI system that communicates the emotion of sadness. In a BCI system situated more toward the semiotic end of the neural congruence dimension, the system interprets the user as sad based on their brain activity, and codes their experience of sadness as a symbol, e.g. the emoji “:(“. As the coding is semiotic, the recipient of BCI’s “:(“ output, whether this is the same user that generated it or a third party recipient, must hermeneutically engage with this symbol, meaning that they must interpret its meaning actively through the application of cognitive constructs like past knowledge, experience, cultural schemas, appraisals, biases etc. The recipient may rationally deduce that the ":(" means that the source experience it was generated by was one of sadness, but that does not mean the recipient feels sad as a result of that information, making the experience of receiving the ":(" not very "neurally congruent". Conversely, in a BCI system situated more toward the engrammic end of the neural congruence dimension, the system interprets the user as sad based on their brain activity, and codes their experience of sadness as a brain stimulation protocol, which actuates neural activity in the recipient associated with sadness, such as gamma and theta band manipulation, alpha asymmetry, and network entropy (Neto & Rosa, 2019). As the coding is engrammic, the recipient has an embodied experience of the coding upon receiving it, without the need for cognitively unpacking its meaning, as the output of the system directly influences their neurophysiology to match the neurophysiology associated with the source experience. Consequently, the experience and brain activity of the recipient on receiving that code is very congruent with the experience and brain activity of which the code was generated from.

In addition, the spatial properties of these two ends of this dimension can be further unpacked through the concepts of environment, viroment, and invironment as proposed by Mann (2021). Mann articulates the idea of the "vironment" as a vessel that exists at the boundary of the external (environment) and internal world (invironment). The vironment can be exemplified by many everyday tools, such as one's clothes, glasses, a bike, a boat, a car. By extension, the author explains that a cyborg is a being that exists together with its vironment (a human and its clothes, or a human and its glasses). With this principle, we can consider the BCI to be a vironment, and the human and BCI a cyborg. Furthermore, depending on whether that BCI is considered semiotic or engrammic based on its neural congruence would determine how this vironment acts as a mediator between the invironment and the environment. Specifically, semiotic BCI systems act as a vironment that takes information from the invironment (brain activity) and brings it out to the environment-as-symbol. Alternatively, an engrammic BCI system acts as a vironment that takes information from the invironment and transmits it to the invironment (either from the same invironment or the invironment of another individual). These relations can be simplified as the expressions below:

Semiotic: Invironment -> Vironment -> Environment
Engrammic: Invironment -> Vironment -> Invironment

7.2 Introducing the Quadrants

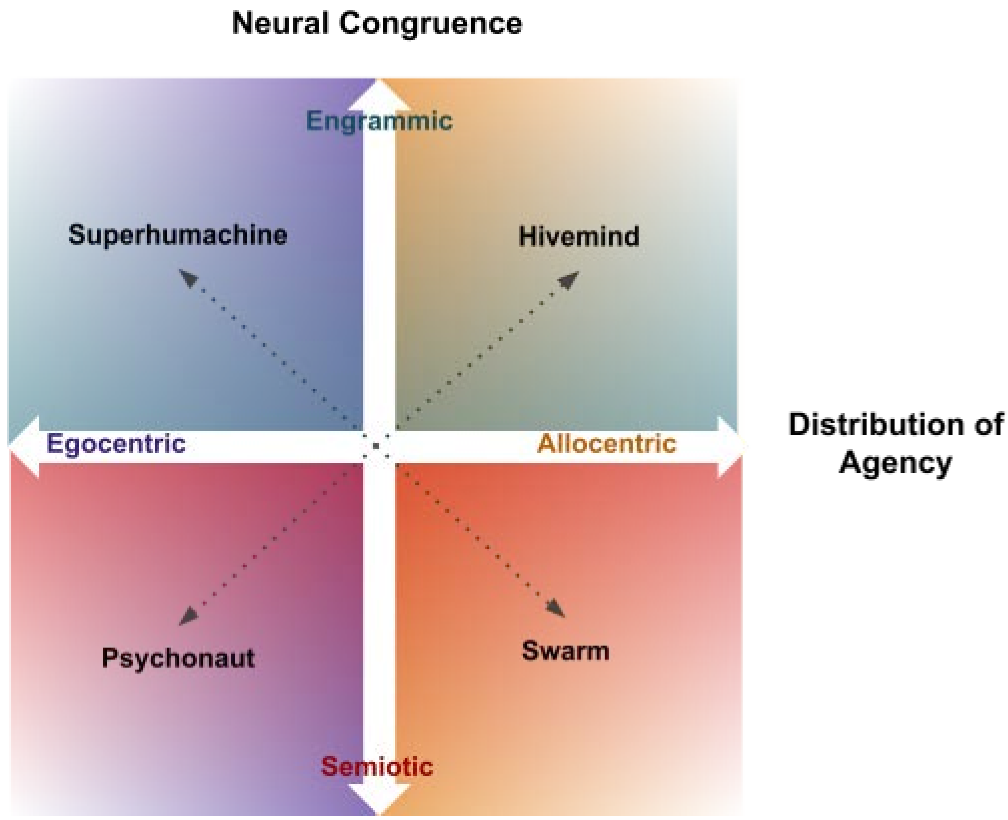

Figure 22. The four user experiences mapped onto the design space.

The design space helps designers to identify the quadrant for which they are designing, further guiding the design process towards attaining the desired user experience (figure 22). The following section describes the opportunities and challenges that designers may face when designing for each user experience, summarised below in table 10.

Table 10. Opportunities and challenges for each quadrant of the design space.

Quadrant	Design Opportunity	Design Challenge
Psychonaut	Ability to actively explore, understand, and regulate one's own mind	Providing a sufficiently deep level of exploration to keep users engaged
Swarm	Ability to actively contribute an individual	Finding the optimal tradeoff between simplicity

	subject to a gestalt object	and complexity of symbols
Hivemind	Ability to passively enhance interpersonal connections	Managing the complex input/output interactions that arise from a highly connected network
Superinhumachine	Ability to passively enhance or modulate neurocognitive processes	Dealing with the loss of habituated increased mental capacity

7.2.1 Lower Left: Psychonaut

In the bottom left quadrant sit systems that are characterised by a low extent of neural congruence and an egocentric distribution of agency. I call this user experience “psychonaut” (greek for “sailor of the mind”) in reference to “psychonautics”: the method of inducing altered states of consciousness through the use of meditation, psychoactive substances or biofeedback, to explore the self and consciousness (Butler, 2019). The results yielded by the case studies of the present thesis suggest that through employing systems in this quadrant, users generally become psychonauts as the system facilitates the exploration of their own consciousness in the form of semiotic sensory feedback.

The majority of contemporary BCI systems find themselves in this quadrant, namely those labelled “neurofeedback” systems. An example of such a system would be the case study 1, Inter-Dream. Psychonautic systems often facilitate solitary experiences in which the user’s brain is a centralised focal point of agency in the human-computer assemblage, although other people can be included in the experience, e.g. “the moment” (Ramchurn, Martindale, Wilson, & Benford, 2019), a cinematic experience in which an audience watches a film where cuts are decided by the brain activity of a single audience member. Through these systems, the user’s neurocognitive activity is interpreted by the BCI and fed back to the user symbolically, typically in the form of sensory metaphors which represent cognitive processes or affective states.

For example, Inter-Dream provides the user with visual feedback in the form of a spherical distribution of motes of light, which change in colour and movement in response to the band powers of the user’s power spectral density. Through this mechanism, unique visual displays are dynamically generated based on the concurrent cognitive processes of the user, communicating this back to them in VR through a kiladiscopic display of movement and light. Similarly, in “Lucid loop” (Kitson et al., 2019) lucid dreaming skills are trained through the visual metaphor of “becoming lucid". Specifically, users begin in a VR environment with blurry visuals. These visuals become more clear as the user becomes more "lucid" as indicated by their EEG, ultimately training the user to move their mind into a lucid state through the system's feedback.

In psychonaut-type experiences, users learn to connect the presented metaphorical symbols to their underlying meaning as they reflect on how they feel while the system dynamically represents their introspective journey. In doing so, an emergent lexicon is formed that users can then use to make sense of future thoughts (e.g., some users of Inter-Dream noticed they could produce specific colours by trying to move toward specific states of mind). Through this affordance, users are enabled to explore their feelings in novel ways, as the system provides the ability to ask "how do I feel about this thought", or "how do I feel now", with the question being met with an informational response in the form of neurofeedback. Again, this can be exemplified in the study of Inter-Dream, with one participant describing how the system "*encouraged introspection, jumping to different thoughts more than usual because it made me a bit more excited about those thoughts [...] I was more active in them and engaged with them more quickly*" and explaining how "*I was thinking about my math assignment, and then the introspective nature changed my thoughts on the math assignment, why do I feel the way I do about that assignment? [...] and they were generally more positive*".

Through this process, users are ultimately provided a platform through which they can explore and learn about their brain, a channel to observe and monitor their mind's reactions to certain thoughts or perceptions. This also opens up the potential for users to experience their "body as play" (Mueller et al., 2018). For example, the study of Inter-Dream ultimately concluded that the affordance of playful self-exploration was instrumental in producing positive affective and arousal states indicative of healthy pre-sleep physiology ((Semertzidis et al., 2019). I believe that the more immersive and complex the metaphor being provided, the deeper the user can sink into their introspective journey, opening up more opportunities for self discovery, self mastery, and self play. Notable examples push these systems toward digitally facilitated lucid dreams in which users can craft digital worlds reflective of the contents of their own mind for them to explore, for example see (Arora, Agrawal, & Choudhary, 2019; Cavazza et al., 2014; Karpouzis & Yannakakis, 2016; Murdoch, 2019; Pinilla, Garcia, Raffe, Voigt-Antons, & Möller, 2021).

Self-exploration provides the user with a heightened ability to self regulate neurocognitive processes, as they are provided with feedback on how their mental actions bring them closer or further away from their target mental state (Sitaram et al., 2017). These regulatory abilities can be quite profound (Casimo, Weaver, Wander, &

Ojemann, 2017; Sitaram et al., 2017), with cases demonstrating the ability to regulate oneself into altered states of consciousness, e.g., promoting pre-sleep states in Inter-Dream. These regulational abilities can be learnt and strengthened with repetitive use, providing users with a translational skill that they can continue to leverage even without the use of the system (Sitaram et al., 2017).

7.2.1.1. Design Opportunity

The opportunity for designers creating systems in this quadrant is to help people explore, learn about, and understand their own minds, whilst ultimately providing them with mental self-regulatory skills that can hopefully be translated beyond the use of the system. I acknowledge that the self-regulatory abilities provided by these systems have been widely documented (Sitaram et al., 2017). However, due to their historical origins in clinical neuropsychological practice, the affordances of engaging with these systems with rich sensory metaphorical symbolism have been given less attention. I therefore extend this prior work by contributing the knowledge that these systems provide a platform for the user to experience their body as play (Mueller et al., 2018), as "players" observe and explore with their own neurocognitive processes which can be fed back to them in the form of engaging sensory metaphors (e.g., procedurally generating a game level based on their neuronal activity) allowing them to "play" their brain. This may be particularly useful in instances in which users are trying to explore sensitive or difficult thoughts or feelings, perhaps providing a means for this challenge to be fun, less daunting, or empowering, making these systems possibly even better suited for psychotherapy than former clinical incarnations.

7.2.1.2. Design Challenge

One challenge is the design of a suitably "deep" level of exploration with regard to the ways in which the system can metaphorically communicate the user's neurocognitive processes. For example, while the commonly employed simple visual metaphors of colours or symbolic objects (Potts et al., 2019) are a good starting point for the user to familiarise themselves with their own neurocognitive processes, they may quickly exhaust the educational and exploratory affordances offered by this medium over multiple uses . Future work may consider the generation of more complex, multisensory metaphorical representations such as narratives or characters, or open-ended environments to keep exploration. An example from science fiction of such a system taken to its extreme would be the "Aleph" from William Gibson's novel "Mona Lisa Overdrive" (Gibson, 1989), a BCI system in which the user's mind projects an artificial reality in which they can learn, grow and act independently.

7.2.2 Lower Right: Swarm

In the lower right quadrant sit systems that are characterised by low neural congruence and an allocentric distribution of agency. I call the user experience “swarm”, as the experience and its tendency to form emergent properties is analogous to the process of semiochemical signalling that many eusocial swarming insects are capable of. One example of this is ant pheromone trails, which have been described as a set of “chemical symbols” (Helms, 1998) which ants use to autonomically signal information to other members of its colony in reaction to that ant’s experience of the world. When the colony collectively contributes to this signalling behaviour, this leads to self organising patterns (such as trails, rafts, structures made of bodies), ultimately form a set of chemical symbols and interpersonal interactions which provide a gestalt “body” for the embodiment of information about the colony and the summed experiences of its members (Deneubourg, Aron, Goss, & Pasteels, 1990; Glad, Buffet, Simonin, & Charpillet, 2009; Theraulaz et al., 2002).

Systems that sense brain activity of one user, and symbolically represent this as a sensory metaphor that can interact with the environment or the representations of other users, find themselves in this category. An example of such a system would be the second case study, Neo-Noumena, as the system utilises affectivally generated fractals which interact with the physical environment (e.g. avoid and land on surfaces) as well as the fractals generated by other users (e.g. they form a single swarm when both users are experiencing the same emotion). Another example is the game “Socio-pathways” (Nijholt, 2019) in which users (usually five at a time) are represented on a screen as dots. As one user's brain activity becomes more synchronous with another, their dots move together, with the goal of the game being the assimilation of all dots into a single ball. This then gives rise to emergent behaviours in the players as they attempt to synchronise with each other, e.g. such as doing the same repetitive movement.

In these examples, the system offers a shared experience in which each individual contributes to the pooled symbolic representations of brain data, in turn altering the gestalt interpretation of that set of data. As a result, the meaning of an individual’s brain data evolves when interpreted alongside the brain data of others, as opposed to if it was presented solipsistically. Furthermore, such systems can allow for representations of brain data to dynamically interact with each other to further provide information regarding the gestalt of the group. For example, when users of Neo-Noumena were experiencing the same emotion, their procedurally generated fractals would join together to create a single flock, signifying affective unity. Similarly, in Socio-pathways the dots representing the brains of the users would join as they became more synchronous, signifying a convergence of mental state. In both these examples, the system provides representations of brain data that can be both interpreted to inform one about an individual, or interpreted to understand the group dynamic as a whole.

Taken together, these systems allow users to collectively contribute to a gestalt of brain data that can interact with itself and combine to form new emergent meanings. This ultimately creates a “semiosphere” of brain data, with semiosphere being defined by Lotman as “the sphere of semiosis in which sign processes operate in the set of all interconnected Umwelten” (from the german *Umwelt* meaning “environment” or “surroundings”) (Lotman, 2002). Specifically, Lotman’s U*mwelt* theory states that the mind and the world are inseparable, because it is the mind that interprets the world for the individual. Consequently, the *Umwelten* of each individual differ due to the uniqueness in the biology, history, and lived experience of each individual. When two *Umwelten* interact, this creates a semiosphere. Thus, for swarm systems, the contribution of one’s *Umwelt* through their brain data ultimately generates a semiosphere of neurocognitive information in which brain data interacts to generate a narrative of the group’s gestalt *Umwelten*.

This can be further unpacked through the *Körper - Leib*; and *Erfahrung - Erlebnis* distinctions given by Mueller et al. (Mueller et al., 2020). Here, the authors use the german lexicon to describe the user experiences afforded by bodily systems. Specifically, they evoke *Körper* to refer to the objectified body that performs its individual functions like maintaining homeostasis and sensing the environment, but holds no lived experience. In contrast, *Leib* is used in reference to the subjective body, imbued with an ontological sense of being that is experienced (i.e., having lived experience). In further unpacking the experiences of the *Leib*, we can evoke *Erfahrung* to signify declarative or procedural knowledge which can be gained and consciously processed; and *Erlebnis* to describe pre-reflective knowledge or lived experience, which only becomes accessible in the process of *Erfahrung*. Using this lexicon, we can then describe the user experience of swarm systems by stating through using these system, the neurocognitive data, produced by the *Leib* of the group is given a collective *Körper,* embodied by the gestalt sum of the group’s neurogenerated semiosphere. In turn, this translates the *Erlebnis* of the group into a *Körper* that provides group *Erfahrung* which can be accessed by the observers or the group itself.

7.2.2.1. Design Opportunity

With the above considered, I see that the design opportunity presented by swarm systems is the enabling of individual agencies to contribute their lived experience to the generation of a gestalt body that can provide information about the emergent group as a whole. In turn, designers can use these resultant experiences to engage users and observers to cognitively appraise and extract information about how a group “feels” as if it is a “superorganism” (a term used to describe how ants and other eusocial species act together as a single body). Furthermore, these systems still retain the opportunity to allow for further investigation of the feelings of individuals within the group if they so wish. From the perspective of a group member, this can allow the individual to ask questions such as “how do I feel”, while concurrently enabling the inquiry of “how do we feel”, and being able to receive an *Erfahrung* (objective) answer to both these *Erlebnis* (subjective) questions. This provides an additional dimension in engaging with a group, as in allowing users to perceive and assess how it “feels” they have access to information we might not otherwise have.

7.2.2.2. Design Challenge

A key challenge designers might face when designing in this quadrant is how to appropriately design semiotic signals that balance complexity, simplicity, and informativeness in representing the gestalt. Specifically, more complex generations of symbols to represent neurocognitive processes can provide the recipient with more details about the feelings that generated them. However, as complexity increases, so too does the cognitive effort to interpret them. This is compounded in swarm systems as each user is contributing their own feelings toward the semiosphere. While designers could aggregate the representations of all users into a single representation, this would disable any ability to make inferences about specific individuals in the group. Instead, designers should consider how to communicate the group gestalt, while still facilitating the opportunity to interpret neurocognitive activity on an individual basis as well. For example, Neo-noumen dealt with this using boid behaviour (the logic underlying the behaviour of flocking birds, schooling fish and swarming insects), where signifiers of similar emotions flocked together across users, but contrasting emotions avoided each other. While this worked with two users, it is anticipated that this may not translate as well for larger user bases.

7.2.3 Upper Right: Hivemind

In the upper right quadrant sit systems that are characterised by a high extent of neural congruence and an allocentric distribution of agency. I call this user experience “hivemind”, as the experience is likened to being part of a decentralised telepathic collective consciousness common in science fiction literature (Danaher & Petersen, 2020; Langsdorf, 2020; O’Sullivan, 2010; Prucher, 2007). Some well known examples of such systems in science fiction include “the Borg” from television series “Star Trek” (Okuda, Okuda, & Mirek, 2011) - cybernetic organisms whose minds are linked to form a gestalt consciousness called "the Collective".

Systems in the hivemind quadrant often harness brain sensing and stimulation technologies to facilitate brain-to-brain neural entrainment or amplify inter-brain synchrony. An example of such a system is the third case study, "PsiNet". Another example is the performative art installation titled "Hivemind" (Nijholt, 2019), in which two performers have the oscillatory electrical activity of their brain converted to strobing light, which in turn entrains neural oscillations in the opposite performer. This process of oscillatory strobing and neural entertainment is continued in a turn-taking maner (like a conversation) until the neural oscillations of the performers synchronise, ultimately achieving inter-brain synchrony localised in the visual cortex. Similar collective neural dynamics have been illustrated in an earlier series of performative art installations, being the musical brainbaths of DECONcert and Telematic Tubs Against Terror (Mann, Fung & Garten, 2007), in which the brain activity of groups of people are used to control music and water respectively. Where these pieces uniquely differ from the prior works mentioned, however, is that their associated experiences form a journey through the quadrants of the design space along the axis of neurocentric agency. Specifically, in both Telematic Tubs Against Terror and DECONcert, the representation of brain activity in music and water respectively do not necessarily implicitly evoke the felt experience of the people generating the output in those that are observing it. However, as the participants are all subject to the same stimuli produced by the pooled output of the BCI systems, a feedback loop is created in which the experience and brain activity of each participant converges toward physiological synchronisation, or what the authors call a "Collective Unconsciousness" (Mann, Fung & Garten, 2007). With this considered, it could be said that the experience moves from a swarm-like experience to a hivemind-like experience over time.

The users of such systems form a decentralised network of minds, with each user being a loci of agency that contributes democratically to the gestalt brain activity of all users in the network. This is ultimately experienced by users as "phenomenological unity", a notion defined by Danaher and Peterson as "*when there is some unity of phenomenological experience across individuals, i.e. where in some sense they are seeing, feeling, hearing, touching, or tasting the same thing" (Danaher & Petersen, 2020)*. This can be demonstrated in the study of PsiNet, where one participant reported *"I'd feel like I just had heaps of caffeine or coffee or energy drinks or something"* as a result of other users concentrating or being engaged in work. Similarly, when one participant was rationalising why another participant may have been stimulated in the way they did, they stated: *"I think maybe if someone was quite agitated or aggravated by the work that they were doing or whatever the topic was, that might explain why our housemate got a phosphene"*. Note, however, that phenomenological unity alone does not necessarily imply complete agreement or cohesion between agents on a rational level, as this is instead explained by the related but independent variable of "rational unity" (Danaher & Peterson, 2020). For example, both Mann and the artist

Stelarc can be said to have some degree of phenomenological unity regarding the experience of being a cyborg, as both have experienced long term altered perceptions of reality mediated through cybernetic augmentations. However, their rational position on the experience of being a cyborg diverge, as Stelarc argues the human body is now obsolete in that cybernetic extensions enable a new post-corporeal physical existence, while Mann alternatively argues that humans have very much been cyborgs throughout much of our history through technological bodily extensions such as phones, the internet, cameras, and clothes (Mann, Fung, Federman & Baccanico, 2003). Taken together these examples demonstrate how Hivemind experiences involve an interpersonal integration of the neurocognitive processes through the sensing and distributed stimulation of brain activity throughout the network. This ultimately leads to a unity of phenomenological experience in which users feel similarly to other group members.

As the phenomenological unity of Hivemind experiences is achieved through neurally congruent signalling, the similarity in how the group "feels" is experienced implicitly and passively, as users are not required to divert their attention to the interpretation of symbols to receive this feeling. For example, participants of PsiNet reported a "*feeling of connection and being able to affect each other without having to really act and do somethin*g" and that *"it automatically sent stuff out, picking up on your emotions and brain states and sending that out for you".* As such, users experience the output of other brains directly as if it were their own conscious experience, exemplified in the study of PsiNet where participants stated that "*you kind of don't know why you are doing things or to what degree you're doing things or influencing each other. You don't really know where things are coming from*".

This ambiguity ultimately allows the output of other brains to be experienced with a high sense of ownership, meaning these individuals feel their cognitive experience to be their own (i.e., generated by their brains' own endogenous neurocognitive processes). As users can find it difficult to separate their own unique cognitions from the collective cognitions of the group, suggesting they can at times experience exogenous feelings, which come from the stimulation of the system as their own naturally occurring endogenous feelings. This is further benefited by the notion that in a Hivemind experience, users feel that agency is homogeneously distributed across all users, as each brain has an equal ability to change the functioning of the system. This allows Hivemind systems to facilitate experiences of collective agency, characterised by the feeling of "we did that" rather than "I did that". An example of this can be demonstrated when PsiNet participants are questioned about who had control in the network, responding "*it was with us*"; "*it seemed pretty equally distributed*"; and "*we had control via our inputs and how we responded to the outputs of the system as well [...] so it was everyone*".

7.3.3.1. Design Opportunities

The design opportunity provided by Hivemind systems is for designers to facilitate experiences of phenomenological unity to amplify interpersonal connections and neurocognitive cohesion within a group. Given that humans are highly social, this has the opportunity to provide benefits in many aspects of life. It has been demonstrated that inter-brain synchrony is much greater when measured between people with close relationships, such as family members and romantic partners (Czeszumski et al., 2020; Nguyen et al., 2021; Pan, Cheng, Zhang, Li, & Hu, 2017; Reindl, Gerloff, Scharke, & Konrad, 2018). This suggests that Hivemind systems could potentially amplify otherwise weak social connections (e.g., co-workers) toward a more empathetic and familiar standing that would ultimately generate a sense of comradery. This comes with functional and performative benefits too, as higher levels of interbrain synchrony have been demonstrated to assist in improved group performance, decision making, cohesion, agreeableness, and empathy (Czeszumski et al., 2020; Hu et al., 2018; Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017; Shehata et al., 2020; Valencia & Froese, 2020).

7.2.3.2. Design Challenges

The main design challenge of the Hivemind quadrant is the logistical complexity of identifying the best information exchange protocol for the system. In simple terms, this is the issue of knowing *when* to send *what* and to *who*. Based on input x from user a, which other users should receive output y and when? Should all inputs and outputs be averaged? Or considered on a case by case basis?

This challenge also raises ethical questions. What if user x does not want to receive a specific input, or does not want to feel how a specific other group member is feeling? What if the collective's phenomenological unity is moving toward a direction one user is uncomfortable with? Should we exclude people with psychopathologies from the Hivemind to prevent the spread of maladaptive cognitions to others? This was perhaps the biggest design challenge in the design of PsiNet, and I answered it by outsourcing the solution to a reinforcement learning algorithm motivated to increase the inter-brain synchrony of the group. While this method worked, I imagine future work would benefit from exploring more efficient, more transparent, and less computationally taxing solutions to this issue.

7.2.4 Upper Left: Superhumachine

In the upper left quadrant sit systems that are characterised by high neural congruence and an egocentric distribution of agency. I call the associated user experience “Superhumachine”, referring to Mann's description of the humachine as a closed-loop feedback system between human and machine from which a symbiotic “cyborg” emerges, which has superhuman intelligence (Mann, 2021). In this thesis, however, I extend the definition to include humachine systems that yield any superhuman ability, intelligence or otherwise, which also do not exclusively have to be of positive benefit for the human in the loop. One example of such a system is Machine_in_the_middle (Dickinson & Semertzidis, 2022), a system that categorises the concurrent emotion of the user through EEG, and uses EMS to force the facial expression of the user to match that emotional experience. Consequently, the humachine closed-loop feedback system forms a kind of symbiosis which is parasitic, rather than mutualistic, forcing the human to sacrifice their ability of expressive deception and affective privacy in order for the machine to achieve its purpose in expressing emotion. The result is a superhumachine assemblage that has enhanced emotionally expressive abilities at the cost of the agency of the human. This raises the question as to whether such a relationship is inducive to being a cyborg or not, given that the “vironment” is no longer an extension of the user’s agency, but rather the user is an extension of the vironment’s agency, similar to Mann’s question of whether a slave galley – a ship powered by slave labour – can still be considered a cyborg (Mann, 2021).

Systems that sense neurocognitive processes and then reflexively entrain desired neural activity through stimulation find themselves in this quadrant. These systems provide an experience in which the user’s neurocognitive processes are passively modified by the system. This modulation may be imperceptible as users experience their exogenously altered neurocognitive processes as their brain’s own endogenous activity, providing a strong sense of ownership in the user over the changes the system makes to their brain (such as in the case of PsiNet). This sense of ownership is closely tied with the sense of agency, and in this instance specifically relates to the degree in which an individual feels their cognitions are their own. This is mostly completed through brain stimulation, but can also include sensory stimuli that can cause neural entrainment (e.g., slowly blowing air through the nasal passage can slow cortical oscillations, leading to altered states of consciousness (Piarulli et al., 2018)). These are typically solitary experiences, although they could also be designed to include others (e.g., a system in which one person's brain controls the brain activity of many, yet the many have no control over the system).

While superhumachine systems contemporarily exist, they are typically medical devices designed to treat clinical populations. These systems are often referred to as “brain-pacemakers” (Tass, Hauptmann, & Popovych, 2020), an umbrella term that encompasses devices that sense neural activity and stimulate specific neural structures to correct pathological neural activity. Some example use cases are the treatment of tremors in Parkinson's patients (Lozano, Dostrovsky, Chen, & Ashby, 2002; Mohammed, Bayford, & Demosthenous, 2018), and the treatment of seizures in epilepsy patients (Zangiabadi et al., 2019). In translating this method toward the stimulation of key neural structures in healthy brains, these systems could be designed to not only maintain the user's homeostatic neurocognitive functions, but modulate or even enhance them. An example of such a system would be one that notices a user's brain activity that the user intends to move, and thus preemptively stimulates the motor cortex, allowing to perform that movement quicker and with greater control (similar to studies employing preemptive muscle stimulation to increase reaction time (Kasahara, Nishida, & Lopes, 2019)). Similarly, a user may be performing a cognitively intensive task and the system might detect the user is concentrating. In turn, the system stimulates the frontal cortex to give an intellectual boost.

As demonstrated in studies of long term use of neural stimulation, through regular use these systems may induce long lasting effects on the synaptic plasticity of the individual, thereby quickening the rate they acquire new skills (Kadosh, 2014; Looi et al., 2016; Sreekumar, Wittig, Sheehan, & Zaghloul, 2017). However as the user is not involved in this process, this is not an ability they themselves can regulate (unless of course the designer has given them such control over the system's functions). Furthermore, the augmentation of the individual is entirely dependent on the system, as users are not taught how to regulate cognitive activity though system use due to its regulation being a passive ongoing process. As such, if the system were to be removed, the benefits it provides would slowly fade away, rendering the user lesser without the system in contrast to with the system. This is in contrast to psychonautic systems, in which the system teaches the user cognitive regulation skills they can then perform without the system.

7.2.4.1. Design Opportunities

The opportunity provided to designers creating systems in this quadrant is to help users extend or enhance their neurocognitive capabilities. With the potential for these technologies to become not only wearable, but implantable in the very near future, this implication goes beyond simply providing users with empowering tools. Rather, users are provided with a potentially permanent passive enhancement to abilities and skills such as learning, reaction times, attention, information processing, and memory for as long as they use the system (Kadosh, 2014; Looi et al., 2016; Sreekumar et al., 2017). While this has obvious benefits for clinical applications such as the treatment of epilepsy, dementia, and parkinson's disease, these systems can go beyond therapy by enabling healthy individuals to passively become their better selves with little to no training, all the while perceiving this enhancement to be their own endogenous abilities.

7.2.4.2. Design Challenges

The challenge faced by superhumachine systems is that the extended abilities provided by such systems might become part of the user's perceived self. As such, if the system is removed, the abilities it provided will eventually subside. Consequently, users may feel lesser, or no longer feel themselves with the system's absence. The design challenge in this quadrant is similar to the design challenges that face the "super body" user experience in Mueller et al's. "bodily integration framework" (Mueller et al., 2021).

7.3 Applying the Brain-Computer Integration Framework

This section describes how the brain-computer integration framework can be applied to describing and modifying the three prototypes presented through this thesis to demonstrate how the framework can be used in design practice (summarised in table 10). The three systems support a variety of application domains and employ different technologies (all the while maintaining the commonality of a focus on BCI as part of the system). This demonstrates the general applicability of the framework to most types of BCI systems.

Table 11. The three systems and their characteristics.

System	**Technology**	**Application**	**Aim**
Inter-Dream	BCI + VR	Sleep	Facilitate healthy pre-sleep
Neo-Noumena	BCI + AR	Communication	Augment emotion communication
PsiNet	BCI + tES	Synchrony	Amplify inter-brain synchrony

7.3.1 Design Example 1: Inter-Dream

Inter-Dream is now examined through the brain-computer integration framework to clarify the advantages of the design while also articulating opportunities to extend Inter-Dream.

7.3.1.1. Explaining Inter-Dream through the framework

Inter-Dream is situated in the Psychonaut quadrant of the design space. Inter-Dream allows users to experience their own brain activity through a hermeneutic relation as semiotic information. This provides the user with objective feedback about their subjective states that they can attenuate to in order to infer knowledge about themselves they would otherwise not have access to. Furthermore, this feedback dynamically changes as their subjective state changes in response to their appraisals of the semiotic representations of their brain activity, creating an ever shifting feedback loop. This puts the user in a position in which they can objectively explore and learn about their own subjectivity, and even regulate their brain activity if they choose to do so. Furthermore, the Inter-Dream user experience is highly egocentric. The user is almost completely cut off from the outside world: VR obscuring vision beyond their neurofeedback, auditory sensation occupied by the ambient score, and even proprioception being obscured to some degree by the weightless sensation provided by the bed. The only causal influence on the system other than the user's brain is the occasional shifting of the bed's position by the artists. Interestingly, participants found that elements of the experience that were under control from external influences to be intrusive to the experience overall (specifically the bed and the score), which at the time led me to infer that all dynamic elements of the experience should be designed to be neuro-responsive.

7.3.1.2. Extending Inter-Dream through the framework

In using the brain-computer integration framework, one can envision moving Inter-Dream from the Psychonaut quadrant to the swarm quadrant, where the system has a more allocentric distribution of agency. The conceptualization of this movement allowed to develop Inter-Dream's follow up project, Neo-Noumena, which takes the artistic generation of semiotic information from brain activity and turns this outward to other users through AR. As such, rather than being disconnected from outside interference like Inter-Dream, Neo-Noumena was more open to situational influences, with digital representation of brain activity being accessed in and interacting with the material world. This allowed users to access gestalt information about the group, the environment, and the influence of the environment on their group. While Neo-Noumena's application domain was emotion communication, we can imagine an allocentric inter-dream in which the gestalt brain activity of themselves, and perhaps a partner they are sharing the bed with, is visualised and projected onto the roof. This would allow them to interpret their joint brain activity as they fall asleep hermeneutically, while also being situated enough to interpret how environment factors might interact with this physiological process (e.g., a notification on their phone triggering a beeping noise might be followed by a change in the visualisation).

Alternatively, one can envision Inter-Dream being designed for the superhumachine quadrant. In keeping with the application domain of sleep, an example of a superhumachine-type Inter-Dream version might take the form of a wearable BCI system. This wearable would detect if the user was becoming sleepy based on an increase in delta wave amplitude. In detecting this, the system would then employ some form of stimulation to increase the entrainment of slow wave brain oscillations, thereby making the user even more sleepy, helping them fall asleep quicker. This could be done through a neuromodulatory technology such as tACS, or even through mechanically stimulating the olfactory epithelium with slow bursts of air (Piarulli et al., 2018). Alternatively, the system might also be able to tell if the user does not want to go to sleep (e.g., there is a growing delta wave amplitude but the user's brain activity also demonstrates high levels of cognitive load, suggesting they are working). In such an event, the system might stimulate their frontal lobe with a high frequency stimulation to help them stay more alert.

7.3.2 Design Example 2: Neo-Noumena

Neo-Noumena is now examined through the brain-computer integration framework to clarify the advantages of the design while also articulating opportunities to extend Neo-Noumena.

7.3.2.1. Explaining Neo-Noumena through the framework

Neo-Noumena sits in the swarm quadrant of the framework, yet its degree of allocentrism oscillates depending on the actions of the user. For example, Neo-Noumena could be used individually, with the system providing a situated visualisation of the emotional state. However, as the visualisation is situated, interacting with the environment to a similar degree as it interacts or is changed by its user, the system is still allocentric enough to not be considered psychonautic (or perhaps just on the border between the two). However, when another user enters the experience, the distribution of agency shifts greatly toward the allocentric end of the spectrum, as the visualisations now not only interact with the environment, but interact with each other and the perceptions of the group witnessing its brain activity as a gestalt whole. This provides users with the opportunity to interpret information about the group that is not readily accessible when the semiosphere is populated by a single individual (with semiosphere being an abstract epiphenomenal space in which physical, energetic and material phenomena interact as informational signals).

7.3.2.2. Extending Neo-Noumena through the framework

In using the brain-computer integration framework, one can envision moving Neo-Noumena from the swarm quadrant to the hivemind quadrant, where the system transmits information engrammically rather than semiotically, allowing for a higher degree of neural congruence between users in the group. The conceptualization of this movement allowed to develop Neo-Noumena's follow up project, PsiNet, which uses neurostimulation to synchronise the brain activity of users in the group, rather than generating visualisations to communicate activity. The original design of Neo-Noumena afforded a hermeneutic relation with the system, in which users had to actively engage in the cognitive task of attenuating to semotic information, and then applying their cognitive schemas to extract meaning from it and make sense of it, allowing to appraise it objectively. However, in PsiNet, changing the information from semiotic to engrammic afforded a fusion relation, in which users no longer actively engaged in the extraction and interpretation of information objectively, but rather subjectively and passively experiencenced the brain activity of other users with a high sense of ownership, as if it were their own brain activity.

Alternatively, we can envision moving the system back toward the psychonaut quadrant, albeit keeping the application domain of emotion communication to avoid it becoming Inter-Dream again. Such a system might take the form of a virtual garden or ecosystem, which represents the user's emotions semiotically in the form of parameters within that ecosystem. As the user experiences certain emotions, elements in the ecosystem might change (e.g. more sun when they are happy, rain when they are sad, increased predation when angry, etc). Thus, if the user maintains a healthy emotional balance, they would expect to see a healthy and thriving ecosystem. A wearable may track the emotional state of the user throughout the day, allowing the user to come back to the virtual environment at any time to "check up" on their emotional health. They may also be able to share this environment with others, allowing them to explore that user's emotional state as a visitor, but not change it (thus keeping it in the psychonaut quadrant).

7.3.3 Design Example 3: PsiNet

PsiNet is now examined through the brain-computer integration framework to clarify the advantages of the design while also articulating opportunities to extend PsiNet.

7.3.3.1. Explaining PsiNet through the framework

PsiNet sits in the hivemind quadrant of the framework. Agency is distributed allocentrically throughout the group, with each group member having an equal opportunity to influence the brain activity of the group. Furthemore, due to the absence of centralisation, the system is scalable, with new users being able to leave and join the group without disrupting equilibrium in the distribution of agency. Furthermore, as the system works passively (i.e., the user is not required to expend cognitive effort or attention to receive information from it), users are free to engage with the environment, adding another channel of influence over the group's collective brain activity. The system also exhibits a high degree of neural congruence, with an oscillation pattern in one person's brain leading to the actuation of that same oscillation pattern in another person's brain. As this information is transmitted engramically, it produces a fusion relation between users, ultimately allowing them to experience each other's brain activity subjectively with a high sense of ownership.

7.3.3.2. Extending PsiNet through the framework

The design space can now be used to help envision alternative versions of the system. For example, we can envision an alteration placing the system in the superhumachine quadrant, in which a single master user has their brain activity sensed by an EEG, and all other users are synchronised to that individual via tES. In turn, the agency of the system is centralised in the master user, being the only one able to have genuine cognitive experiences. In contrast, the brains of other users will be enslaved to feel what the master user is feeling, in a sense becoming "possessed" by the master user. Frighteningly, given that the insights from the study of PsiNet suggest that individuals experience altered brain activity with a high sense of ownership, users with enslaved brains might not even realise they are being manipulated (besides the obvious fact that they are wearing a mind-altering wearable). This would be particularly problematic in the cases in which the system's neuromodulatory capabilities were obfuscated by being incorporated invisibly into a hat or bike helmet for example. Furthemore, with sufficiently advanced brain stimulation, it is possible that such systems might result in the master user imprinting their "self" onto the enslaved users, with the enslaved users experiencing a high sense of ownership to the master's brain activity wherein they ultimately believe they are them. This would in effect clone the master's consciousness, making copies of themselves, similar to agent Smith in the Matrix trilogy.

Alternatively, there are several existing examples of systems which represent what PsiNet might be like after being moved toward the swarm quadrant. One of these is the game "SocioPathways" (Nijholt, 2019). In SocioPathways, players are represented as dots on a screen, with the closeness between dots representing the degree of inter-brain synchrony between those two players. As the players' brains become more synchronous, their dots draw closer. This process continues until the brains of the group converge on a singular synchronous oscillation and all the dots move into a singular large clump. To achieve this, players can engage in a number of different activities in an attempt to synchronise, such as subjecting themselves to the same environmental stimuli, staring into each other's eyes, dancing, or doing repetitive movements.

8 Design Strategies

While the framework can be used to *descriptively* provide a taxonomy of the possible user experiences afforded by brain-computer integration systems, it must also be considered how the framework can be used *prescriptively* to elucidate how designers can evoke these experiences. Therefore, I now present a set of strategies which designers might benefit from when developing brain-computer integration systems. These strategies are informed by my own experience in designing, developing, deploying and trialling brain-computer integration systems. Furthermore, these strategies are also grounded in my own studies evaluating these systems. Taken together, my research insights and craft knowledge have synthesised into the following strategies (table 11). Three strategies focus on neural congruence, an additional three on distribution of agency, and a further two strategies concern the design of BCI integration systems in a more general light.

Table 11. Eight design strategies

Dimension	Title	Strategy
Neural Congruence	Exploration	Consider procedural generation to facilitate exploration
	Continuous	Consider continuous codings rather than categorical codings
	Perceptual transparency	Consider designing for perceptual transparency
Distribution of Agency	Centrality	Consider maximising centrality for egocentric experiences
	Spatiotemporality	Consider how data is actualised spatiotemporally
	Social Context	Consider social context
Integrated BCI in General	Learning	Consider fostering ongoing integration through learning

8.1 Consider procedural generation to facilitate exploration

BCIs provide users with a powerful means to learn about themselves and develop a more nuanced understanding of their brain activity, and the complex thoughts and feelings it drives. Semiotic encodings of brain activity fed back to the user provide a medium to explore the mind through informative or metaphorical codings, and the stories these codings generate through the brain's dynamically reactive and ephemeral processes. However, as these representations, metaphors, and narratives typically require a designer to design them, the array of forms these representations can take are limited to how many hours designers are able to spend creating content for each given state. This in turn either limits the permutations of outputs a system is capable of generating, or leads to designers creating very simple representations in order to communicate varied information efficiently (e.g. associating emotion with colour or using graphs and charts). As a result, the explorative affordances of these systems can often suffer from a deficiency in depth and breadth of explorable content, limiting the user's engagement and learning potential.

To avoid this limitation, designers should consider incorporating procedural generation in the design of BCI output to facilitate exploration. Procedural generation is the method of creating digital content algorithmically as opposed to manually, typically involving the employ of mathematical parameters and some degree of stochasticity to guide the modification of designer-generated content into entirely new and unexpected forms (Freiknecht & Effelsberg, 2017; Greuter, Parker, Stewart, & Leach, 2003; Greuter, 2008; Raffe, Zambetta, Li, & Stanley, 2015; Raffe, Zambetta, & Li, 2012; Short & Adams, 2017). This is a common strategy in video games in which exploration is a core gameplay mechanic, as new and varied content invites exploration from users, procedural generation provides a breadth of experience far more expansive than what can be hand-crafted by a designer (Ito et al., 2017; Raffe et al., 2015; Short & Adams, 2017). For example, the game "No Man's Sky" places players in a universe containing 18 quintillion fully explorable planets which are generated as the player discovers them, each with their own unique terrain, weather, flora, fauna, and even alien civilisations for the player to explore (Tait & Nelson, 2021). Taking inspiration from such applications of procedural generation, future BCI designs could facilitate deep self-exploration through the generation of detailed and expansive content generated by dynamic brain-data-fed algorithms.

However, procedural generation does not necessarily require the complexity of a universe simulator to benefit the design of BCI systems. For example, consider Neo-Noumena, whose application domain of emotion communication imposes the tradeoff of a need for complexity to adequately express the user's emotion, while also requiring simplicity enough for the recipient to effectively interpret it without overloading their senses. Here, rather than generating universes, procedural generation was employed to subtly assist the semiosis of emotion between individuals. For example, the procedurally generated behaviour was given to the fractals to give the fractals an added extent of emotional expressiveness through their movement. Specifically, the fractals were programmed with "boids" behaviour (Hartman & Bene, 2006), which procedurally-generated movement in a group of agents ultimately simulating flocking behaviour of birds. Here, the brain activity of the user was fed into the parameters of the boids in order to change the fractals' movement behaviour based on the user's emotional states. These movement patterns were not manually animated, but rather procedurally generated from user brain activity. Similarly, the fractals representative of user emotions were generated by information extracted from the user's brain activity, in turn representing the user's emotion through the symmetry and geometry of the fractal. Thus through the example it is demonstrated that brain-driven procedural generation need not be limited to the creation of expansive vast universes for the individual to explore, but also in the creation of simple but unique semiotic signifiers for applications such as communication. Nonetheless, these are examples of procedural generation that can serve as a method to drive the exploration of both the self and others, and as such I suggest designers consider procedural content generation to facilitate exploration.

8.2 Consider continuous metrics for more nuanced output

Coding brain activity into categorical classifications (e.g. designating a given set of brain data as "sad", "relaxed", "awake", etc.) comes with some advantages when designing a BCI system. Categorical codings allow BCI designers to develop a fixed amount of discrete and hence predictable outcomes, making it relatively easy to curate the resulting experience of every system state permutation. For users, this comes with the added benefit that the output of the system is easily interpretable and associable with single word categories that can compress a lot of information into a single code. However, there are also significant tradeoffs. I found through the studies of this thesis that participants interpreted categorical classifications as authoritative and objectively correct. For example, even though Neo-Noumena's classification accuracy was around 56%, participants always interpreted the system's output to be the objective truth, even rationalising classifications they found inconsistent with how they were feeling by reasoning that it was they who were wrong, that they were perhaps not in touch with their inner selves, and that the system was correct.

This aligns with the fact that others within HCI have stressed the importance of refraining from designing categorical feedback for biofeedback systems due to their oversimplification, arguing that it may lead to the “calculability of human subjectivity” quantizing the individual into information for psychographic models through which individuals can be digitally categorised against their best interests (Stark & Crawford, 2015; Stark, 2018). Considering this, it has been suggested that rather than designing for discretely classified presentations of BCI activity, designers should instead consider ambiguous representations that allow the user to form their own meaning (Howell, Devendorf, et al., 2018). However, the proponents of this argument push this direction perhaps too far in suggesting that there are no such things as brain states. The postulation of the denial of states in biological systems runs contrary to the contemporary understanding of human physiology (DiStefano, 2015; Palsson & Abrams, 2011). For example, recent discoveries in neuroscience point to clear states, boundaries, and transitory tipping points in between, which characterise the dynamics of networks of brain structures and their functions (Gautam et al., 2015; Meisel et al., 2015; van de Leemput et al., 2014). Proponents against a stateful approach to physiological activity sometimes also advocate against the computational processing of biodata, suggesting this should be left to the human decoder (Howell, Devendorf, et al., 2018). This approach is particularly non-progressive in the context of BCI, where it is often the case that much of the informative content of a given physiological signal is embedded in its frequency component, or in some other extra dimensional geometry of the signal that is not accessible in its time series form (Vaid, Singh, & Kaur, 2015). Thus, such an approach would limit BCI to pre-1960’s capabilities, where the height of neurotechnology were machines that spat out batches of paper with scribbled lines which took teams of trained neuroscientists weeks to decode by visual inspection (Shipton, 1975).

With these points considered, I suggest designers adopt a more nuanced approach to dealing with brain state classification, rather than refraining from classification all together. Specifically, I encourage designers to consider that the brain is a highly dynamic networked system, and that the recognition of any given state is highly dependent on the frame of reference and the question being asked. In practice, I suggest that designers consider translating categorical classifications to continuous metric predictions (a brain-derived metric that is represented as a continuous variable rather than a categorical variable). Rather than classifying if someone was “sad” or “happy”, the system could provide a normalised dynamic happiness quotient that rises and falls based on the valence of the user (rather than switching a binary category). Similarly, in the case of a system designed to interpret someone’s state of consciousness, it may be more helpful to derive a continuous metric describing their state of consciousness on some sort of scale (e.g., like using the metric of integrated information “phi” (Tononi, 2010)) and using that to drive representation generation or neurostimulation, rather than using the outputs of “awake” or “asleep”. Such an approach would increase the ambiguity of the output, whilst also increasing its informativeness, thereby avoiding the absolutism, oversimplification and technological determinism that comes with a categorical approach. Thus, to facilitate more nuanced output in BCI integration systems, I suggest designers consider adopting continuous metrics.

8.3 Consider perceptual transparency to support high neural congruence

Low neural congruence does indeed have advantages. Abstracted semiotic representations of brain data promote hermeneutic human-technology relations in which the user can access subjective experience as objective information, meaning that these systems necessitate the user cognitively engaging in the process of extracting information or meaning from the representation of brain data, being filtered through the user's appraisals, biases and past experiences.. This allows users to extract easily interpretable and actional information from coded brain data. However, this comes with the cost that using such a system requires the user's attentional resources, adding to the ever growing ecosystem of displays, apps, and notifications that compete for our attention. This is particularly the case for semiotic information communicated visually, as vision is a channel already heavily occupied through our interactions with the world (Arakawa & Yakura, 2021; Beattie, 2020a, 2020b). Other works in HCI suggest that people engage in bodily activities such as sports and physical exercise to unplug from or escape the "always on" and constant connectedness afforded by contemporary pervasive media (Mueller & Young, 2018). However, as integration systems lend themselves to being designed to always be on the user (Mueller et al., 2021), integration BCI's with low neural congruence would make this escape impossible, as the body itself becomes a channel for pervasive media to manifest in the user's life.

In contrast, high neural congruency afford the design of BCI systems that allow for unplugging, whilst still being connected, as brain-computer technology integrates into the brain's pre-reflective endogenous processes, freeing up attentional bandwidth and facilitate fusion human-technology relations. To do this, I suggest to consider designing interfaces with "perceptual transparency" (Mueller et al., 2020). This involves the communication of information through artificial sensory experiences (Mueller et al., 2020), borrowing parts of the user's body for input and output (Lopes, 2018), and exploiting psychological phenomena such as intentional binding - strategically timing the reaction of the system to a user's biophysical output to create the feeling the action was congruent with their intention - (Danry et al., 2021), to ultimately intertwine the user and the technology for seamless bilateral information exchange without the necessity for attenuating to the system's output. Ultimately, the use of a BCI system with high neural congruence should feel as if the user is not using technology at all, but rather performing mundane bodily processes that are as unconscious as, for example, breathing and digestion. Such processes do not sit at the forefront of perception, competing for the user's attention, but rather are so integrated with the body that they are in essence what defines us as living entities.

One example of this in action are people with magnetic implants, who's brains have adapted to perceive magnetic fields as though it is an endogenic ability rather than a technologically afforded novelty (Doerksen, 2017). Studies of the nervous systems of these individuals demonstrate that the body physically incorporates the input of these implants directly into its self schema, undergoing synaptogenesis and innervation to accommodate for this new sense (Doerksen, 2017; Strohmeier & McIntosh, 2020). Another example is the work of neuroscientist David Eagleman, who designed a haptic vest that leverages the largely unused real estate of the user's back to communicate auditory information through haptic vibration, allowing deaf people to understand speech (Eagleman, 2020). Similarly, the cyborg Neil Harbisson is implanted with an artificial sensory device that allows him to perceive colour through intracranial neurostimulation even though he is colour blind (Harbisson, 2018). Neurological studies have demonstrated that his brain has learnt to integrate this information into his physiological processes as if this were the endogenous input of colour information from auditory receptors, which phenomenologically allows Harbisson to experience colour as sound, rather than vibration (Kadlecová & Krbec, 2020).

Therefore, taken together, I suggest designers of integrated BCIs striving for a high degree of neural congruence consider perceptual transparency.

8.4 Consider maximising centrality for egocentric experiences

Moving a BCI system toward a higher degree of egocentricity is not solely a matter of designing solitary experiences or single user systems. While this is indeed a factor which may influence how egocentric a given BCI system is, this is not enough on its own. Rather, designers should consider how strongly connected elements of the system are to the user intended to be the "ego" in the egocentric experience. That is, designers should consider maximising centrality when designing egocentric systems. To do this, designers should strive to minimise the influence of externalities, confounding, or extraneous variables on the processes of the system, especially in the coding and generation of the system's output. At the same time, designers should also strive to make all other components of the system highly reactive to the brain activity of the "important node" of the network - the central user. This should be apparent to the user or observers to the degree in which the system obviously fails to function if it is not being fed the brain activity of the central user.

In the study of Inter-Dream, participants reported feeling that elements of the experience that did not respond to brain activity detracted from the experience, specifically noting that they found the movement of the bed and the music discordant or intrusive as those elements commonly stole their attention while they puzzled over weather they could control these elements or not. At the same time, the user experience of Inter-Dream was designed to draw attention to the neuroreponsivity of the system through the careful design of the user's journey in interacting with it. When participants were introduced to Inter-Dream, the system was running, albeit in a static state due to the absence of input. The visualisation was still and lifeless, an unmoving sphere. However, as soon as the EEG was fitted to the participant, the visualisations came to life instantly and explosively, often followed by an exclamation of excitement from the participant. Here, the neuroresponsivity of the system was made obvious though demonstration of how much the presence of the participant's brain activity influenced the system.

Initially, these findings from Inter-Dream lead to consider that it was of utmost importance for BCI systems to provide users with a high sense of individual control, with demonstrable neuroreactivity and a high degree of responsivity. However, in later studies, I found this property to be increasingly less important the more allocentric the distribution of agency was. For instance, during the development of Neo-Noumena, I encountered a bug in which the fractals swarms would leave their users and instead join together in the middle of the room when a pair of users were experiencing the same emotion. I opted to keep this as a feature, appreciating the visual metaphor of unity and oneness the display communicated, which participants also found equally appropriate despite the lack of control over the flocks that came with it. Similarly, individual control was further relinquished in PsiNet: control over the analysis of inputs and choice of output is ultimately given to the reinforcement learning agent managing the group's stimulations. This dynamic ultimately allowed participants to feel like each had an equal contribution of agency in the group, rather than a sense of unease or discordance, as I would have originally assumed from the findings of Inter-Dream alone, demonstrating that emphasising centrality becomes less desirable as the system becomes increasingly allocentric. Thus, I suggest that designers consider maximising centrality for egocentric experiences

8.5 Consider how data is actualised spatiotemporally to better facilitate the intended distribution of agency

Regardless of the distribution of agency in a BCI integration system, the *spatiotemporal actualization* of brain data - how information changes (or does not) over time and how it is manifested in the world - was found to be consistently important to how users interacted with brain data throughout the studies. In actualising brain activity into the world either semiotically or engrammically, it becomes subject to interaction with other properties such as location. Furthemore, if this information can be revisited, either by its creator or an observer. This thereby alters the way it is interpreted, thus highlighting the influence of time. Taken together, these properties of space and time can ultimately dictate or modify how a user interprets the actualised brain data, while also providing unique affordances for the embedding of additional information in actualised brain data specific to those spatiotemporal conditions. In the study of immersive analytics, this property has been referred to as “situated” data (Ens et al., 2021). However, *spatiotemporal actualisation* of integrated BCI data tends to go beyond the boundaries of situatedness as described by immersive analytics, in that BCI data can also be situated within the biology, or physiological processes and rhythms of a user’s brain, particularly when information is actualised engrammically.

With this said, I suggest that designers consider the spatiotemporal affordances of the application domain when designing an integrated BCI. For example, Neo-Noumena could be rebuilt to be a BCI-powered, neuroreactive, automated version of the review system Yelp. In this variant, the brain data of the users, specifically measures of valence, could be sensed and then communicated to other users in and around the restaurant they are dining in, which then other users can interpret to help choose a restaurant to eat at while they browse the city by interpreting the BCI output of other users while also noticing what restaurant they are eating at. Furthermore, the BCI output of diners could remain in the space they were dining at after they leave, and remain there over time, similar to how Yelp reviews are not taken down after a given length of time but are instead persistent and added to a pooled aggregate of reviews. Taken together, the strategic *spatiotemporal actualisation* of brain data in this context has ultimately reproduced enhanced decision making processes found in nature, like how ants use the pheromones of explorers from the same colony to better inform themselves of where good sources of food are.

Designers could also take advantage of the contextual information of the application domain itself, and its interaction with neurophysiological processes, to further capitalise on this. For example, it has been well documented that smell is strongly connected to the formation of memory, emotion, and also the experience of taste. With this considered, in returning to the aforementioned Yelp-like BCI system, it would make sense to use olfactory stimulation as the information communication medium of this specific BCI integration system. As smell is strongly related to emotion, the BCI valence readings of diners would cause the interface to produce positively or negatively valenced smells. Due to the connection between smell and memory, other users passing by will have either positive or negative experiences autonomically recalled when passing by the olfactory output of other users dining, producing a strong reaction in the brains of the observers. Furthemore, as smell interacts with the perception of taste, diners could have their eating experience augmented positively or negatively by the output of co-diners, leading to a powerful feedback loop in which the valence of the food items being served are strongly reinforced in proportion to the number of people eating in that given space. With this in mind, it is evident the amount of interplay between the brain and the environment the system permits greatly influences the resulting user experience the system can produce. Controlling the impact the environment can have on the user's brain (e.g. by blocking out sound and vision) would limit the amount of impact the environment can thereby have on the resulting user experience, pushing the system toward an egocentric distribution of agency. Conversely, opening up the system to environmental influences (e.g., brain data controls the behaviour of a robot which also interacts with the environment autonomously) pushes the system toward an allocentric distribution of agency. Thus, I suggest that designers consider how data is actualised spatiotemporally to better facilitate the intended distribution of agency.

8.6 Consider how social context can enhance the BCI experience in games and play

Similar to how time and space are influential on the interpretation of BCI data, social context is also particularly impactful. As the human brain is constructed to extrapolate inferences about the state of the world through interpersonally oriented neural processes like empathy and social comparison, interpretation of a BCI output is highly influenced by the social context it is appraised within (Gerber, 2020; Valencia & Froese, 2020). For example, users of Neo-Nomena were able to determine if other players were dealt good or bad hands while playing a card game based on their emotional output; and users of PsiNet reported feelings of cooperatively distributing cognitive processing abilities across group members when playing a videogame together. With this in mind, I suggest that designers consider the social affordances of the application domain they are designing for, and how these social activities can be used to enhance the BCI experience.

One application domain that would particularly benefit from this is that of games and play. While the potential for BCI as a gaming technology has been explored to some depth (Kerous, Skola, & Liarokapis, 2017), a review of the relevant literature reveals that the role of the BCI in such explorations is usually limited to that of a game controller, most typically in a single player experience. However, rather than their traditional role as a controller, I propose that BCIs in a social gaming context could instead fulfil their potential as channels of communication between players, or in-game systems (such as game-world game-states). From this perspective, one could imagine a game of charades where the subject matter is hinted exclusively though BCI output, or a team strategy game where team members are neurostimulated with enhanced concentration if all other team members are concentrating, encouraging participation. Alternatively, one could also imagine a variant of Monopoly, a game notorious for triggering fits of rage. In this variant players could be given the impossible task of trying to not upset any of the other players (detected by the BCI), as this would trigger a “game over” for all, leading to play strategies which oddly contradict with the central aim of the game. Thus, I suggest designers consider how social context can enhance the BCI experience in games and play. Furthermore, while play presents a promising social context based on the findings of this thesis, it is also anticipated that these affordances will be translatable to many social applications in general. One notable context that represents a promising opportunity for further exploration is that of VR social spaces (such as VR chat) which have recently exploded in popularity, partially in reaction to extended isolation brought on by COVID-19.

8.7 Consider that the user and the system must learn together in order to work as an integrated entity

A key part of the integration between the human body and technology is the process the body takes in integrating the technology into the user's body schema (Maravita & Iriki, 2004). This is particularly prevalent in BCI, as BCI use is often a skill that the user must acquire over time to make full use of the system (McFarland & Wolpaw, 2018). This is a process that necessitates that the user learns to think differently to gain full leverage of the system’s affordances, which ultimately culminates in notable adaptive changes in neurophysiology and synaptogenesis. However, I suggest that this is only half the story, and encourage designers to consider how their BCI integration system can be designed to learn from and adapt to their users over time, reaching an understanding on how to better integrate with them. This is particularly important in the context of BCI as every brain is unique, making it difficult to design general purpose algorithms that are consistent between users (McFarland & Wolpaw, 2018). With that said, designers should be aware that BCI use is a skill that the user and the system must learn together.

One implementation of this is the use of machine learning to improve the system’s interpretation of brain activity. This is often completed as some form of supervised machine learning task and has been demonstrated to be very effective in applications in which the system has complete information, such as games (Hosseini, Hosseini, & Ahi, 2021; Lotte et al., 2018). However, this becomes challenging when the system has incomplete information, or no way to verify if what it is learning is in fact correct. One way to address this challenge would be to design BCI systems with contextually-aware computing capabilities in mind, allowing the system to associate brain activity of its user with their concurrent context and extrapolate patterns and inferences from that (Hübner, Schall, & Tangermann, 2020). However, another less explored approach that could be applied in tandem would be to have the system learn as an agent through reinforcement, being rewarded for helping the user achieve personal goals. For example, PsiNet exhibited this form of learning in that it was rewarded every time the group's neural synchrony increased, helping the system learn how it could best help its users become more synchronous. Similarly, an app by the neurotechnology startup "Neurosity" builds spotify playlists based on how long they can keep users in a flow state. Thus, in allowing the system to learn, both the user and the system can work together as an integrated entity to help each other achieve their goals synergistically.

9 Validation

I purport that the brain-computer integration framework can describe integration BCI systems and their associated user experiences, and prescribe design strategies to guide designers toward facilitating an intended user experience. In order to qualitatively evaluate the validity of this proposition, I conducted a validation workshop.

The choice of validating the framework qualitatively through a workshop was informed by previous work in HCI which conventionally employs design workshops for the validation of their frameworks (Khot, Hjorth, & Mueller, 2020; Mueller, et al., 2020). I acknowledge the framework may also be validated in other ways, and discuss this in the "*Limitations and Future Work"* section of chapter 10. Learning from these past examples and combining their approaches, I validated my framework through a workshop in which BCI experts applied the framework to ideate novel BCI system designs, and to then describe and modify the designs they generated for each user experience.

9.1 Workshop Methods

The following section details the methods employed in the validation of the brain-computer integration framework. The procedures of this validation workshop were approved by our ethics board.

9.1.1 Workshop Participants

The workshop cohort (*N* = *8*) consisted of participants who held previous experience designing brain-computer interface systems, including people from research and industry backgrounds. This included five identifying as male, three identifying as female, and none identifying as neither. Participants were recruited via email invitation through selecting known BCI researchers and practitioners in the Exertion Games Lab mailing list, as well as advertising the workshop on BCI related Slack channels and

Discord servers. To meet the selection criteria of being a person with "experience designing BCI systems", the prospective participant was expected to have at least one peer-reviewed publication if a researcher, an exhibited artwork involving BCI if an artist, and contribution toward a completed product or a product in production if an industry practitioner. The recruited cohort included four researchers, one artist, one industry practitioner, and two individuals who were both researchers and industry practitioners. Participants were not offered compensation for participation and most participated due to their desire to benefit from the knowledge the framework provided. However, some participants appeared to also be interested in turning the workshop's results into a publication, indicating some may have been incentivised by the possibility of publication.

9.1.2 Workshop Procedure

The workshop was structured as an asynchronous experience in which each participant self-directed their activities and completed them individually. Participants were given a timeframe of one week to complete their assigned activities, which took approximately 15-30 minutes to complete.

Participants were first instructed to familiarise themselves with the brain-computer integration framework through exploring an online interactive version of the framework at https://nathansemertzidis.com/brain-computer-integration/, which presented a condensed version of chapter seven. Subsequently, each participant was assigned their own application domain according to their research area of focus, although participants were also given the choice to pick their own application domain if they would rather not design for the allocated one. These application domains included: empathy (x1), smart cities (x1), neurorobotics (x1), making art (x1), mediation (x2), sports (x1), memory (x1), emotion (x1), and games (x2).

Participants were instructed to pick one of the four user experiences of the framework and then use the framework to design a BCI system that addressed their assigned application domain through the user experience they had chosen. Participants then sketched an illustration of their ideated system. Sketches were accompanied by a 100-word maximum description. Finally, participants were instructed to journey through the design space by making alterations to either the neural congruence or distribution of agency of their initial design until they had four alternate versions of their system - one for each of the framework's quadrants.

9.2 Workshop Results

Once participants had completed a sketch and a written description for each of their four BCI systems, their designs were submitted to me via email. There was a great variety of the designs produced, with many intriguing and creative applications, such as transcranial magnetic stimulation games, EEG thermostat meditation mats, neuro-reactive companion drone swarms, and many more. A sample of the designs can be found below in figure 23, and the complete corpus can be found at https://github.com/Nephron00t/BCIntegrationValidation.

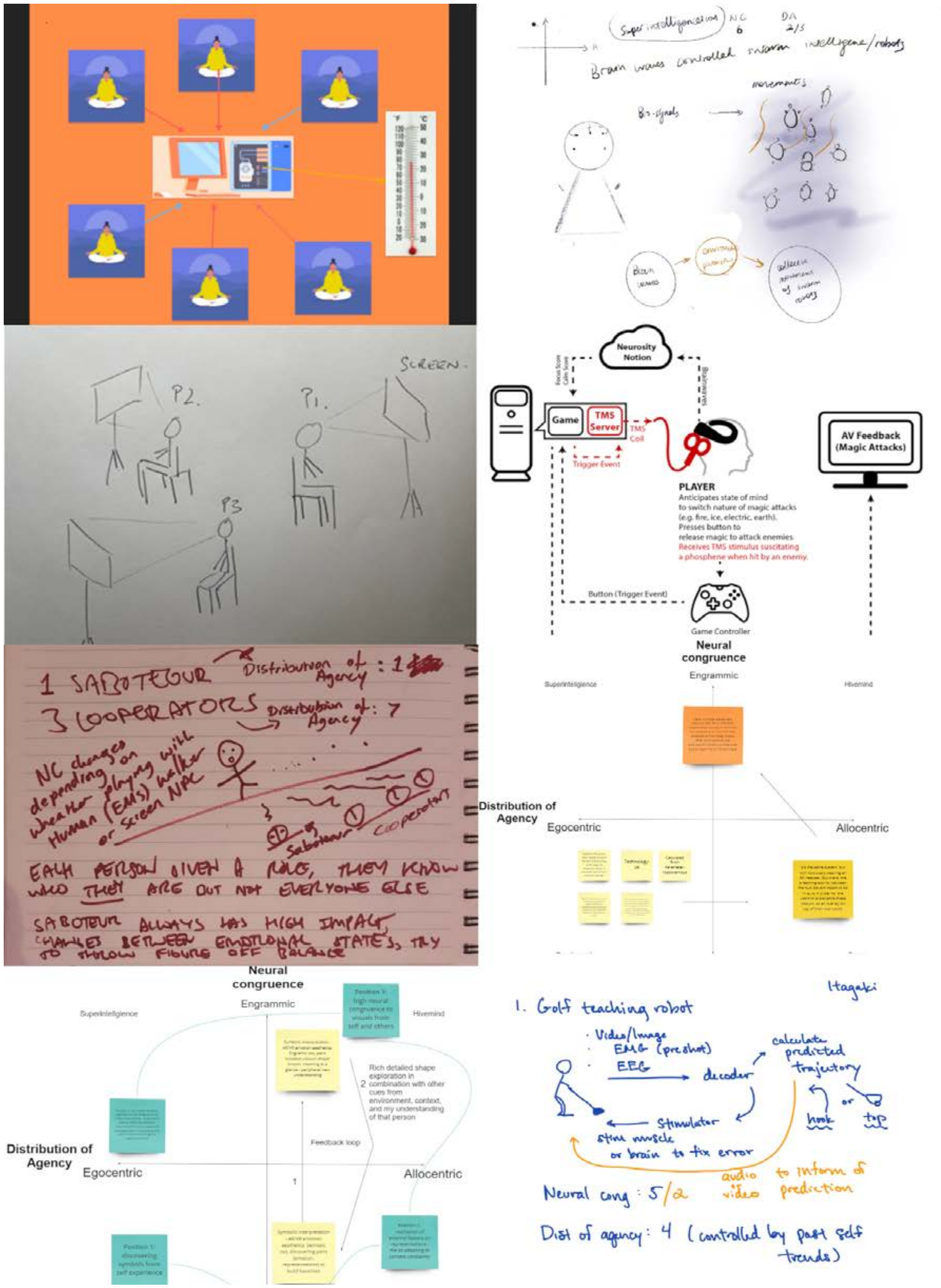

Figure 23. A sample of eight systems (one from each participant) designed using the brain-computer integration framework.

In total, 25 designs were submitted, including 8 psychonautic systems, 3 swarm systems, 3 hivemind systems, and 5 superhumachine systems. There were also three systems in between superhumachine and hivemind, and two systems in between psychonaut and swarm. Finally, there was a single system that was classified under all four UX's simultaneously, with the designer of that system pointing out that the UX moves through the design space depending on the user's familiarity with the system and the context they are using it in. The larger number of psychonautic systems was due to one participant misinterpreting the instructions, creating four variations of a system in a single UX quadrant with varying degrees of neural congruence and distribution of agency. In addition, one participant uniquely submitted a single design that involved all four UX's simultaneously (a turn-based BCI-driven board game). Participants typically illustrated their designs as system architecture flow diagrams.

Following the submission of their designs, participants were interviewed by me in order to provide a qualitative account of the validity (or lack thereof) of the framework based on their experience employing it. Interviews were completed individually for each participant via teleconferencing and lasted for an average of 10 minutes per participant. Interviews were semi-structured, with a script of questions that was iterated through by the interviewer (myself), while also allowing for participants to lead the direction of the content if they had something they wanted to say. The script of questions included the following:

- Were there any obvious differences in designing a BCI system with the framework versus without the framework?
- How did you employ the framework in the ideation of your system?
- Did the framework help you conceptualise and describe your design? If yes, how so?
- Did the framework help you conceptualise and describe the user experience of your design? If yes, how so?
- Did the framework help you make design decisions regarding the systems functions and architecture?
- Did the framework help you make design decisions regarding the system's intended user experience?
- Did you find any elements of the framework particularly helpful? If so, which and why?
- Did you find any elements of the framework to be incorrect? If so, which and why?
- Do you feel there is something missing from the framework, if so, what?
- If you had to make any changes to the framework, would you? And if yes, what?

To qualitatively evaluate the framework's validity in having descriptive and prescriptive power in regards to brain-computer integration and BCI design, interviews were transcribed and analysed through thematic analysis with these properties in mind. This involved the coding of transcripts in Nvivo and then iteratively clustering these codes (*N* = 11) into high-level groupings *(N=3)* which were inductively consolidated into three emergent themes: *descriptive validity, prescriptive validity,* and *suggestions for improvement*. The following section reports these themes with evidence from the transcripts.

9.2.1 Descriptive Validity

It was found that participant reports of using the framework confirmed the proposition that the brain-computer integration framework can be used to conceptualise and describe their integration BCI designs. Participants often attributed this to how the framework "*operationalised*" (P1) the "*factors*" (P2) important in integration BCI systems, and helped them recognise the user experience their design afforded, which ultimately "*helped* [them] *conceptualise* [their] *designs*" (P3). This became apparent when comparing their experience designing *with* the framework versus designing *without* the framework, with P1 stating: "*I guess when I designed previously, I wasn't literally thinking about what kind of experience I wanted to create for the user, especially in terms of it being operationalised. So especially in an operationalised way, like 'I want to give them this amount of agency', and also like the goals of the system, what I wanted for the user*". Similarly, P2 described how *"without this framework, I would think more of the functionalities of the system. But with this framework, I'm actually thinking more about the agency and the congruency".* Participants further stated that they: *"think these are two very important factors in designing these systems that I wouldn't otherwise think about explicitly when designing systems"* (P2), with the framework helping to "*outline these two design considerations"* (P2), which led them to consider "*would this experience be different for the users if I change one of the design factors?"* (P2). P5 also echoed this sentiment, stating: "*This framework gives you a much clearer idea of, 'oh, okay, so there could be this other possibility and this other possibility' bringing this qualitative experience to the user as well'. Not just the quantitative data then just trying to bring that in motion with engineering*".

Participants also appreciated that even though the framework created UX categories, the axes were still continuous, giving them a language to articulate their designs, with P1 stating: *"I appreciated the language. Something that frustrates me with other frameworks is that they're very categorical. But I appreciated the fact that this one has continuous axes. Which lets you say your system's in one of these quadrants, which is categorical, but at least you can put it more on the scale of...where that is".* This property allowed participants to make comparisons between their own designs and the general properties of systems in the UX quadrant they were aiming toward to better elucidate the categorical identity of their own design and thus predict what kind of user experience it could generate, with P2 stating: *"I first understood which category I was aiming for and thought about a possible user scenario for this potential category, and then I iterated, so for example, first I'd think that the experience fits into one category, but after some exploration, I would realise, 'oh, actually it fits in another category'"*. Other participants also voiced their appreciation for the new lexicon the framework provided, lamenting that "*there was no language to describe those things prior to the framework*" (P6). P6 further described how "*previously I didn't have any experiential terminology to think about when I was designing BCI systems.* [With this framework] *I actually have language that allows me to think of experiences that I wanted to design for, and then choose a particular space in which I can design my system"*. P5 described how this was particularly helpful in the design of BCI games, stating: "*I think that at least the symbiotic engrammic access is very important for me as a game designer. Because beforehand I was just thinking just about the semiotics of it. It's just the symbols back and forth, but when we start getting closer to the brain and stuff, just the interaction in between our interfaces, but also getting direct into the brain, getting information directly from and into the brain, then we have to start thinking about in engrammic experiences in and of themselves. So I think that opens a new avenue for me to think about"*.

Taken together, the participants found that the frameworks "*operationalised*" (P1) "*factors*" (P2) helped them design "*more complex*" (P3) systems. P3 stated that they were *"learning things while reading and understanding the framework"*, which in turn "*made me think more deeply about the design"*, stating that it gave them: "*more depth to work with, without having to do too much"* thanks to the *"X-Y axis"*. P1 similarly stated the framework helped them *"work out the complexity of the system"*. Participants also described how the framework allowed them to interpret and categorize systems based on the technology employed, with P2 stating: *"I can definitely see how different technologies could be located in different categories. For example, at the high agency and high congruence, I just automatically think about networks, like social computing and the cloud. It's obvious because of these two factors, and you can see different structures of the systems that you're designing for, and then the particular kind of technology that can suit these kinds of architectures."* Similarly, P8 stated: "*how you display the information determines what kind of technologies you're able to use, whether that's directly stimulating the brain or some muscle is completely different technology"*. In contrast however, other participants argued that the concepts generated by the framework were too abstracted to be tied to specific technologies, with P7 stating it was "*more abstracted to the user experience*" and P6 explaining that "*it was quite easy to shift the same sort of idea to various technologies across a quadrant and over time*".

9.2.2 Prescriptive Validity

It was found that participant reports of using the framework confirmed the proposition that the brain-computer integration framework can be used *prescriptively* through guiding participants in their design decisions, helping them achieve their desired user experience. P3 stated: "[the framework] *totally helped me make design decisions*", and described how "*it definitely allows me to articulate a reason for why I would make some of those choices* [...] *I looked at the framework and I wanted it to kind of 'sit within this kind of area' because that's where I felt it would be stronger. So I aimed it a little bit towards that, so it would place it in 'this part of the axis'"*.

Participants also explained that they employed the guidance of the framework iteratively, first ideating, then placing their design in the framework's design space, and then using the framework's axes to determine how to change the design to match their desired user experience, with P6 stating: "*I sort of compared what my idea was in relation to the idea that was already presented for that particular pattern. And then try to draw a parallel and try to design accordingly"*. P1 describes this process in detail, stating: *"You gave us a prompt. And then I just loosely thought of an idea. And then I came up with a first iteration of it and then I tried to match it to one of the areas. And then I didn't really like what I'd come up with. So it helped me iterate on that, develop the idea and also flesh it out a bit more. So that's what I did. I kept trying to think, okay, well, 'if this was giving more agency, how would it be?' Or 'if I wanted more people' and whatever"*. P3 also echoed this sentiment, stating: *"I kind of went off on an idea and then thought of the user interaction and then I looked back on it and thought 'where does that actually sit in the framework?' Rather than just trying to design exactly to the framework, I would start with an idea, go off on ideas and design, get into something that I think is going to make some kind of sense, and then refer it back and go, 'oh, what have I actually done here?' And then that gives me more insight to further design on it, to try and make it something which I could articulate as to where it sits"*. P7 also explained how they iterated through the framework to achieve their intended use experience more accurately, stating: "*you question: does it fit in this quadrant, or not? And if it doesn't, you can go to another quadrant or think about why it doesn't work. What can I do to make it work? So it becomes a restriction, but at the same time, that's a good restriction to have, because it allows you, it gives you some small parameters to play with. So then you can fine tune the system*".

Participants also reported that the framework allowed them to make technical decisions and resolve design trade-offs when designing their systems. For example, P1 stated that: *"I essentially realised that if you wanted* [the system] *to be more 'engrammatic', you needed a more sophisticated 'machine' side of it. Whatever* *hardware are you gonna be using, it needs to be better at interpreting whatever signal you're measuring. And then also your machine system needs to be a better classifier with more options* [...] *The level of complexity needs to be greater. And if you're looking for something more semiotic, I think it's kind of easier."* However, P3 disagreed with the frameworks propensity in guiding technological decision making, stating: *"Technically, I don't think it pushed me in a totally new direction because I was more concerned about the design and what it was trying to achieve than trying to do something super technical or super subtle in terms of technology or programming".*

9.2.3 Suggestions for Improvement

In addition to confirming the propositions of the framework's descriptive and prescriptive properties, participant responses also highlighted opportunities to further develop and improve the framework in the future. To begin with, some participants felt that reducing BCI systems to two factors was an over-reductionalisation. P2 stated: *"It's really hard to categorize all neural interfaces simply into four categories. So I guess that is one limitation of the model, as it over-simplified the variety of experiences, but I still appreciate this framework as it is, to my knowledge, the first attempt in categorizing and describing this kind of experience, which always starts off simplified."* Similarly, P1 stated: *"I guess you could add another axis... It could even take into account hardware and equipment, the portability of the equipment or how accessible it is. Like, can they build it themselves? Can they buy it easily?".* P8 also made the same suggestion, saying: "*maybe there could be a third or fourth dimension*". In contrast, P3 disagreed with this sentiment, stating: "*I didn't think it was* [oversimplified]*, I thought it was in-depth.* [...] *It was complex enough for me and complex enough that I had to read a little bit and then go: 'Okay. Yeah, I've got that'".*

Some participants discussed how a "time" dimension would be a good candidate for an additional dimension for the framework. For example, P7 stated that: *"One thing that was really useful about the framework for me thinking about time as another dimension in the framework",* further explaining that users "*could actually transit between the quadrants as they become more familiar with the system".* P6 described how this could be applied to a game for improving motor memory, stating: "*With my games, you kind of tend to get used to those games and the experience, the superhumachine experience that you're speaking about might not be so super intelligent after the period of time".*

In addition, quantifying the framework was suggested as a way of improving it. P1 stated that in addition to the framework's *qualitative* operationalisation, a *quantitative* operationalisation could be beneficial, stating: "*It would be good, I guess, to help* [designers and researchers] *think of how to evaluate literally. Cause you know, it's all* *very well to say like, oh, it's engrammic, but it's like, how do you know?*" Similarly, P5 questioned: "*So, but what about the gray areas, right? Am I really in a psychonautic space? Or am I getting to the superhumachine if I'm feeding information back into the brain?*" P1 also stated that a quantifiable operationalisation of the framework would allow researchers to benchmark systems: "*Some kind of scoring system would be the next step. To help you think it out and evaluate and grade the system for those qualities*".

Finally, some participants voiced how they felt if the framework were to be interpreted by non-academics, the language would need to be simplified. P5 described how this would benefit non-BCI specialist who still needed to develop for BCI systems, such as game designers as well as society in general, stating: "*I would keep the vocabulary as is for academic research and discussion, but I think that this integration framework would be very valuable for designers in the streets. So you may want to have a new version with simplified language It should not have a very high entry barrier so that everyone can just start thinking about these new axes and quadrants in a much more pedestrian way, which could start a larger dialogue, which would be very, very valuable for, for the society at large*" P6 and P7 both echoed this saying: "*The framework is useful to help the designer describe the user experience, but not for the user itself to understand the user experience*" (P6), and: "*There was just too many new words that made me think, like, I need to learn all these things, which is fine, but it kind of create a little barrier to start using it right away*" (P7).

9.3 Workshop Discussion

Taken together, the results above are confirmatory of the proposition that the brain-computer integration framework possesses descriptive and prescriptive abilities in regard to the design and evaluation of integration brain-computer interfaces. That is to say, the results qualitatively validate the framework. Specifically, it appears that with the establishment of two *"important factors"* (P2) of integration BCIs, participants are able to conceptualise their design in reference to the desired user experience. This is done through an iterative process, in which the designer or researcher compares the BCI system of interest to the framework's descriptors, conceptualising the design by projecting it onto the design space and inferring the resulting user experience based on its location. If their design is not in the desired location, the designer then adjusts neural congruence and/or distribution of agency until their system inhabits the area of the design space relating to their desired user experience. Results suggest that this is mainly accomplished through adjusting the technologies employed in the implementation of the system, the design of the system's architecture, and the number of participants the system is used by.

In addition, the results have highlighted the opportunity for further improvement of the framework. Namely, the framework stands to benefit from the identification of additional dimensions, or "*factors*", as the participants tended to say. It is expected that the framework's axes will continue to mature as more integration BCIs are developed and evaluated in the future, further adding to our understanding of brain-computer integration. In addition, the framework could be strengthened through quantitative operationalisation. This would allow a more objective evaluation of integration BCI systems, permitting researchers to quantitatively benchmark and compare systems on performance metrics of interest, helping the field produce better integration BCI systems, which will be discussed further in section 10.3 "*Limitations and future work*".

10 Conclusion

Through this thesis, I sought to answer the research question: *How do we design Brain-Computer Integration systems?* I have answered this question through the exploration of three case studies and the development, presentation, and analysis of three integration BCI systems and their resulting user experiences: *Inter-Dream, Neo-Noumena,* and *PsiNet*. In synthesising the results yielded from the evaluation of these prototypes, I constructed the Brain-Computer Integration Framework. This framework descriptively explains the user experiences afforded by BCIs, and prescriptively demonstrates how designers can develop systems to produce an intended user experience. Ultimately, it is intended that this framework contributes a theoretical basis through which theorists and researchers can discuss integration BCIs, while also providing practical guidance in the design of future integration BCI systems.

10.1 Research Objectives

In the introduction chapter, I presented a set of research objectives that would guide my pursuit in answering the central research question. Here I describe how I addressed these objectives.

10.1.1 Understand the interactions between brain activity and technology afforded by brain-computer interfaces, and identify opportunities for new knowledge presented by looking at these interactions through a human-computer integration lens

This objective was achieved through the literature review involving the critical analysis and discussion of related works reported in chapter two. In consulting existing theory and the works of those who had come before me, I was able to identify where our understanding within the context of these concepts was most lacking, and thus where I should begin in exploring the design space of brain-computer integration.

In reviewing the contemporary state of brain-computer interface research, I came to find that the most recent design framework was published in 2003 (Mason & Birch, 2003). In spite of this, I came to find technical research had progressed rapidly since 2003, vastly outdating the design framework. In addition to the rapid technical development of BCI technology, application domains both in terms of industry and research interests have also vastly changed from being largely clinical, to now being applied to a vast array of daily life activities and general consumer use cases (Hammond, 2011; Stegman, Crawford, Andujar, Nijholt, & Gilbert, 2020).

Furthermore, I found that much of the more theoretical literature surrounding BCI discussed how the technology possesses unique affordances that allow for complex interactions and intertwinings between the user's physiology and the system's processes. This included things such as altered and novel perceptions of agency, the tendency for the brain to change itself to better integrate the technology into itself, and the ability for the technology to dynamically modulate the user's state of consciousness, which reflexively and iteratively in turn perpetuated an alteration in how they used the device, or thought in general, exemplifying BCIs potential for powerful physiological feedback loops (McFarland & Wolpaw, 2018; Steinert, Bublitz, Jox, & Friedrich, 2018). However, while acknowledging these advances in the basic sciences of BCI, I lament that most contemporary BCI designs still design the technology in the capacity of a traditional command-response human interface, rather than cyberphysical systems with powerful feedback loops. I reason that this is due to the limitations of understanding BCI through a traditional lense of human-computer interaction and propose BCI should instead be understood through the human-computer integration paradigm, which accounts for machinic agency and bidirectional actuation (Mueller et al., 2021; Mueller et al., 2020), ontologically accommodating the complex cyberphysical mechanisms underlying BCI.

10.1.2 Develop an appropriate method of investigating the core research question.

Considering the literature critically analysed throughout chapter two, a research methodology was constructed considering the conventions in the fields that informed this thesis, being HCI, the neurocognitive sciences, and psychology. It was in adopting these research methods that I was able to address the multidisciplinary research question core to this thesis.

10.1.3 Explore the design space of brain-computer integration

Through the completion of the objectives above, three prototype systems were designed and evaluated through deployment and subsequent user studies. In turn, the design space of brain-computer integration was revealed through reflecting on each prototype.

10.1.4 Create a theoretical framework articulating brain-computer integration

Through completion of the above objectives, the brain-computer integration framework was synthesised, articulated in chapter 7. This framework emerged from the evaluation of all three case studies and their resultant findings, with the latter being analysed across case studies thematically. In chapter 7, this framework is presented descriptively, illustrating how it can be used to describe brain-computer integration systems. Further, in chapter 8, the framework is presented prescriptively, illustrating to designers how they could employ the framework to design for any user experience they are striving toward.

10.2 Contributions to knowledge

This work makes the following contributions:

1. This research contributes to design knowledge by documenting the design of three experiences of brain-computer integration, along with the insights gained from the process of their development and evaluation. The case studies and design prototypes demonstrate how brain-computer interfaces can be designed with human-computer integration in mind.

2. This research contributes to design knowledge and theory by extending the existing paradigm of human-computer integration to consider how technology can be integrated with the human brain to participate in, mediate, and modulate its underlying neurocognitive processes through brain-computer interfaces.

3. This research presents the brain-computer integration framework. It is the first theoretical conceptualisation of how to design for the integration of neurocognitive processes between humans, computers, and ultimately, other humans. The framework was derived through the synthesis of the findings of three case studies. Each case study consisted of recurring themes and functional mechanisms. These insights provided a high level understanding of the design space and possible user experiences of brain-computer integration, while also beginning to explain the functional mechanisms that allow for these documented user experiences to emerge. These themes also informed the articulation of design strategies, which ultimately inform designers in the development of brain-computer integration systems and how to achieve the desired user experience exemplified in the themes.

10.3 Limitations and future work

One limitation of this thesis is that the brain-computer integration framework has been articulated from a mostly qualitative perspective. While some quantitative methods were employed in the analysis of each of the case studies, this was mainly applied toward the validation of specific qualities of each corresponding proptype (e.g. sleep or inter-brain synchrony) rather than toward the establishment of the higher level concepts of the framework itself. The framework was synthesised through the combined thematic analyses of qualitative user interviews describing the experiential properties of brain-computer integration systems. Considering that this is a new and underexplored area of research, I argue that a qualitative approach was the correct path to take, as it has been acknowledged that qualitative research is particularly useful for theory building, especially in areas where little exploration has been made and there are no existing “strong concepts” (Dalsgaard & Dindler, 2014; Lynham, 2002). Nonetheless, given that this thesis articulates the brain-computer integration framework, there is now the opportunity to operationalise the framework such that brain-computer integration systems can, in the future, be evaluated though objective quantitative methods. For example, future work could explore how the axis “neural congruence” can be operationalised through information theory analyses (Dimitrov, Lazar, & Victor, 2011; Tononi et al., 2016), rather than this thesis’s approach of Verbeekian postphenomenology (Rosenberger & Verbeek, 2015). Similarly, the axis “distribution of agency” could be operationalised through dynamic network analyses (Bassett & Sporns, 2017), rather than this thesis’s approach of actor network theory (Latour, 1996; Tass et al., 2020). Furthermore, this transition of a quantitative rendition of the framework also brings the opportunity to use already existing terminology (e.g., such as terms from information theory, graph theory, etc.) to discuss the concepts presented. As a participant in the workshop suggested, the density of novel terminology present in the framework may be a barrier to entry; the adoption of existing terminology from well-established fields may be helpful in communicating these ideas beyond HCI.

Future work could also further contribute to understanding the design of brain-computer integration by expanding or extending the framework. It should be noted that distribution of agency and neural congruence are not the only factors present in the experience of brain-computer integration. For example, future studies may do well in understanding how crowd size specifically influences the experience of brain-computer integration systems. While such a factor has some overlap with the already present dimension of “distribution of agency”, distribution of agency is chiefly concerned with how causal actors interact within the system rather than sheer number of humans. Furthermore, it is also possible to deconstruct distribution of agency into two factors: “crowd size” and “free will”, the degree to which actions originate from the users own mind without outside influence (Mann, 2001), allowing for more nuanced expressions of combinations of agency and number agents. For example, this would allow for the design space to illustrate the experiential distinction between an individual acting on their own free will or not independent from their immediate social surroundings.

An additional limitation was the asynchronous and online-only nature of the workshop. This workshop format was chosen to the social distancing measures in place at the time of the workshop, as the workshop was conducted during a lockdown as a result of the COVID-19 pandemic. Furthermore, the asynchronous format was chosen to accommodate workshop participants engaging from a broad array of time zones. Nonetheless, these choices prohibited workshop participants from engaging with each other, which would have further enriched the results of the framework validation study through providing insight on how the framework can be used collaboratively to brainstorm and iterate system designs in groups. Future research may consider further contributing to the evaluation of the framework by assessing its usefulness in groups of participants.

Additionally, while each of the prototypes neatly fit in their own quadrant on the design space, there is one quadrant, namely superhumachine (high congruence and egocentric distribution), that does not have a representative prototype. In the framework chapter, I describe other systems that fit this category, yet also note that all current incarnations of such systems exist for clinical applications (usually in correcting epilepsy, parkinson's disease, or alzhiemers) (Tass et al., 2020). With this considered, the framework would benefit from a non-clinical exemplary system of this quadrant, which presents a clear opportunity for future research.

10.4 Final Remarks

Throughout this thesis, it has been difficult to express prosaically and impassionately the extensive, far-reaching, world-changing potential that I believe brain-computer interface technology possesses. Similarly, it has been difficult to address questions such as "what is the benefit of this?" or "what is the application?" without responding: "everything". Through the integration of the nervous system with the computational machine, we ultimately become ontological engineers, given the tools to design, not merely novel human-machine assemblages, but rather infinitely unimaginable new beings, ways of being, and things to become. I predict that as our brain further integrates with computers, we as a species will no longer conceive of concepts like mortality, life, time, space, the self, and consciousness like we currently do. Rather, we will be aliens of vastly unknowable ability and cosmic intellect, unrecognisable to our current selves. With that said, it pains me to see these technologies as they currently stand are regarded simply as novelty remote controls.

Nonetheless, I am optimistic that in my lifetime I will see my predictions begin to take fruit. Furthermore, it is my sincerest hope that the guidance I have provided through the contribution of this thesis, the research in it, and ultimately, my framework for the design of brain-computer integration, inspires researchers and the designers of future BCI systems to spur the progression of these technologies forward, and ultimately actualise the utopic futures they will inevitably lead to.

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