Temporal properties of consciousness

A thesis submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy

by

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Certificate

It is certified that the work contained in this thesis entitled **"Temporal properties of consciousness"** by **Ishan Singhal** has been carried out under my supervision and that it has not been submitted elsewhere for a degree.

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Declaration

This is to certify that the thesis titled **"Temporal properties of consciousness"** has been authored by me. It presents the research conducted by me under the supervision of **Prof. Narayanan Srinivasan**.

To the best of my knowledge, it is an original work, both in terms of research content and narrative, and has not been submitted elsewhere, in part or in full, for a degree. Further, due credit has been attributed to the relevant state-of-the-art and collaborations with appropriate citations and acknowledgments, in line with established norms and practices.

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Abstract

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https://cgs1.cgs.iitk.ac.in/user/ishan20/main.html Thesis title: **Temporal properties of consciousness**

Thesis supervisors: **Prof. Narayanan Srinivasan** and

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Are our experiences fundamentally idiosyncratic? And are the contents of human experience condemned to be private and inaccessible? If the answer to either of these questions is yes, then a science of human experience is not possible. Subverting this pessimism, this thesis took a minimal unifying model approach to consciousness. This approach prescribes identifying and describing properties of experience that are universal and those that can offer integration of current evidence. The present thesis is an investigation in the hunt for a minimal unifying temporal property that is universal in all visual experiences. The thesis motivates the candidacy of time in understanding the structure of how our experiences unfold.

First, using a nested hierarchical framework based on these properties, we show how the empirical and phenomenological findings in consciousness research can be unified. Allowing us to make systematic predictions regarding timescales and phenomenology of content evolving over those timescales across disciplines of cognitive and consciousness science. Thereafter, in three studies, we present empirical and phenomenological evidence to support the temporal properties postulated in this thesis. Not only as a demonstration of the prowess of our proposed hierarchical framework of time-consciousness, but also to test its fundamental assumptions.

In the first empirical study we show that a perceptual organisation is sensitive to a temporal manipulation, and how the perceptual organisation reciprocally changes temporal resolution. Specifically, showing that figure-ground segregation can be brought about by relative differences in flicker frequencies of two regions and, that seeing a region as figural or as a background changes the temporal sensitivity within that region. We use this as evidence for temporal correspondence of visual representations.

Next, in the second empirical study, we show that temporal experience of duration matches the extent of persisting conscious contents over time. The experience of a perceptual switch while viewing a bi-stable figure (Necker cube) contracts felt time. Simultaneously, using a phenomenological demo, we show that there is also a blink in visual awareness for the contents inside this bi-stable figure. This study grounds the principle of structure-matching thesis of temporality between contents and vehicles of experience.

Finally, using a novel variant of continuous flash suppression, we show how visual contents evolve and devolve over distinct timescales from our awareness. We do this by varying the flicker frequency of the suppressor, to show that different flicker rates selectively impair different kinds of psychological tasks. Here, the nature of the tasks, flicker rates and phenomenological modes of different timescales inform each other. This acts as a demonstration of multi timescale experience.

With the help of the proposal of a hierarchical framework to combine temporal phenomenology, time perception, and timing of cognition, along with our experiment results we offer support for three temporal properties of consciousness. This dissertation contends that these three properties be prepended to the study of consciousness. These three properties are (i) reciprocal temporal correspondence between perceptual organisation and temporal resolution of perception, (ii) a temporal structure-matching between the content and structure of experience, and (iii) evolution and devolution of experience over multiple timescales.

Deployment of the temporal properties identified in this thesis can offer crucial constraints in theorizing and testing the nature of mental representations. Formulating representational systems to have temporality as an intrinsic and necessary can allow the study of mental content to cross sub-discipline boundaries. This thesis allows for postulating a scaffolding of temporal experience, over which theories of attention, perception, emotion, action, awareness, and other psychological faculties can be built. Moreover, this scaffolding can offer an avenue to bring together currently warring theories of consciousness as well. Overall, this thesis describes the temporal structure of experience, offering properties that scaffold how our experience endures, persists, switches, and evolves over time. Our hope is that these temporal properties guide any and all inquires of conscious experience.

Acknowledgements

In the entire thesis, this section has been the most arduous to write. This is because I have had a very fortuitous and privileged 'paid holiday' (PhD) for the last five years. During these five years, I was never ailed with the anxieties or crises that afflict graduate students. This anomalous feat required three of the most exceptional people I had ever met in my life. An attempt to do justice in acknowledging their contribution is thus not easy.

The first of these people is Prof. Narayanan Srinivasan. If not for him, I would have never joined a PhD. I am not sure there is a single word to capture the role he has played in my life for the last five years. Though I am sure that words like guide, supervisor, mentor, captain or PI certainly do not capture his multitude. I am sure, no matter where I go, I will never find another Professor like him. The genesis of this thesis was conversations he had with me from his bedside over evening coffee, where he lay having broken his leg. The framework of this thesis was written at his home. Where in the midst of the pandemic, with the institute closed, he invited me into his home for 3 months to write up our ideas. These and many such anecdotes have shaped me and my work with him. Sure, I have been as anrgy at him as much as I have been in awe of him. But, and this remained true every time, there was no one who has been as patient, as fair and as encouraging of me and my work as him. For this, and everything else, I am eternally grateful.

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Being able to do a PhD, in a field and a place completely unkown to me, required a jump. The person preparing this jumping board for me was my father. I bow to him for pushing me (sometimes literally) and grounding me. He allowed me to see what I dreamt, and gave me confidence in taking steps to realize it. I am not worthy of the sacrifices my mother made for the sake of my education. I am grateful to her for her patience and understanding. I must also acknowledge the patience, and support for me from Ramya‘s parents and sister while I continued my PhD. And to all my family, for always trying to engage with my work.

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Finally, I must thank the avians of IIT Kanpur. I hope they continue to capture the fascination of those who come after me.

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Abbreviations

SOA	Stimulus onset asynchrony
TOJ	Temporal Order Judgment
CFS	Continuous Flash Suppression
pCFS	perturbatory Continuous Flash Suppression

List of Publications

Publications from Thesis

1. Singhal, I., & Srinivasan, N. (2021). Time and time again: A multi-scale hierarchical framework for time-consciousness and timing of cognition. *Neuroscience of Consciousness*, 2021(2), niab020. 10.1093/nc/niab020.

2. Singhal, I., & Srinivasan, N. (2022). A wrinkle in and of time: Contraction of felt duration with a single perceptual switch. *Cognition*, 225, 105151. 10.1016/j.cognition.2022.105151.

3. Singhal, I., & Srinivasan, N. (forthcoming). Temporal correspondence in perceptual organization: Reciprocal interactions between temporal sensitivity and figure–ground segregation. *Psychonomic Bulletin and Review*. doi.org/10.3758/s13423-023-02373-4.

4. Singhal, I., & Srinivasan, N. (in preparation). Visual awareness evolves and devolves over a hierarchy of multiple timescales: evidence from a novel perturbatory CFS paradigm.

5. Singhal, I., & Srinivasan, N. (in preparation). Greater than the sum of its parts: A time-based minimal model to unify six theories of consciousness.

Others

1. Singhal, I*., Mudumba, R*., & Srinivasan, N. (2022). In Search of Lost Time: Integrated information theory needs constraints from temporal phenomenology. *Philosophy and the Mind Sciences*, 3. doi.org/10.33735/phimisci.2022.9438 (*Equal Contribution).

2. Singhal, I. (2021). No sense in saying 'There is no sense organ for time'. *Timing and Time Perception*, 9(3), 229-240. doi.org/10.1163/22134468-bja10026.

Dedicated to transitions,

those that refuse to let me be.

Chapter 1

Introduction

Time is the substance I am made of. Time is a river which sweeps me along, but I am the river; it is a tiger which destroys me, but I am the tiger; it is a fire which consumes me, but I am the fire.

Jorge Luis Borges

Our experiences can be of endless categories and qualities. The smell of rain, the sounds of a keyboard clacking away, the dancing hue of a sunset on the waves of the sea, the craving of a cigarette or the headache that ensues. In these endless set of experiences, is there anything universal? Can we point to a quality that is ubiquitous between these experiences? How about a step further; What about between me and you, and between our endless sets of experiences? And what about me, you and everyone else? Or any conscious being for that matter. Is there a common law, property, or aspect that all our experiences share?

The hope is that finding a putative omnipresent property may allow us to (i) specify necessary properties of our experience, (ii) offer better descriptions of what determines certain conscious phenomena and (iii) unify and integrate existing literature in consciousness by identifying common universals. This is akin to a 'minimal model' approach (see Wiese (2020)). The claim is that this approach offers the possibility of "developing an idealized model of universal and repeatable features serving to gradually isolate the fundamental, explanatorily relevant, and structurally stable properties that underlie different forms of conscious experience" (Metzinger, 2020, p. 4).

Several properties of experience have been proposed as candidates for being omnipresent over the last 3,000 years or so of philosophical, phenomenological and scientific investigations. Examples of these are privacy, introspection, unity, transience, multifacetedness, intentionality, subject-object distinctions, selfhood, perspectival, anticipation, control, and temporality.

This dissertation explores temporality as a possible answer. Since, no matter what we experience, it has an ephemeral nature. Experiences evolve and devolve, they persist, they have order and succession, they flow and endure for specific duration intervals. This dissertation is an investigation of temporal properties of consciousness. In trying to draw a minimal model of temporal consciousness, this thesis discusses original empirical, phenomenological and philosophical work done by us over the last five years.

1.1 Background

Pursuit of such an investigation faces several hurdles. The first being metaphysical. Is it the case that each of our experience is precisely unique? Or are there fundamental laws that govern what we experience? One must be able to assume[1] that conscious experience is not idiosyncratic. This means assuming there are enough *regularities* in our experience for there to be attempts at a science of experience. This follows from assuming that it would be highly unusual for laws and regularities to apply to some aspects of a universe and not others. It would also be extraordinary for societies, technologies, language or any agreement to exist between humans (let alone across species) if there was nothing fundamentally universal between our way of *being* in the world.

It is important here for me to make a distinction that is crucial to understand the study of experience. One that is rarely made explicit in popular literature, or perhaps simply ignored. It is the distinction between contents and structure of our experience. Instead of a definition, let us start with an example. In our experience, we can discriminate nearly an endless number of colours. Colour labels do not capture the granularity of our colour perception. It does not even come close. That is why, we find colour experience incredibly hard to communicate. This often leads one to ask if we can establish that two people ever see the same colour. Can we equate the contents (here colour) of consciousness? Given the inherently closed first-person nature of experience, we possibly cannot. The result is the reinforced idea of idiosyncrasies in human consciousness. However, how is it

[1] Within valid reason.

possible then to have a production line of televisions that sell the same product across the globe? Samsung does not have to make televisions for individuals, tailoring each monitor to capture an individual's unique and idiosyncratic experience. How is it possible for us to agree on shapes, colour and beauty? If engineers at Apple do not know what red *looks* like to me or you, how are they making excellent cameras? One reason I believe this is possible is because of the understanding of the structure of our visual experience. Even though we might not be able to equate contents between people, we can equate their relationships. For instance, colour spaces that match for similarity of hue or lightness between two colours. And then, what we can show that colour property relationships (of hue, saturation, and lightness) are similar across people[2]. These universal constraints and relationships between colour experiences are governed by the structure of colour experience.

Similarly, our interest here is the structure of time in experience. Can we possibly come up with laws that apply to how experience unfolds in time? Irrespective of what we are experiencing? Are there universal structures to how our experience changes, persists, switches, evolves and devolves in time? Do these structures represent the same content? Do they have the same phenomenological mode and timescales? Can understanding these structures invigorate our understanding of mental representations? Does a general understanding of time-consciousness constrain theories of consciousness? We[3] answer these questions and more in this thesis. This thesis takes a phenomenological, theoretical and empirical approach in exploring these topics. However, before we dive in, some grounding is required. Specifically, what is being referred to (and not) by "consciousness" in this monolith, and what are domain general structural properties in psychology. A brief discussion of this allows me to introduce you to this thesis.

1.2 Consciousness: What do I mean?

It has become more exhausting over the years for me to introduce to people what "consciousness" research is and is not. Academic writing, media coverage and overly enthusiastic TED talks are not helping. If you're familiar with the academic literature on

[2]As an example of this three-way relationship: more saturated hues of blue look darker than more saturated hues of yellow.

[3]I have used 'we' in several places across this dissertation. I am cognizant of the fact this breaks the norm and convention of dissertations. Because I am not going to stop using the 'we', I want to make the reasons behind its deployment explicit. I use the 'we' most often with a hope of inspiring joint action. When I write 'we will review time', I mean you and me. I also use the 'we' sometimes to act as a stand-in for everyone who has worked on similar ideas. Finally, maybe the 'we' comes from an idea of collective identity in my head. I am *not* using it to refer to me and my supervisor (or collaborators). I am also *not* using the royal we.

consciousness, you'd see people describing consciousness as the state of being like something. Usually with examples that list the seeing of a colour or tasting caviar and so on. This is true[4]. Consciousness research is about what we experience. However, this definition is not complete. We study contents of experience, but we also study structures of these experiences. Going back to our example of colour, we not only study whether you see a colour or not, what colour is that you see, but also how this colour relates to other colours (over several dimensions of interest). For instance, if I flash in front of your eyes a bright blue square, which colour do you see as an afterimage? How long does this afterimage stay? Is the clarity of this afterimage affected by how you saw the square when it was flashed? And so on. We also study similarities between colours, does yellow look closer to red or blue? And also interactions between properties of colour, do different hues of the same luminance appear equally bright? Thus, I am not just interested in knowing how one experience appears to you, but if it bears any relation with other experiences of the same category. And more importantly, whether this relationship is common across people. In this thesis, when I talk of consciousness, this is what I mean, the experience of a content and the structure of this content. Here, we are interested in temporal contents and structures. Specifically of duration intervals, persistence, order, flicker, change, evolution, and devolution, amongst others.

I think it is equally important for me to list what "consciousness" discourse is *not* part of this thesis. We are not going to discuss whether machines can be self-aware. Reading this thesis will not inform you whether ChatGPT feels you type too slowly. Nor am I going to be able to explain why certain mental states co-occur with certain physical states. I am not even going to try. I am also not going to propose theories of consciousness, nor am I going to create an instrument that tells me whether my basil plants are annoyed by the sound of my keyboard's clacking. Finally, this thesis is not about raising or lowering one's consciousness or awareness. My sole humble offering to my reader is a description of a temporal scaffolding, which I argue can be used as a skeleton to understand how our experience unfolds in and over time. Also, some experiments designed to test aspects of this scaffolding. My aim is to offer general structural properties of time that apply to all individuals and all experiences. To give you an example of how this would work, I discuss some generic structural properties of experience next.

[4]Though sadly we do not do many experiments with the taste of caviar or dancing hues of sunsets.

1.3 Universal structural properties of experience

So far, I gave you the example of colour relationships and tried to convince you that we can equate colour experiences between individuals using these relationships. But are there other examples of this? In this section, I discuss some more generic structural properties that apply to our experience, irrespective of their modality or individuals. One such property is of fatigue. Fatigue can be thought of being similar to effects of habituation or saturation. Whether it is touch, taste, sounds, meanings or sights, all of these experiences have the flavour of saturation or habituation. You get habituated to the feel of your chair, repeating a word over and over again seems to lose its meaning, your eyes hurt when you come out of a theatre and so on. Another structural constraint on our psyche is resource allocation. Whether it is trying to remember a phone number as you rush to dial, or trying to listen to another person while you are reading these words or prioritizing one task over the other[5]. More formally, attention, memory, action, and perception all involve allocating mental resources. You know this from your own experience. There seems to be a capacity to the number of things you remember from your grocery list, the number of actions you can perform when driving at high speed, or the number of things you can pay attention to while you type out a message to someone on your phone. These constraints of resource-limitation seem to apply to most things psychological, and the constraint holds across individuals. Sure, people might have systematically different saturation thresholds and differences in individual capacity limitations, but the structure itself is universal. Along the same lines, here, we look at temporal structures. We collate over hundreds of findings to look for whether they are regularities in temporal aspects of our experience. Temporal resolution, bottlenecks, changes, duration, order, flicker, and persistence. Do these co-vary similarly across people and timescales in human cognition? We build a structural model of this and then test some predictions made by it, hoping to create an understanding of domain general structure of temporal properties of consciousness.

1.4 Organization of the Thesis

The thesis first charts a course through foundational ideas in three distinct but related fields. Namely, time perception, timing of cognition, and temporal phenomenology. We review existing ideas and disputes in how time is understood in these fields of investigations. Specifically, to introduce the reader to various aspects of psychological time (Chapter 2).

[5] Hopefully reading this thesis over the dozen multiple tabs you have open.

In Chapter 3, we develop a framework to resolve the disputes discussed in Chapter 2. Moreso, we show how a unified study of time is possible. We combine more than 30 existing findings in cognitive science from various disparate fields of attention, learning, perception, action, awareness, and emotions to elucidate a scaffolding of time-consciousness. The framework not only allows itself to be the first model of a temporal structure of conscious experience, but it also allows us to make testable predictions. Many of these are discussed and highlighted in this chapter. We also discuss three fundamental constraints on the temporal structure of experience, arguing how these three can be considered universal temporal properties of consciousness.

From Chapter 4 begins the empirical foray in testing and supporting the proposed temporal properties of experience. I employ phenomenologically driven empirical experiments to show a temporal mirroring of visual content in experience. Here, we show that our experience is reciprocally sensitive to time. Specifically, that if perceptual organization of our experience is sensitive to a temporal property (think flicker), it can reciprocally also affect how we perceive time. We detail this as an example of a temporal mirroring constraint of the structure of our experience.

Chapter 5 tests our second proposed temporal property. Here, we test and highlight the structure-matching thesis of temporal experience. The aim is to show that timing of cognition and the experience of duration are inexorably linked. This chapter presents empirical results again along with a phenomenological demo to illustrate this link.

Chapter 6 details the third and last empirical study of this thesis. It describes a study using the continuous flash suppression paradigm, where I used manipulations of flicker rate to demonstrate differential timescales over which different aspects of our experience evolve. This is the final temporal property we discuss in this thesis, that is, of different aspects of our experience evolving over different timescales in tandem.

In a general discussion of the thesis in the penultimate Chapter 7, I try to summarize the implications of this thesis for studying consciousness. I also make an attempt to offer how the realization of the temporal properties discussed in this thesis can alter the way we conceptualize representations in cognitive science. I extend the findings from this thesis to theories of consciousness, to show how they can be unified and what each can gain from understanding temporal properties of consciousness. I also speculate about the possible future scope of my work. I close by offering conclusions in Chapter 8

Chapter 2

Literature Review

2.1 Precursor

In this chapter I go over different distinctions, explanations, and models in various fields of time. Specifically, I present to the reader prevailing ideas in temporal phenomenology, time perception, and timing of cognition research. I am cognizant of the fact that it is not an easy task in expecting a reader to switch between these fields of study, each detailed enough to merit individual chapters of 'literature reviews'. However, this chapter can make for an easier reading by following these two principles. One, to look for the distinctions in explanations *within* each of these fields. Second, to see if these distinctions connect *between* these fields. After overviews of these fields, I will conclude this chapter with some discussions of the methods and paradigms used in these fields, specifically those that are important for this dissertation.

2.2 Philosophy of Time Consciousness

The nature of our temporal experience has been a matter of interest for well over 2,000 years. It has featured in almost all major philosophical schools, and it continues to invite debate. Here, we will very briefly summarize different philosophical conceptions of temporal experience. For the sake of convenience and keeping things brief, we will broadly divide these conceptions into three categories (see Figure 2.1). These categories are based on whether they propose the contents of our experience and its structure to have temporal

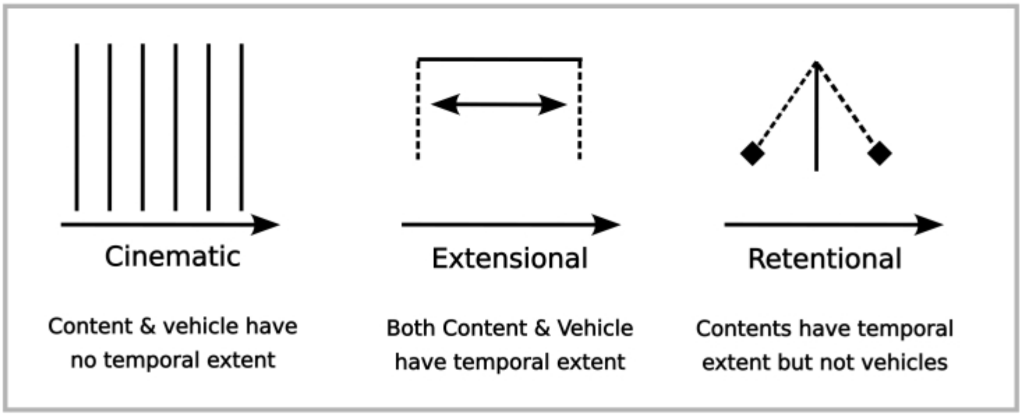

FIGURE 2.1: Illustration of phenomenological models of time-consciousness.

extent (or not). These categories are cinematic, extensional and retentional models (for a full review see Dainton (2010)).

Cinematic models as the name suggests use the movie metaphor to explain temporality. The conceptual ideas of this model can be traced back to Buddhist philosophy. In recent years they have been defended by Hume, Reid, Koch and most recently by Arstila. They posit that our temporal experiences are entirely explained by 'frames' being presented really quickly, just like how motion 'emerges' from a movie projector showing stills at high refresh rates. It postulates that neither the content of our experiences nor its structure have any temporal extent. These ideas are generally employed to explain phenomena such as chronostasis, wagon-wheel illusion and so on (Dainton, 2010).

Extensional models try to remove the structure/content distinction between consciousness and experiences. For them, both are temporally extended (Dainton, 2010). Again historically they can be traced backed to ideas in Indian philosophy namely to Nayayika and Vedanta schools (Sinha, 1934). More modernly they were defended by Kelly, Gallagher and Dainton. There are debates whether James was an extentionalist, arguments for which are beyond the scope of this monolith. These intervals of consciousness update every few milliseconds. They allow for and explain the difference between succession of experiences and experience of succession. Thus, they seem to have more strength in explaining phenomenology. However, these models cannot explain 'future' oriented illusions, for instance phi phenomenon and cutaneous rabbit illusion. This is because the temporal extent of consciousness extends along experiences and cannot 'overtake' it.

Finally, we have the retentional model, classically proposed by Brentano and developed by Husserl. They also speculate a difference between content and vehicle of consciousness, but they do so using two dimensions. For them, time is one dimension and protention and retentions are another. Retentions are small sparks of just past moments left over after an event has taken in. While protentions are predictions and anticipations about upcoming stimuli and events. They argue that consciousness itself is durationless, the sense of duration comes from the decay of just-past experiences and hypothesis about just arriving stimuli (Dainton, 2010). This model is adept at explaining both phenomenology and future oriented time illusions. It can also incorporate predictive processing. However, retentions are defined as necessarily perceptual. These models have crucially added an excellent theoretical basis for empirical exploration into the temporal structure of consciousness. Aligning with different positions, psychologists, neuroscientists, and phenomenologists alike have proposed various theories and done empirical tests for and against each of these positions. These are discussed in the next sections, both in the context of time perception and timing of cognition.

2.2.1 Lack of Resolution

Even though these phenomenological models have been around for a better part of 2,000 years, and have been formally studied for the last 100 years or more, there is little if any resolution in sight. Paradoxically, all of these models are able to explain many phenomenological and empirical findings, but fail to find common ground. Given each of these models have different assumptions about temporal extent built in, they necessarily operate in windows of different timescales. For instance, the extent-less cinematic models are supported by theories that argue that conscious moments update every 30–100 ms (VanRullen & Koch, 2003), whereas the extensional models find support for conscious moments to be extended on the order of 300–500 ms (Dainton, 2008a). Retentional theorizing on the other hand offer moments of conscious experience to be influenced by factors extending up to 3 seconds or longer ((Dainton, 2010).

Arguments that all of experienced temporality and its associated illusions could be explained by employing a single timescale have recently come under scrutiny (P. A. White, 2018). Similarly, different mechanisms are proposed for sub-second and supra-second discrimination of time intervals in the field of time perception (Gibbon et al., 1997), making it difficult for a single timescale to explain our subjective experience of time. The point here is that these phenomenological models have become isolated from one another because their explanations involve different timescales. Theorizing in these mutually exclusive temporal regularities has left not room for conciliation and cross-talk.

Another reason for the tension between these ideas is their phenomenological *essence*. These models individually highlight different aspects of the temporal nature of our experience. In assuming the temporal nature of all of experience to be like that of only one phenomenological mode, these models lose out on being able to make a dent in explaining temporal phenomenology. These models exclusively assume that our experience only evolves as frames or is only extended or can only be captured by retentional models. Therefore, cinematic models are unable to tackle temporal phenomena that are essentially extended in time, for instance, the experienced rhythm of two musical beats more than a few hundred milliseconds apart. Nor are cinematic models equipped to explain the endurance of content over time. Consider the example of an opera singer holding the same note for an unceasing duration. The unchanging note, held by the singer, eventually comprises the notion of duration in our experience. As if we could hear her holding the note over time. Such experiences cannot be explained within a cinematic grounding of temporality (Kelly, 2005).

Likewise, extensional models have trouble accounting for postdictive phenomenon in perception, where something occurring briefly later revises the percept of something that occurred earlier (Dennett & Kinsbourne, 1992). Similarly, retentional models are currently invoked indistinguishably for explaining subpersonal, perceptual and belief-like predictions over time (Wiese, 2017). Moreover, existing elaborations of these models of temporal consciousness are unidirectional, explaining either how content in the world is represented temporally in our experience or how we come to act in the world temporally. There are no conceptualizations through which a correspondence can be built that accounts for both bottom-up and top-down factors under a common framework (Kon & Miller, 2015).

A general limitation that applies across the board is that these models is that while they are about *time*, they do not necessarily offer explanations about time perception. Perhaps because the study of time perception is not bound to a timescale (duration in time perception studies range from a few milliseconds to several minutes). Whereas the models of temporal consciousness are bounded by the breadth of a psychological 'now' (Atmanspacher et al., 2008; Kelly, 2005; Montemayor & Wittmann, 2014; Pöppel, 2004). Later in this thesis, we will see how time perception and temporal phenomenology are two sides of the same coin. Before we get to that, it is necessary that we get introduced to the literature of time perception and timing of cognition.

2.3 Time Perception

Any discussion of temporal experience is remiss without consideration about how we perceive time itself. Time perception in itself is a substantially large field with a fairly long history. We will limit our discussion of this literature here by adding two boundary conditions. (1) We will not discuss the literature on precision and accuracy of estimates of time. Since how well we can tell time involves a correspondence with clock-time and not the dynamics of our experience. (2) We will limit our discussion to models that talk about time perception up to a limit of ~ 5 seconds. This limit is drawn from the putative distinction between judgement and perception. We will work under the assumption here that these short intervals of duration are perceived and then estimated, and not just a product of memory judgements.

Explanations of how we perceive time have been proposed through various implementations, computations, and equivalences. Early explanations linked perceived time to muscular-skeletal structures, with the rationale that since motor movements need to be finely refined in time, they themselves must be representing time. Another speculation was linking perceived time to body temperature and chemical makeup. With psychological explanations increasingly adopting computational metaphors, in the early 1970s time perception also underwent the cognitive revolution (see Whitrow (1980) for a historical account). It was argued that we possess pacemakers that generate pulses incessantly. These pulses are accumulated inside an accumulator and then fed to a comparator, which proportionally translates accumulated pulses to estimates of duration (Ornstein, 1969a; Treisman, 1963). Over the last three decades this clock model has been extended to include effects of attention, emotion, and arousal on perceived time (see Matthews and Meck (2014) for a review). However, whether and where such a "clock" exists in our brains remains elusive. Moreover, clock models are criticized for being circular in explanations, not explaining any other temporal phenomena or cross-modal time perception and making a category mistake (Gorea, 2011b).

The last two decades have seen a plethora of new theoretical frameworks being proposed for how we perceive time. Some equate it proportionally to the amount of neural activity, claiming that the larger the neural activity, the longer perception of time. These frameworks account for findings wherein larger, faster, brighter, louder and novel stimuli prolong felt duration intervals (Ivry & Schlerf, 2008). Presumably because each of these are associated with increased neural firing. These 'intrinsic' models of time perception, also have the convenience of neural distribution. Since, sense perception is distributed throughout the brain, then so is time. Such models typically do not look for 'clocks' in any particular location of the brain, but consider the entire brain to be a timekeeper (Ivry & Schlerf, 2008).

There are also models of time perception that equate perceived time with information processed in an interval, complexity, and number of events in an interval (Roseboom et al., 2019) or compressibility of an interval (Kurby & Zacks, 2008). For instance, the more times an event can be segmented into parts, the smaller the perceived time of that interval. Whereas intervals in which not much seems to happen are felt to drag. Experiments here ask participants to reproduce intervals of a few seconds, with these intervals having more or few events (e.g., fast-paced vs. slow movies). The general finding is that participants perceive intervals with fewer events as dragging.

Although there exist findings in time perception which show that these factors affect felt time only when they are experienced as such. For example, not just flicker, but *perceived* flicker affects felt time (S. K. Herbst et al., 2013b). Similarly, *perceived* speed, not just absolute speed, affects felt time (Gorea & Kim, 2015b; Kaneko & Murakami, 2009). However, no current theoretical positions in time perception care to relate perceived time with visual awareness or consciousness. However, many proposals of their relation were explicitly made in the past (Fraisse, 1963, 1984). Time perception models also in general ignore other temporal phenomena or dynamical workings of psychological processes. They seem to primarily be interested in estimation of elapsed duration, but not in persistence, switches, endurance or devolving of the contents of our experience. Thus, current developments in time perception ignore both other temporal phenomena and timing of cognitive processes.

On the other hand, order and change perception literature does look at whether experience of order and change are mirrored to changes in psychological processes (Nishida & Johnston, 2002). Put another way, whether the contents of our experience are also represented in the same manner in the mechanisms that realize this experience. In this literature, the contention is between whether experience is itself temporal or whether temporal markers are tagged separate from experience. For instance, a speed-o-meter in a car represents the speed of the car in an instant as a temporal marker. The same goes for the way time is represented by the date stamp on a letter. Applying this metaphor to the mind entails that processing of content of experience and its temporal information (order) is done separately (called the event time view; see Figure 2.2). The opposing view proposes that time is intrinsic to mental representations (brain time view). For a metaphorical contrast, consider how speed is represented by an anemometer that measures wind speed (see

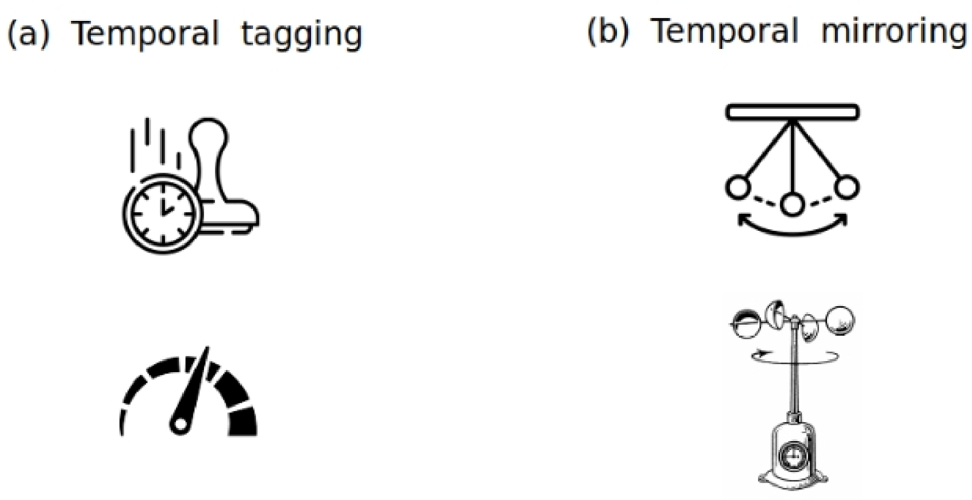

FIGURE 2.2: Illustration of representational formats of time

Figure 2.2). Here the meter represents wind speed by itself rotating at that speed. The same applies to the dynamics of a pendulum. Temporality is represented in these case by the representational vehicle itself possessing temporal properties. These representational formats have been debated under several names (brain time vs. event time; temporal mirroring vs. temporal tagging; intrinsic vs. dedicated timers). However, duration has thus far remained absent from this debate. Perhaps because it is hard to formulate a design that would allow one to test this question (in Chapter 5 we make an attempt).

Similarly, another distinction largely ignored in time perception literature (despite suggestions) is that 'time is not one thing' (Eagleman, 2008). Specifically, that distortions of perceived time have several distinctions. Time does not slow down or speed up just the same way across timescales. Eagleman argues that the study of time perception does not differentiate between actually *seeing* time slowing down or speeding up vs. judgements of elapsed duration intervals. In one of his experiments, he tests the hypothesis whether fear slows down time. Specifically, whether people are judging fearful intervals as lasting longer or whether in, like a movie, people's perception of the world actually happens in slow-motion. To investigate this, he tied small screens to people's wrists and threw them for the top of a tower onto a safety net. While falling, participants were asked to look at the screen. The screen had a flickering stimulus constantly being masked around their individual thresholds for flicker perception. If participants' time was really slowing down, they would see the masked stimulus. He found no such evidence. However, participants did overestimate the duration of their fall. He illustrates three examples of time alterations, differentiated by timescales and their phenomenological nature. First, he discusses chronostasis where actions compresses a duration and elongates felt time for their outcomes. Here he argues that how we 'see' things in time actually change. However, this happens only at an order of ∼80ms. On the other hand, odd-ball effects occur where novel stimuli in a series of item feels as though it dilated in time. He proposes a second kind of time alteration where novel stimuli attract more attention and stand out against a temporal context in the order of ∼500ms. Finally, he talks of the kind where events are remembered as having taken less or more time on the order of a few seconds. He proposes that these kinds of time alterations occur at different time scales have different kinds of phenomenology.

Before we move on to the literature on timing of cognition, let us quickly summarize this section. Time perception research has elucidated several correlates to perceived time, in the form of stimulus and psychological properties. However, the relation of duration experience with the experience of duration itself and its dynamics is missing. Similarly, time perception models have little to say about timescales of working of psychological processes in general. Finally, we also saw that phenomenological differences exist in how felt time is dilated, and these have regularities over specific timescales. In the next section, we will look at whether there is some clustering of psychological processes over specific timescales.

2.4 Timing of Cognition

To best appreciate this section, I would ask you to think of the last perception-based experiment you designed or came across. Did the design have a specific stimulus display time? An inter-stimulus interval, stimulus onset asynchrony, a cue to target interval, masking duration or a response window? Where did these values come from? How is it that we know at least the range of these values while studying a process? And more importantly, how is there a regularity in these values across paradigms and labs? Is there a meta-view of the values we fix for these independent variables of time, that throws light on the temporal workings of our psyche? In this section, we first briefly look at clusters of timescales across different sub-fields in cognitive science. Then what have we learnt from these clusters, and what remains to be unearthed still.

Time specific findings are littered in every field and sub-field of cognitive science. In attention, cueing only works at specific time scales, and different kind of cues work at different time scales (∼50ms for direct cues, ∼300ms for symbolic cues). Crossing these time scales can bring about 'return of inhibition', the 'cost' of cueing a location, which again works in a fixed interval(∼300ms). Attentional blink also occurs at a fixed time range (∼200-300ms). Failure to notice change between two alternating frames also have specific temporal requirements for them and for the mask interspersed between them. Attention and time interact when time is a dependent variable as well. Felt time seems to expand for attended objects and for those that draw attention, while it seems to contract for ones that get fewer attentional resources (Brown, 2008).

In perception research, a certain SOA between two frames can bring about motion, causality judgements, filling in of stimuli, direction preference or even grouping. Judgement of synchrony and succession are also limited by time between stimulus presentation. There are various illusions in perception that can arise with specific frame rates of stimulus presentation. Again, perceived time is also influenced by the content of perception as well, as we saw in the previous section. Perceptual features like flicker, speed, stability, size etc. can all alter duration judgements for a particular stimulus (see Eagleman (2008) and Grondin (2010) for reviews).

It is also obvious to us that movements are not only planned within the surrounding space, but also with respect to time. There are specific time gaps in which movements are planned and executed. There are points of no return (in time) beyond which movements cannot be stopped. If action and perception are indeed coupled, they do seem to be coupled over time as well. In action, too, there are interactions with time as a dependent variable. Intentionally caused outcomes seem to expand in time (Makwana & Srinivasan, 2017b), seeing a rhythmic stimulus after an action seems to slow it down initially (chronostasis; see Merchant and Yarrow (2016)).

In fact, in any study that uses time as either a dependent or independent variable, its reported effect waxes and wanes at different time scales. These effects do have their own you explanations within their own sub-fields. For instance, some effects are attributed to processing priority, some to capacity limitations, some to neural fatigue and some just explained away as illusory or epiphenomenal. However, can something universal be abstracted out? As mentioned in the beginning, can these effects inform us about the structure of time? This is not the first time this question has been asked. In philosophy and phenomenology, several attempts have been made to excavate the temporal structure of the mind, as we saw in the philosophy section. But what about in psychology and cognitive science?

Perhaps the pioneer work in trying to combine different time scales for conscious experiences was done by Pöppel (1997). In his work, he looked for fast and slow regularities in psychological processes. His work elucidated two timescales which he proposed worked hierarchically in updating the contents of our sense-perception. He proposed a fast-updating process at the scale of 30-50ms. His rationale for this timescale came primarily from the fact that stimuli have to be roughly separated by this amount of time for us to tell their order when they are briefly presented (irrespective of their modality). Also, reaction time and eye pursuit movement distributions for several attention, memory, and perception tasks are distributed with modes separated by ∼40ms.

Concurrently, he proposed a slow-updating level of the duration for which metaphorically described as the interval after which the brain asks "what next?". He argues that this happens at intervals of about 3 seconds. He bases these values on findings from perceptual switches while viewing bi-stable images or in binocular rivalry setup, the ISI required for highest mismatch negativity, duration which we can more accurately reproduce and the extent of a perceptual echo. There are also more sociological findings for such regularities, for instance average meter of lines of poems seem to be around three seconds.

Another attempt to draw out a relationship between different temporal regularities was made by Atmanspacher and colleagues (Atmanspacher et al., 2008). They extended the work of Pöppel (1997) by showing a relationship between the 30ms and 3second levels. They added a third level of ∼ 300ms, as the duration it takes for large scale integration of information in the brain, as measured from the time of stimulus onset. They showed that the time it takes for a bi-stable image to switch, is a ratio between the time it takes for large scale integration (300ms) and order thresholds (30ms). Changes in either of the two, would change the perceptual dwell times.

Another recent proposal of hierarchical relations between multiple timescales of experience came via Montemayor and Wittmann (2014). They proposed another three level hierarchical structure for the psychological present moment. Their proposal included a functional moment of now (∼ 250 ms), a conscious now (∼3 seconds) and a self-narrative evolving over 30 seconds. Their main motivation for this proposal was to explain continuity of conscious experience and the idea of a self. Their putative timescales are motivated by similar evidence, as we have seen over this document. That is, via how long it takes one to become conscious of some content and act on it (∼ 250ms), and the duration of a present moment proposed before (∼ 3 seconds). In recent developments, they have tried to accommodate a general framework for temporal evolution by linking their ideas with evidence from attention and action literature.

Another tripartite treatment of time comes via Varela (1999). Revitalizing the field of cognitive neuroscience with an injection of phenomenology, Varela aimed to ground the understanding of neural processes via developments in understanding temporal phenomenology. His work to date remains the best demonstration of incorporating ideas from phenomenology into mainstream empirical cognitive science. He extends the Husserlian framework of time into cognitive neuroscience. His idea was that the basic temporal units of neurons could be in the range of (10-30ms), integration of neural assemblies would take (100ms) and the descriptive narrative phenomenological timescale would extend to three seconds. The novelty of Varela's work was connecting neuroscience with phenomenology.

Of all the work we surveyed on temporal hierarchies, a key feature is that there are temporal regularities for different psychological phenomenon. However, all of them fail to extend their work to time perception, or resolve existing phenomenological disputes in the field of time consciousness. Moreover, while they do attempt to incorporate timing of cognition, their ventures are limited and lacking in concrete predictions or mechanistic interactions.

2.5 Methods and Paradigms

In this section, we try to introduce the reader to some of the design and methodological aspects of the research done in time perception. How do we measure felt time? Are there methods to study different properties of temporal experience? What kind of paradigms do we use for such studies, and what kinds of stimuli are used to study people's visual experiences?

2.5.1 Measuring felt time

The work in this thesis is largely concerned with how time is experienced inside a moment of a psychological 'now' (a duration of $\sim$ 5 seconds or so). Therefore, the methods of measuring of time that I detail here, are relevant for those timescales. Let us say that I want to measure whether you experience time as passing differently when looking at pictures of attractive vacation destinations vs. pictures of office spaces. How do I go about this? First, we already have two stimulus sets. Vacation destinations and office spaces. To compare their felt duration, we must first present them for equal time intervals, so that comparisons can be made. This ties down our second independent variable, presentation time. Let us say that I present, in an experiment, each of these pictures for one second.

I want to see, whether you experience this one second of a duration interval differently. How do I measure your estimates for this duration?

A starting point is to adopt the scaling method of psychophysics into time. We can fix a standard duration anchor and ask participants to bisect a scale of duration one trial at a time. For instance, we can present a neutral image for a fixed duration before presenting a vacation and an office space picture for a variable duration. We can ask participants in each trial whether the target picture felt longer or shorter than the fixed duration of the neutral image. In this way, we can figure out how participants judge and represent time for a range of duration and how this representation is different (or not) for different categories of stimuli or situations. This method while intuitive is limited by requiring presentations of two stimuli in each trial (a standard and a target). Of course, this can be avoided by training the participant on two anchor intervals of time (one declared as short and another as long). And then ask participants to classify each target using this learned scale. This too would grant us a psychometric function over the range of duration intervals for us to measure how coarsely felt time is represented.

Another method of measuring estimates of duration is by training participants to create their own scale and asking them to explicitly quantify time. This method is called the 'verbal estimate' where participants type in estimates of time numerically. At first, this method sounds absurd. How can a person be asked to list that they thought a duration interval lasted for 1140 milliseconds? However, the method is not used to compare time estimates to actual duration. Nowhere in this thesis are we measuring how accurate people are in estimating time. Only how a person's own estimate (however accurate) changes across two conditions. Second, this method requires training participants how to convert anchor duration into numerical estimates. Initially, they are given a range. And then asked to extrapolate numerical values within that range based on exemplars of different duration intervals. After the experimenter ensures that these extrapolated values can differentiate the exemplars, the participant proceeds to do the main experiment. The advantage of this method is that it gives great resolution and freedom to the participant to translate a felt duration into a report for the experimenter to examine. This is the method we use for duration estimates in Chapter 5.

Moving beyond duration judgements, there are methods to measure synchrony, flicker sensitivity, order thresholds and persistence. For instance, participants can be asked to tap in sync with a tone or asked to indicate whether they see a light as flickering or not, whether participants can individuate objects in time and how they can reproduce the duration of an event. I will describe in more detail here the paradigm of 'temporal order judgements', since we employ it in Chapter 4. In an order judgement task, two stimuli are presented sequentially with a temporal gap. Participants are asked to indicate which of the two stimuli appeared first. By using a range of duration intervals as the gap, an experimenter can measure the way participants resolve perceived order of stimuli in time. The same task can be performed under different conditions to see if order resolution changes as a function of task conditions.

2.5.2 Common Stimuli and Paradigms

The second feature of the methodology behind this dissertation is the choice of stimuli and paradigms. One way to study visual experiences involves using pictures that are bi-stable. That is, those images which, without themselves physically changing, can be seen and interpreted in two (or more) ways. Examples of such images are Necker cube, Rubin's face-vase drawing, and the duck-rabbit illusion. The advantage using such images is that experimenters can induce changes in visual awareness without physically changing a stimulus itself. This allows one to eliminate several confounds of stimulus complexity and low-level visual properties of perception. Moreover, it allows for a phenomenological paradigm where participants report the contents of their own experience. Another variant of a bi-stable design is binocular rivalry. Here, visual awareness spontaneously oscillates between two competing inputs that are exclusively presented to each eye. In this dissertation, we employ both bi-stable images (Chapters 4 and 5 and a special case of binocular rivalry in Chapter 6).

The special case of binocular rivalry we refer to here is a case of 'continuous flash suppression'. Instead of using two competing perceptual inputs, an experimenter can also actively suppress a perceptual target from entering awareness. This is typically done by presenting one eye with a bright, colourful, and flickering suppressor made up of densely packed shapes. Participants in this case initially see only the suppressor, and slowly their perceptual system allows for the input from the other eye (the target image) to break into awareness. Here, one can measure the duration taken to break through or the proportion of trials in which a breakthrough occurred. And these dependent variables can be compared across stimulus and suppressor variations.

2.6 Summary

It is no easy task for me to give an expansive review of three different fields of study from philosophy, psychology, and neuroscience of time. Each looking at different aspects of perceived time, phenomenology, and dynamics of cognitive mechanisms. All of them, themselves, form enormous fields of study. Thus, my only aim here has been to give you a flavour of the stances in each of these fields of inquiry. Specifically, to act as a springboard for the rest of this thesis. Before we dive into the contributions of this thesis, I want to earmark three distinctions in this literature review for my reader. One, that each of these sub-fields of time research (phenomenology, time perception and timing of cognition) have different regularities for different timescales. For instance, there are phenomenological aspects of time which feel too quick to grasp, aspects which extend and flow, and also aspects which are echoic and anticipatory. Similarly, the experience of time distorts in distinct ways. We can have change-order mismatch of stimuli, we can perceive events as lasting for longer in a given context, and we can misremember the duration of events. Finally, in the timing of cognition too, different aspects involved in our experience seem to have distinct temporal regularities. That is, within these fields there are phenomenological distinctions of how experience unfolds, gets distorted and persists. The second point to take home is that while there are distinctions based on both timescales and phenomenology across these three fields, there is a dearth of formulations to reconcile them or systematically collate their regularity.

Chapter 3

Universal framework for timing of cognition and time perception

Where do we stand now? If you have read through, we have handed you a box with the following puzzle pieces. There seems to be some truth in all of the philosophical conceptions of time consciousness, they seem to all somewhat apply to specific phenomena. Each resisting refutation, but also failing to encompass it all. Is there a way that these can be reconciled? There seems to be specific time scales over which psychological constructs unfold. These time scales seem to cluster and have been exploited to draw out temporal regularities. What do these regularities tell us about the evolution of our experiences in time? Do these relate to how we perceive time? Is there a way to draw out a temporal scaffolding over which we can tie what we know from phenomenology of time-consciousness, the rich literature of timing of cognition and how we perceive time?

To the reader, we leave the following chapter to try out for a taste. We begin by assuming that temporality is a minimal-unifying property for consciousness. Using this as a foundational structure, we build a framework that combines both timing of cognition and time perception (for the published version, see Singhal and Srinivasan (2021). To draw out the commonality of 'time'. Such a framework would then allow us to inform both time perception and timing of cognition from a common ground, for a plethora of sub-fields in cognitive science. As a hypothetical example, one can predict whether a particular process will dilate felt time, and at what timescale. Correspondingly, whether an alteration of felt time is accompanied by a change in the dynamics of a psychological process and at which timescale.

This framework would also accommodate the warring philosophical conceptions of time-consciousness under a unified hierarchical framework. With them all operating in tandem, each working in its own temporal boundary, limited to a different nature of phenomenological experience. Perhaps an example of a temporal hierarchy might be useful before we proceed. Think of how we comprehend speech. At the finest given moment of listening to someone talk, all you can probably here are phonemes that form a word. Our auditory system combines information over multiple timescales for us to be able to extract meaning from listening to a sentence. Over very short timescales, phonemes are combined to form words, at slightly longer timescales we can figure out the subject-object distinctions in a sentence, and timescales longer still, there are temporal regularities of intonations. In tandem, we recognize speech hierarchically over these multiple timescales.

The rest of this chapter details this hierarchical framework, both in terms of timescales and phenomenological attributes. Additionally, we will see three temporal properties of consciousness that this framework allows us to derive. Finally, empirical evidence in favour of this framework is discussed. The chapter concludes with predictions and tests drawn from the framework.

3.1 Combining phenomenological models of time consciousness

In the previous chapter (specifically in section 2.2), we reviewed the different philosophical conceptions of time consciousness. Here, we begin by combining these into a three level hierarchical framework (illustrated in Figure 3.1). First, we describe the attributes of these levels individually. Later, we discuss interactions between them and possible mechanistic explanations.

3.1.1 Level 1: Cinematic

A fast-updating cinematic level in the hierarchy with its represented content updating every 30–50 ms is postulated as the level 1. The range of its temporal updating steps comes from similar estimates of order thresholds [1] in existing models (Atmanspacher et al., 2008; Grush, 2016; Pöppel, 1997, 2004).

[1]Note that these are modality general order thresholds, i.e., minimum gap required between two stimuli to be able to accurately report their order. Simultaneity thresholds or resolution of a modality are bound to be different. The framework here is currently not modality specific. it may need to be modified in the future to account for resolution differences.

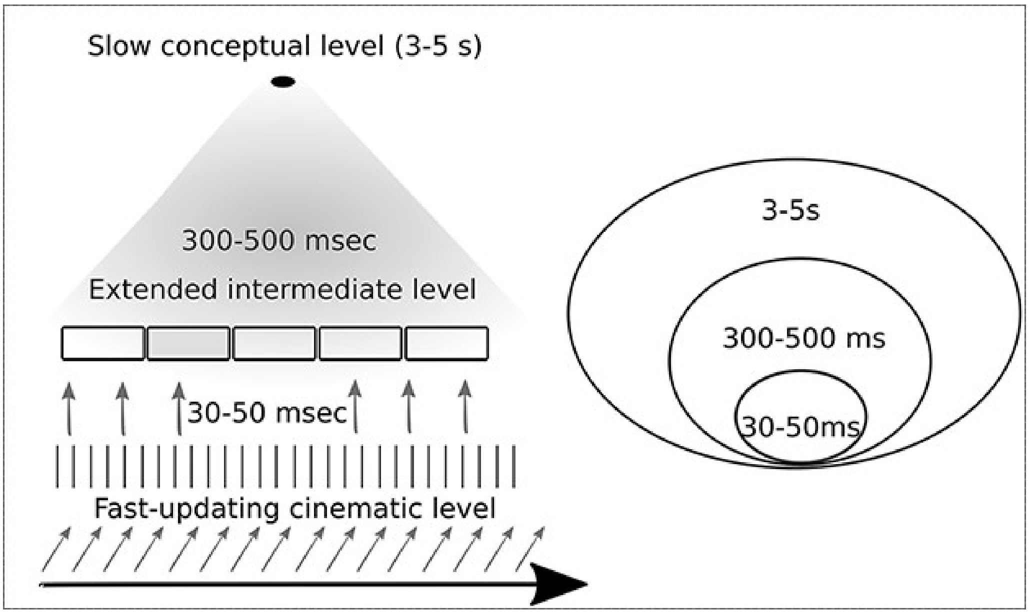

FIGURE 3.1: An illustration of the nested hierarchical framework of time-consciousness

The phenomenological nature of the level is proposed to not have an extended felt duration nor an extended representational duration. That is, neither, the content nor its representations are extended in time. Thus, we are not immediately or directly conscious of the content and temporality of this level. From an objective point of view, we speculate that the representations at this level are updated with a non-zero temporal breadth (30–50ms). As discussed in the previous sections (see 2.2) we think of the content evolving at this level as 'cinematic', with a phenomenological nature of being frame-like and too quick to grasp, this is based on our proposal of a lack of temporal extension of content at this level. However, it should be noted, that since in our framework this is not an isolated level and that it interacts with the other levels, it can be thought of in terms also of 'dynamic snapshots' (Prosser, 2017). Since the timescale at which its representations update is constrained by the intermediate level within the hierarchy.

3.1.2 Level 2: Intermediate & Extensional

Within our framework, the intermediate level is one with an extensional structure that operates and updates over 300–500 ms. Its phenomenological essence is borrowed from the extensional models of time consciousness. Hence, the content and representations at this level are both extended in time. The intermediate level is privileged to match the extension of content in our experience based on similar speculations elsewhere (Jackendoff, 1987; Marchi & Hohwy, 2020; Prinz, 2007).

The rationale behind proposing the intermediate level as representing the content of our experience stems from its extension in time. It is at this level that we propose a temporal mirroring occurs, i.e., this levels follows the structure-matching thesis of time. Here, the temporal structure of the contents of our experience mirrors the temporal structure of experience itself. To put simply, any content experienced via the intermediate level has a matching temporal structure in its content and representation.

Despite the framework being a nested temporal hierarchy, the contents of phenomenological experience are still primarily tied to the intermediate level. The other levels across the hierarchy constrain and feed into the intermediate level. The intermediate level is connected hierarchically to both the fast-updating cinematic level and to the relatively slowly updating retentional-conceptual level through a multiplexing mechanism (more on this in the forthcoming sections). The content from the intermediate level is fed forward to the slower conceptual level over time. The intermediate level also constrains the time-evolution of the fast-updating level. These workings are proposed to occur within the granularity of the intermediate level (i.e., over 2–4 Hz). The values for temporal extension (300–500 ms) of this level are derived from empirical data investigating integration cycles within conscious experiences (Herzog et al., 2020; Herzog et al., 2016).

3.1.3 Level 3: Retentional and Conceptual

The endmost level in this hierarchical framework is sculpted as a relatively slower conceptual level that overarches retentionally over the content at the intermediate level. This slower level is proposed to span 3–5 seconds in time. Similar to the interactions proposed earlier, not only does this level retain the contents from those below, but it also constrains the evolution of the intermediate level. This duopoly of feed forward and feedback interactions are proposed as retentions and protentions, respectively. Thus, the slower level 'retains' experiences of the 'just past' from the intermediate level (the primal impressions of the intermediate level) up until and over a span of 3–5 seconds. Complementarily, forward-looking intentional acts (protentions) constrain the dynamics of the content at the intermediate level (over a span of 250-500 ms). The proposed span for this level comes from the various previous temporal hierarchies and estimates of the psychological "now" (Dorato & Wittmann, 2020; Kelly, 2005; Kent, 2019; Pöppel, 1997; Varela, 1999).

The phenomenological kind of contents that comprise retentions have been under dispute. For instance, do retentions solely comprise perceptual or conceptual content? From arguments made by Wiese (2017), we too see no reason for this distinction, especially in our framework. Thus, the nature of representations at this level are conceptual/belief-like, pertaining to some perceptual content. Same as the original retentional models, the anchor of a now has no temporal extent. Due to their lack of temporal extent, these concepts are not experienced. Along similar lines as Prinz (2007) who argues the same, we speculate that the reason concepts are not experienced is because of a lack of temporal extension. Just how Prinz (2007) argues that we can only experience perceptually-linked representations of concepts, we too propose that the content of the slow representational level can be experienced only via the intermediate level as percepts or imagery (Kemmerer, 2015).

3.2 Possible Implementations

This section discusses one possible way this framework might be computationally or neurally implemented, i.e., via multiplexing (Piper, 2019). Two oscillatory signals can be modelled to interact through six different coupling mechanisms in a multiplexing system (see Figure 3.2). For instance, their phase, amplitude, or frequency could be coupled (Jirsa & Müller, 2013). Thus, the frequency, phase, or amplitude of one rhythm can be modelled to modulate the phase, frequency, or amplitude of the other rhythm. Just with these six simple interactions, one can have a possible avenue to model both feedforward and feedback constraints as cross-frequency coupling. On the one hand, this implementation might seem too simple to account for the evolution of experiences, however, it is our contention that the framework is aimed as a scaffolding that can be co-opted into existing models of consciousness. Along the lines of minimalist models, cross-frequency coupling seemed to us as a more amenable mechanism for communication. There are several promising facets of a multiplexing-based approach. It is the only currently widely accepted modelling strategy that can simultaneously account for time-extended representations and reconciling discrete-continuous effects under one mechanistic conception. Piper (2019) work anchors this approach in a time-extended explanation of apparent motion.

Of course, this is only one possible way in which our framework could be implemented. We choose this rudimentary set up as a starting point to draw out a simple, plausible neural mechanism for our framework. An advantage of such an implementation is that it would find an easy crossover with most EEG based timing studies. Multiplexing of frequency band specific oscillations provides easy accommodation of existing EEG/ERP evidence. However, the phenomenological and psychological aspects of the framework are not tied

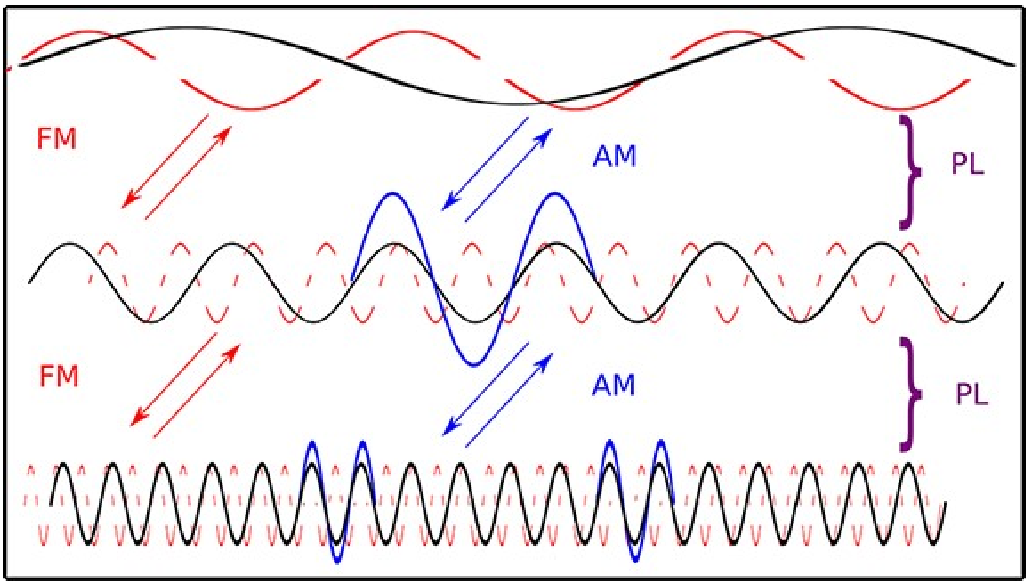

FIGURE 3.2: A possible instantiation of the interactions between different levels of the temporal hierarchy. Presented here as multiplexing, specifically through amplitude modulation (AM), frequency modulation or phase locking (PL).

to only this specific implementation. In the couple of years since this framework has been proposed, I have received multiple alternate suggestions[2] for neural implementations.

The role of oscillations or general periodicity in the brain have recently come under heavy criticism (Brookshire, 2022; Sohal, 2016). Thus, it is warranted to at least explore alternate corresponding neural signatures of our hierarchical model. For instance, non-periodic but spontaneous coupling models have also tried to account for temporal phenomenology. An example of this comes from the recent work of Rabuffo et al. (2022). They propose an aperiodic dynamic snapshot conception of awareness, where incoming information is integrated over windows and made conscious in bursts. While their framework does not have the phenomenological modes discussed here, a spontaneous avalanche of neural activity based model can be a fruitful avenue to explore constraints imposed across several timescales like those mentioned in our hierarchy. The only additional assumption one needs to make to use such a framework is that a hierarchy of time consciousness spontaneously forms and devolves several times aperiodically. Instead of an inherent incessant periodic structure. I am currently uncommitted to either accepting or rejecting this additional assumption.

Along the same lines, in a recent investigation, Vishne et al. (2023) explore the different temporal representation profiles in different regions of the brain. Their motivation stems

[2] I am thankful to Giovanni Rabuffo and Gal Vishne for these alternate suggestions and related discussions.

from comparing impulse vs. persistent representational formats to look for neural correlates of experience. Although their work does not directly address the phenomenological modes of experiences, their approach is a great exemplar for exploring aspects of experience which persist in time and which are transient. The specific temporal profile of the brain's mechanisms is beyond the scope of this thesis. While we do want to constrain the guesses about how the brain works[3], we currently cannot adjudicate between these two or more interpretations. However, I am convinced that temporal properties of experience can inform the search for a pinning down neural mechanisms.

3.3 Tying together the threads of timing and time

So far, I have jumped across various sub-disciplines without really being able to tie things down together. These digressions were necessary to put into place the context of the framework we will now employ. From here on in, I hope I can introduce you to the empirical prowess of this framework. The forthcoming sections will look at a myriad of interactions between several (seemingly) disparate phenomena and effects in cognitive science and consciousness research, and how they could be integrated. This is accomplished under the support of two key assumptions. One, that there are real and felt aspects of our conscious experience which evolve both *in* and *over*time. Put simply, not only do we have an experience *of* time, but our experiences themselves dynamically evolve *over* time. This assumption allows us to bring together 'time' as a common thread to tie together independent and dependent variables of the experiments that have been conducted and continue to be conducted in cognitive science.

The second assumption that allows us to unify findings is that there is in some form or another an abstract structure of time. Specifically, that the way we experience time has a law-like regularity over which our experiences unfold. There is no denying that each psychological phenomena we discuss here has its own explanation. There is also no denying that each person may experience time differently. However, the attempt here is to sketch a common temporal skeletal structure among these phenomena and across people. The only assumption is that the there is some non-arbitrary rule and law-likeness of 'time' across these psychological phenomena and individuals. The strength or the expression of this law might change across individuals, but not the regularity or relationship. This temporal skeleton, then, can be used as a scaffolding over and around which explanations

[3] A point I wish I could discuss in greater detail in this thesis is how the temporal properties discussed here cast a doubt on present day conceptualizations of mental (or neural) representations. I touch upon this in the General Discussion in Chapter 7

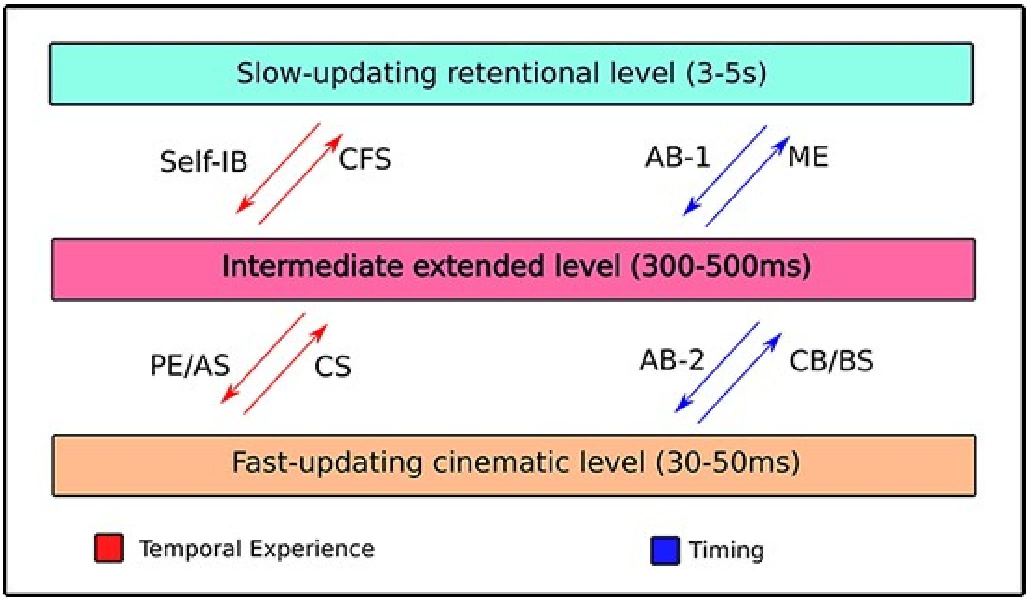

FIGURE 3.3: Figure illustrating the interactions between different levels of the hierarchy. Effects from temporal experience and timing are depicted separately. See text for more details

may be built. Akin to a structural property of consciousness or a minimal unifying model of experience (Metzinger, 2020; Wiese, 2020).

Finally, there is also a very clear boundary condition to what effects can be explained using such a framework. One boundary limit comes from the temporal range over which a phenomenon of interest occurs. The timescale for which should not exceed ~5 seconds to be included in the framework. Since our framework is limited to the extent of a psychological now, any cognitive or psychological phenomena that takes place outside of it cannot be currently accommodated here. One reason for this is that it is unclear to me whether trying to understand cognitive processes that occur over large timescales would necessitate another level of temporal regularities in our hierarchical framework? Or whether these process would be conceptualized as a concatenated series of duplicates of various 'nows'[4].

With these disclaimers in place, we now discuss the possible interactions between the different levels of the hierarchy, and how these interactions show that effects from timing of cognition and temporal experiences can be combined (see Figure 3.3 for an illustration of the interactions discussed in the next few sections).

[4]I would love to see a phenomenological model or description of the way nows are connected. The literature, at least in my reading, becomes more and more scant once the timescales become longer. Is there a special phenomenological way in which hunger persists over the day? Or the way earworms persist over a week, or the way identities persist over a lifetime? I have seen some daring attempts at these questions, if these interest you, please see the works of Kent (2019) and Montemayor and Wittmann (2014)

3.4 Interactions between the fast-updating and intermediate levels

3.4.1 Fast-updating to intermediate level: timing

One EEG-based marker and correlate of conscious visual experience is the presence of theta-gamma phase coupling between the fronto-parietal regions (Buzsáki, 2009; Cohen, 2011; Doesburg et al., 2009). For instance, there is evidence that participants' percept alternation while viewing bi-stable images or in binocular rivalry settings (Başar-Eroglu et al., 1996; Doesburg et al., 2009; Kruse et al., 1996) is correlated with phase-coupling between these two bands. Evidence of similar nature has been extended towards proposals that conscious experience unfolds at moments of phase coupling between these two bands and is interrupted during periods of decoupling (Droege, 2009; Madl et al., 2011; Van Leeuwen, 2007). We use this as a basis within our framework to model the interaction of the fast-updating level (updating frequency falling in the ∼gamma band) with the intermediate level (∼theta band) to explain how visual content is multiplexed as it unfolds over time in our experience. The theta-gamma phase coupling is not only consistent in terms of timescales with our proposal, but it is also used here as a necessary condition for conscious visual experience, i.e., there is no conscious experience when there is no phase coupling between these two levels.

Along the same lines, a plethora of visual awareness associated phenomena that fit with the interactions here are change blindness paradigms brought about by disruptions (gaps, masks and or flickers; see Breitmeyer (2015) for a review). The classic change blindness paradigm used by Ronald Rensink is a handy example to illustrate this interaction (Simons & Rensink, 2005). Here, near ∼300 ms chunk of stimuli are displayed repeatedly in a loop until participants can detect and report a change. Each 300 ms loop usually consists of one scene presented for 100 ms, a blank interval for 80 ms and the same scene with a changed attribute is presented again for 100 ms. Participants initially fail to notice this change. Generally, participants take up to a few seconds to report the change, presumably after searching each quadrant of the image and remembering serially where a change does not occur (Simons & Rensink, 2005). Our proposal here is that the integration of content at the intermediate level is reset by the gap/mask that is interleaved between the two scenes (for ∼80 ms). Hence, the dissimilarity of the mask unfolding at the fast-updating level individuates (splits in time) the two frames as separate events. This presumably breaks the succession between the two frames and makes it more strenuous to find the change. While presently only a conjecture, there is evidence from EEG studies to warrant exploring these ideas further (Koivisto & Revonsuo, 2003; Pourtois et al., 2006). Specifically, these studies show both an early (∼100ms) and late-sustained (∼350ms) changes in EEG components when trials with and without a detected change are contrasted.

Several temporal illusions have been used to argue for a putative discrete mechanism responsible for perception (similar to a cinematic conception of temporal experience). These temporal illusions include those of phi motion, waterfall reversal after adaptation, wagon-wheel rotation illusion, Michotte launching effect and kappa illusions (Eagleman, 2008; Grondin, 2010). Phi illusion is a case where one sees the motion of a dot moving from one location to another, before the other dot is perceived. This paradoxical effect of where something coming later can revise something currently being perceived is explained through discrete sampling delays and revisions of perceptual content. In opposition to these illusions being interpreted under the scope of discrete models, alternate proposals argue that these illusions reflect instead a nested structure of discrete perception within an underlying continuous structure (Fekete et al., 2018; Kon & Miller, 2015). These are entirely consistent with how we conceptualize the interactions between the cinematic and extended levels of this framework.

3.4.1.1 Fast-updating to intermediate level: temporal experiences

In parallel, we look at the phenomena of perceived time over the same timescale and one that shares its phenomenological nature within this same interaction. One such effect is of performed actions dilating felt time (chronostasis). Stopped-clock illusions, perceived delay in periodic beats after an action, and tactile chronostasis are examples of such temporal alterations (Grondin, 2010). These effects are apparent directly in our experience. The magnitude of these temporal dilations are equivalent to the half-width of the intermediate level (∼120–150ms); thus, we place them in the intersection of the cinematic and intermediate levels within our framework. In our phenomenology, the content of our visual experience may seem to pause and continue updating cinematically (as if there were delayed snapshots) just after an eye movement (think saccadic chronostasis; stopped clock illusion), we can only experience the delay because of a continuing extensional frame of our experiences. If our experience was only frame-like, the content of our experience would still be delayed (w.r.t. objective time), but it would never be apparent in our experience. Why? Because we need a continuous reference in comparison to which we can experience delay. Such an interaction can only be explained over an underlying extended structure within which frame-like updating of content comes about (see also Fekete et al. (2018)).

3.4.2 Intermediate constraints on the fast-updating level: timing

Reverse hierarchically, this proposed framework also allows the intermediate level to constrain the time-evolution of content at the fast-updating level. An example of this is the prioritization of one perceptual property over another. Let us take the example of the 'silencing illusion' (Suchow & Alvarez, 2011). In this illusion, a set of stimuli are presented clustered around a ring. This set is made up of several circles that differ in size and color. The color of these circles keeps changing over time. Think of them like blinking Deepawali lights. One can very easily notice changes in the colours of these individual circles when they are stationary. However, when the stimulus set starts rotating (along its global cluster of a ring), the colour changes of the individual circles are now not noticeable. The unfolding of the whole/global content here is prioritized over local changes, altering the way in which temporal relations are integrated and represented.

Another way the intermediate level constrains the unfolding of content at the fastest-updating level is seen in an attentional blink when the stimuli in a rapid serial visual presentation (RSVP) are pieces of a shape that make a complete figure (Akyürek et al., 2012). Herein, the RSVP has frames of stimuli presented at a fast timescale (∼50 ms). Participants often report seeing an integrated T1 and T2 if they meaningfully join to form a complete image. However, order information is often lost (Akyürek & Wolff, 2016). The intermediate level extends over to perceptually complete or integrate a figure at the cost of temporal order.

3.4.2.1 Intermediate-level constraints on the fast-updating level: temporal experience

Similarly, the intermediate level may constrain the temporality of the content unfolding at the fast-updating level. An example of this comes from temporal attention sampling information at 4Hz (A. Nobre & Van Ede, 2018), bringing about the prior entry of attended stimuli in simultaneity judgement and Temporal Order Judgment (TOJ) tasks (Shore & Spence, 2005). Here, temporal attention sampling occurring at the intermediate level could lead to prior entry of content at the fast-updating level by increasing the amplitude of the representations of the contents (Vibell et al., 2007) or by improving temporal precision through frequency modulation (Yeshurun & Levy, 2003).

3.4.3 Interactions of the intermediate and slow levels

3.4.3.1 Intermediate to slow level: timing

An existing paradigm that is best set up to explore the interactions between intermediate and slow levels is continuous flash suppression (CFS). In this paradigm, a stimulus is presented to one eye and a flickering noise mask to another. Initially, participants see an intermixed percept dominated by the mask, and slowly (over say 3s) the stimulus breaks into awareness. A key factor that drives these breakthrough times is the frequency of the flickering noise mask. Previous studies have reported this to be around 3-7Hz when the stimulus must be identified (Drewes et al., 2018a; Han et al., 2018a; Zhu et al., 2016). In our framework, these results act as a 'temporal lesion', bringing to light the timescale at which objects in our experience reach awareness and are identified. Here, the flicker perturbs the interaction between the intermediate level and its slow-updating content representations at the conceptual level[5].

3.4.3.2 Intermediate to slow level: temporal experience

How would the content of our experience lead to estimates of longer durations? We account for some of these effects (Eagleman, 2008; Grondin, 2010) as arising out of the interaction between the intermediate and slow-conceptual levels. One such example is the effect of 'bigger equals longer'. Here, stimulus properties of numerosity tap into a common magnitude representation of numerical quantities (space, time, number, etc.) and are reported as longer (Walsh, 2003). The conflation between common magnitude representations could bias our judgements of time. For instance, a circle with the number '9' written on it may be reported as lasting longer than a circle with the number '1' written on it. However, our hierarchical framework proposes that these differences are based on conceptual conflations of magnitude representations and are thus not likely to have perceptual effects (a circle with a larger number would not have a different flicker frequency thresholds, for example).

Similar accounts can also be drawn from the effects of emotion on time perception literature. Accounts of fear dilating judged time (Eagleman, 2008) is one example of this. One way this comes about is based on how we parse events into meaningful units. Emotional

[5]Later in this thesis (Chapter 6), the reader will see how this proposed interaction can be used to test some of the assumptions behind this hierarchical framework.

events receive greater scrutiny in time, for example, a more fine-grained narrative parsing of events (see Eagleman (2008)). In our framework, we think of this as a frequency modulation of the slow conceptual level, which alters the extent of event boundaries. Or amplitude modulation, which alters the fuzziness of the event boundary representations. Herein, again, emotional events would lead to judgements of longer passage of time without necessarily slowing down perceptual frames or altering flicker frequency thresholds (see Eagleman (2008) for evidence).

3.4.3.3 Slow-conceptual-level constraints on intermediate level: timing

In an earlier section (3.4.1.1), we discussed an attentional blink (AB) effect to demonstrate the constraints imposed by the intermediate level on the fast-updating level. Here, we use another AB effect to demonstrate the constraints that the slow-conceptual level places on the content unfolding in our experiences at the intermediate level. This AB effect is of the kind where T2 is experienced but not reported (N. Block, 1995; Vogel et al., 1998). Consider again the 'perceptual episodes' over which selective attention operates (Snir & Yeshurun, 2017). The concepts employed at the slow-updating level can then constrain what is selected (read retention) in an RSVP unfolding at the intermediate level. An example of this is the increased number of blink trials when T1 and T2 are faces belonging to the same emotion category, although being individually different(Ray et al., 2020). Here, the conceptual task-relevant category of emotion retains the emotional category of T1. This leads to participants missing the T2 when they belong to the same emotion category and appear in successive lags in an RSVP task by forming a single perceptual episode. If the slow-updating level constrains the content at the intermediate level, it should also be able to facilitate recognition of T2 when T2 completes a perceptual episode. Supporting evidence for this can be found in Meijs et al. (2018), where the predictive contingency of T2 on T1 reduces the number of trials where an attentional blink occurs (see also Alilović, Slagter, et al. (2021)). These form examples of the slow-updating level constraining what is recognized (T2; ∼300ms) over an RSVP (1–2s).

3.4.4 Slow-conceptual-level constraints on intermediate level: temporal experience

The previous section showed how the slow-conceptual level constrains what is 'picked out' from an RSVP stream. This section explores a similar possible constraint from the slow-conceptual level to the temporality of experiences at the intermediate level. For instance, intentional binding is thought to be modulated by action–outcome contingencies and conceptual relations to self (Makwana & Srinivasan, 2019); thus an initial speculation that follows is that the slow retentional level downwardly constraints the temporal evolution of the contents at the intermediate level. Therefore, contents that match the predictability of the action and or are conceptually related to a concept of self appear in our awareness faster, bringing about intentional binding.

3.5 Revisiting philosophical and Consciousness phenomenological debates in light of the framework.

This juncture is as good as any to reiterate the purpose and motivation of this framework. The goal behind it was to describe regularities that seem systematic within "nows" of our experience. These regularities are of three kinds. One is the regularity of duration interval periods of the different levels, second is the regularity of the phenomenological content evolving at each of these levels and third is of the nature of constraints that these levels can impose on each other (modulations of amplitude, synchrony, and frequency). Using just descriptions of these three regularities, we can start to reconcile philosophical debates and make phenomenologically divergent ideas congenial to each other. In this section, I will try to highlight examples of these possibilities.

One pervasive issue in phenomenology of temporal experience is whether contents evolve and devolve out of our perception in a discrete or continuous manner. Answers to these debates have come forth from both camps, championing cinematic, extensional, retentional, and their variant models. All of these have generally tried to argue for mutually exclusive possibilities, where human experience *only* follows one kind of temporal updating. Here, via the framework discussed in this chapter, we sought to neutralize[6] this debate. We tried to demonstrate which aspects of our experience endure and have temporal extension, and which kinds of content do not seem to perdure in our experience. Essentially, we tried to demonstrate that the continuous vs. discrete debate involves a lot of talking past each other because the proponents of either side are talking about different levels of temporal content. Of course, this applies more generally to the phenomenological models themselves.

[6]Perhaps it is warranted that I point out that I do not think of this framework as being diplomatic. The intention of the framework is not to build a middle ground, but to systematically show which parts of our experience follow which kind of temporal updating. Not to merely create a more amenable or digestible solution.

Another resolution we tried to offer with this framework was to assign different temporal modes of evolution to different kinds of contents. Specifically, showing which aspects of our experience and when, can seem snapshot like, and how they are presented within and modulated by an extended stream of experience. The aim of the framework is to highlight the duality[7] of our temporal experience, where it is more than *just* discrete or continuous. In my opinion, there is no denying that some perceptual illusions seem to occur in our experience in a manner where there seems to be an absence of temporal mirroring. For me, there is no better example of this than chronostasis. A perceived delay in occurrence of a perceptual event (usually following a periodicity) after an action has been performed. It seems undeniably true in one's experience that one's expectation of the world and the events occurring in the world have gone wildly out of sync. This is used as evidence to argue for a discrete[8] access to conscious contents. However, let us assume that both the mechanism responsible for chronostasis and our experience unfold at a single timescale. And the nature of this unfolding is discrete. If these two are true, then one cannot experience the delay of the chronostasis in their experience.

Let me take a moment to detail this example. Consider the Adam Sandler movie Click (2006). In the movie, Adam Sandler's character gets hold of a TV remote, with which he can control the flow of events in the world. He can fast-forward, slow down, or pause real life, like one would do to a movie. In one of the scenes, angry at his boss, Adam pauses his boss to strike him. When he resumes the world, the boss does not know what happened and why his head is hurting. Leaving the unsophisticated nature of the incident aside, the reason Adam's boss cannot know what happened is because nothing in his experience persists over the time of the world being paused. There is nothing in his awareness which keeps track of the delay. The world for him feels instantly stitched together from before and after the pause. Coming back to our discussion with chronostasis, if the mechanism responsible for the brief pause in our perception leading to chronostasis and our awareness evolved over the same timescales, there would be no way that we would register a delay in the world. Our experiential time would be frozen and then unfrozen, with nothing persisting over time to *experience* the delay. The fact that we *do* experience the chronostasis actually indicates the something persists in and over the mechanism responsible for pausing our perception. In terms of the framework, one can think of the mechanism pausing our perception acting over the cinematic level, whereas our experience

[7]Multiplicity is what is more appropriate. I do not have the space here to argue against the framing of temporal experience as an artificial duopoly of discrete vs. continuous.

[8]For the moment I am not differentiating discrete models based on static or dynamic snapshots. If you are interested in these, please refer to Prosser (2017).

overarching and enduring along the intermediate level. Both modes of temporality and their phenomenological nature are necessary for us to experience chronostasis.

The last bit that I feel I should explicitly emphasize before we move on is the property of nestedness. In this section so far I discussed multiplicity of temporal phenomenological models in our framework, I also want to highlight to you the fact that we propose these models to co-exist and evolve in tandem; nestedly. To unpack it a little more, I will revisit the example of a classical Rensink change blindness paradigm. People miss seeing obvious and central changes to two alternating sets of scenes. This happens as people's experience evolves and is manipulated at three timescales. There is a disruptive frame inserted between the looping pictures of the scenes. This mask like frame is generally presented for a duration between 30–80 milliseconds. The images of the scene itself persists for a duration of ∼200 milliseconds, totalling to a chunk of ∼300 milliseconds. Finally, the change itself is registered over a few seconds. The integration of frames, extension of chunked frames in our experience and the retentions of the previously inspected parts of an image all evolve together over different timescales. A change in any of these timescales would drive away the effect of change blindness from its optima.

With respect to the previous literature on temporal phenomenology, the framework thus differs in these three key ways. It tries to harmonize existing models of time-consciousness, in a nested and systematic manner, and show this can resolve existing debates in time-consciousness. In the next section, we make empirical predictions from the framework and highlight three of its key tenets. The same three tenets that are the contributions of this thesis.

3.6 Assumptions, Implications, and Tests

Our framework can offer robust and immediately empirically testable predictions[9] and further the research of timing of cognition and time-consciousness. The paramount assumption behind this framework is that temporality is fundamental to conscious experience. And that this same 'time' holds a correspondence between timing of cognitive events and the experience of time itself. To state this more formally, the representational format of conscious experience is such that there is a temporal correspondence between the timing of conscious events and their awareness. Debates in philosophy of representations and

[9]Many of them are listed in the published work (Singhal & Srinivasan, 2021) that discusses this framework, thus for a full list I would redirect the reader there. Here, I will majorly discuss predictions that are related to the script of this monolith.

time-consciousness have interpreted various illusions and phenomena to argue for different representational formats for conscious experience and for time. The framework that is developed here is inexorably tied to a temporal correspondence thesis. The question though is whether an empirical test is available for this tenet? An attempt at this is discussed in the next chapter (see Chapter 4).

Another fallout of the framework is that of temporal mirroring. A key question in investigations of time perception is trying to answer how humans estimate the passing of time. Our framework entails that when time is estimated for consciously experienced moments, perceived time is directly related to the contents of one's awareness. In other words, there is a structure-matching doctrine between the structure of conscious experience and the content of conscious experience. Your experience of time, is directly equal to the time over which the representations of that content persist. Such an approach bypasses the requirement of stopwatch like timers in the brain and of event tags that mark duration intervals. To concretize this intuition in an empirical setup, I would like to redraw the example from an earlier discussion on perceptual switches and periods of coherence intervals. A notion in perceptual switching is that these switches seem instantaneous but take some time. Thus, this entails, that it is possible that there is a brief period during a perceptual switch where our awareness of a bistable image is interrupted. The question, now, is this: given the same duration interval with and without a perceptual switch, do people feel that time passed differently? Do they actually fail to perceive something during a perceptual switch? These questions are answered, and empirical support is offered to the notion of temporal mirroring and structure matching thesis for perceived duration (see Chapter 5).

Another key pillar of the scaffolding of our framework is the idea that any given moment of experience involves content evolving simultaneously at different timescales. Put another way, the levels of the hierarchy work in conjunction to all its levels in and over time. When we covered a review of similar proposals of temporal regularities over different timescales in Chapter 2, we saw that different models had proposed two or three hierarchical levels over which perceptual content evolves. However, the support for such frameworks (including ours) comes from pooling together and clustering a large number of findings. The hope is that these temporal regularities are incidentally present in studies, even where they were not explicitly manipulated or tested. And that these regularities emerge when more and more findings are pooled. However, an unavoidable criticism of this is of cherry-picking. The more you look for data that support your postulations, the more likely you are to keep finding them. To subvert this limitation, we thought of implementing a new empirical test for multiscale temporal perception. Given that we now have a clear description of which temporal regularities (think frequencies) are tied to which kind of phenomenological content (over the three different levels), we needed to show that we can selectively perturb perceptual processing within that temporal regularity. Not only this, that we can also perturb exactly that phenomenological content with which it is tied. An implementation of this study is discussed in the final empirical chapter of this thesis (see Chapter 6).

3.7 Conclusion

In this chapter, we discussed our proposal of a multiscale temporal hierarchy. A hierarchy that allows us to accomplish several unifications across investigations of time. Firstly, of making time-consciousness and timing in cognition two sides of the same coin. Secondly, of compiling together various temporal modes of updating in phenomenological literature and tying them down to specific timescales. Third, providing an intersection for various sub-fields of cognitive science to come together with diverse phenomena and make cross field predictions about the experience of time. Fourth, we explicitly formulate and develop three key temporal properties of consciousness that form the brick and mortar of this framework. We concluded this chapter with a teaser of how the framework allows for empirical tests for these postulated temporal properties.

Chapter 4

Temporal Correspondence in Figure-Ground Perception

As we discussed at the end of the previous chapter, in being able to bring together experience of time with experience in time, a postulation of a 'temporal correspondence' was made. This chapter discusses a study where we empirically demonstrated an example of this temporal correspondence (see Singhal and Srinivasan (2023) for the published version).

4.1 Background

Irrespective of our framework, the question of whether mental representations have temporal properties has been asked in philosophy, cognitive science and neuroscience (see Dennett and Kinsbourne (1992), Nishida and Johnston (2002), and Pylyshyn (1979) for classic examples). The current debate remains split between temporal tagging and temporal mirroring theses. Continuing from our emphasis in the previous chapter, temporal tagging is a way to represent temporal properties via markers. Similar to how dates and timestamps represent time-markers in a static way. In the same vein, mental representations could mark onsets or offsets of stimuli via event tags, and then represent duration intervals as the difference between them (onset – offset). On the other hand, time could be an intrinsic property of mental representations. Here, no extra tagging is needed. The perseverance of a mental representation over time itself would represent duration (for a quick recap, you can revisit Figure 2.2).

Arguments in favour of either forms of representation have been resplendent in various sub-fields of cognitive science. To add to this debate, we first assumed a mechanistic temporal correspondence, and set out to find empirical evidence in favour of it. If mental representations themselves have temporal properties, then they should be reciprocally sensitive towards time. Consider, for instance, a perceptual organization that is elicited by flickering an image at a particular frequency. Then, a reciprocal correspondence entails, that when this organization occurs on its own, it should also reciprocally bias perception towards the same temporal frequency of sensitivity.

To clarify and understand the nature of temporal aspects and perception, we investigated the possibility of a temporal correspondence in figure-ground perception. If temporal mirroring is an inherent feature of visual representations, then it should be possible to discover a temporal correspondence for a visual phenomenon. For instance, being able to instantiate a figure-ground segregation using a temporal property, and then showing a reciprocal change in a temporal property of experience by inducing a figure-ground segregation. A similar spatial counterpart of this, i.e., a 'spatial correspondence', would entail showing that regions with lower spatial frequency are seen as backgrounds and regions with higher spatial frequency are seen as figural. And correspondingly, it would be easier to detect sharper targets on 'figures' and blurred targets on 'background'. In fact, this spatial correspondence has previously been shown (Klymenko & Weisstein, 1989; Wong & Weisstein, 1985).

Spatial features such as symmetry, blur, colour, grouping, and edge features have been studied to explain underlying processes of assigning figure-ground judgments to ambiguous images (see Palmer and Brooks (2008) as an example). However, temporal phenomena have received relatively less attention (for exceptions, see Fahle (1993), Kandil and Fahle (2001), and Leonards et al. (1996)). Temporal aspects involved in figure-ground perception form the ideal basis for investigating the nature of visual representations for our purposes.

This is because studies have argued that figure-ground perception can be realized by specialized frequency channels that are tuned to specific temporal and spatial bandwidths (Klymenko et al., 1989). These studies are grounded by reference to the antagonistic interaction of magno and parvocellular pathways. Studies done along these lines have shown that stimulus properties that create larger activity along parvocellular pathways (higher spatial but lower temporal frequencies) biased regions to be seen as figural (Klymenko et al., 1989; Wong & Weisstein, 1985, 1987).

Although such theories have not been used to discuss or investigate whether visual representations have temporal properties. For instance, Wong and Weisstein (1987) showed that regions divided by a boundary could be parsed as figure-ground, when one region had stationary dots and the other had flickering dots (respectively). Similarly, Klymenko et al. (1989) showed that this antagonistic relation also extended to flickering gratings, with the flickering regions being seen as backgrounds for a longer proportion of time-based on spatial frequency characteristics. That is, regions with lower spatial frequencies were likely to be seen as backgrounds when they flickered compared to a region with high spatial frequency. In general, the faster-flickering region grating was seen as the background more often as the flicker frequency difference between the two gratings increased (Klymenko & Weisstein, 1989; Klymenko et al., 1989). These findings have supported theories of figure-ground segregation that depend on the interactions between the two pathways of the visual system.

On the other hand, attempts have been made to investigate whether visual temporal resolution is different for figural/ground regions. There is initial evidence to support this claim, specifically showing a prior entry effect for ground regions compared to figures (Hecht & Vecera, 2014; Lester et al., 2009). They appeal to the magno and parvo cellular pathway based mechanisms for figure-ground segregation as the explanation for such effects (Hecht et al., 2015). These complimentary prior studies provide an ideal link to investigate whether mental representations possess mirroring temporal properties. This is the link we explore in the present study.

4.2 Present study

In the current study, we were interested in using figure-ground segregation to determine the nature of visual representations. We hypothesized that if visual representations have temporal properties, then not only should we be able to induce figure-ground segregation of ambiguous displays using different flicker frequencies, but we should be able to also show a temporal correspondence. For instance, if faster flicker frequencies are responsible for classifying a region as background, then when viewing something as a background, people's perceptual systems should have a higher temporal resolution for this perceived background region. That is, there should be a reciprocal temporal correspondence between flicker frequencies responsible for inducing figure-ground segregation and temporal resolution.

Previous studies have shown that flickering regions compared to static regions (Wong & Weisstein, 1987) and regions that flicker relatively at a faster rate (Klymenko & Weisstein, 1989; Klymenko et al., 1989) are biased towards being seen as background. Thus, if there exists a temporal correspondence in our visual representations, these findings would predict that regions seen as background would have higher temporal resolution than regions perceived as figural.

To demonstrate and elucidate this reciprocal link, we conducted two experiments. In experiment 1, we used a range of flicker frequencies to show that figure-ground segregation is a function of relative difference in flicker-frequency between two regions. In experiment 2, we showed participants a bistable Rubin's face-vase display and asked them to make temporal order judgements for two flashing dots in the central region. This region was perceived as either figure or ground by the participants. We then calculated their temporal resolution when they viewed the same region as figure vs. ground, to show that temporal resolution differences were present in the predicted direction (better temporal resolution in the ground region).

4.3 Experiment 1

4.3.1 Methods

4.3.1.1 Participants

Twenty-four participants (11 females, mean age = 25.1 years) with normal or corrected-to-normal vision provided informed consent and participated in the experiment. Sample size was calculated apriori based on a conservative estimate of the effect size from a similar previous study ($\eta 2 = 0.3$, Power = 0.8; required N = 24), for the main effect of flicker frequency on perceived figure-ground segregation.

4.3.1.2 Apparatus and Stimuli

The stimuli for all experiments were designed in Inkscape image editing tool and were presented using Python-based Opensesame software. Participants were presented with a white square that was split into two halves by arbitrarily shaped contours (4 unique). Participants were shown this square for 1.5 seconds. On either side of this contour, an equal number of dots (n = 16) flickered at different frequencies (2Hz, 4Hz, 8Hz, and 16Hz). Based on these parameters, we created 48 unique flickering stimulus clips (4 contours x 6 unique frequency pairs x 2 counterbalanced left/right). Participants were shown these

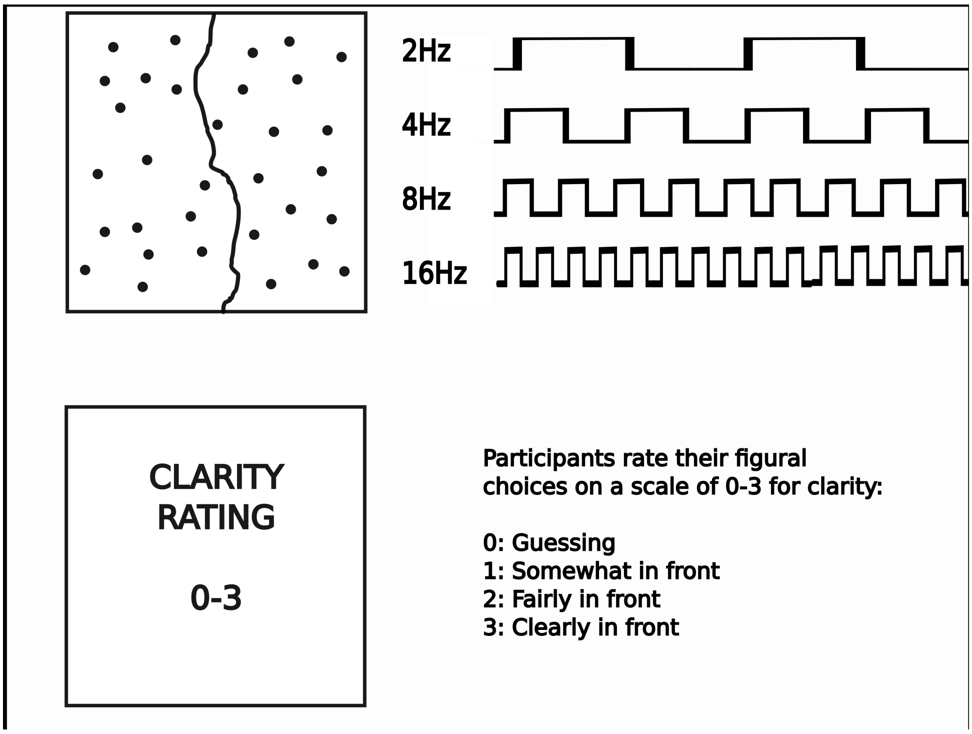

FIGURE 4.1: The figure shows the experimental procedure for experiment 1 of study 1. The square on the top left is split into two halves by a contour. On either side of the two contours, the dots flicker with different flicker frequency pairings. The frequencies are shown as pulses on the top-right (2, 4, 8 and 16 Hz). In each trial, participants reported which side looked like it was in front, and gave a clarity rating for their decision (see text for more details).

clips at a distance of 55 cm from a 17" CRT monitor with a resolution of 800×600 and a refresh rate of 100Hz. Participants were instructed to report which region (left or right) looked like it was in front (closer to them). After their report, participants were asked to rate the strength of their response on a 4-point scale (0-3) with a 0 rating for a total guess, a rating of 1 'somewhat looked like it was in front', 2 'it fairly looked like it was in front' and for 3 'it clearly looked like it was in front' (refer to Figure 4.1 for the trial structure). We adopted the rating paradigm from Palmer and Brooks (2008) to get a richer subjective report. A new trial started after the rating was given. Participants performed 192 such trials.

4.3.1.3 Procedure

In each trial, participants were shown a white square split into two halves by an arbitrarily drawn contour. This square was presented for 1500 milliseconds. During this period, dots on either side of the contour flickered with a specified frequency pairing. Participants

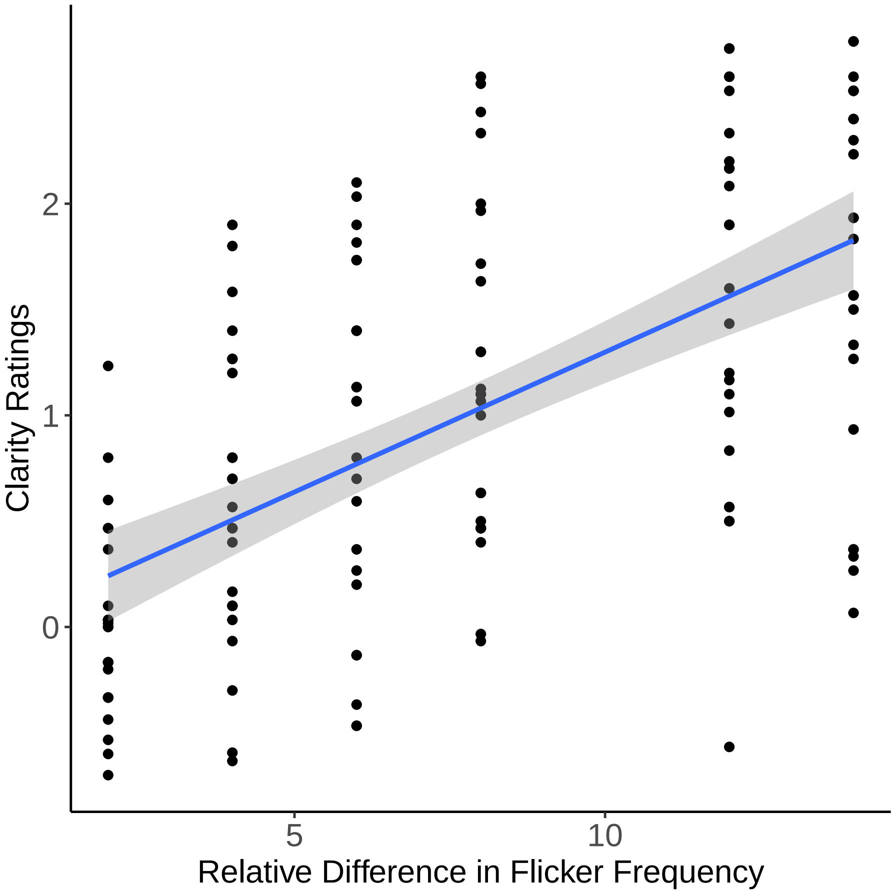

FIGURE 4.2: Results of Experiment 1. The plot shows that participants see a side of the ambiguous square as being the foreground more clearly and more often as the relative difference in flicker frequencies keeps increasing. The side with the slower flicker is the one seen as being in front. The plot shows individual data points and a regression line with a 95% confidence interval.

were instructed to report which region (left or right) looked like it was in front (closer to them). After their report, participants were asked to rate the strength of their response on a 4-point scale (0-3) with a 0 rating for a total guess, a rating of 1 'somewhat looked like it was in front', 2 'it fairly looked like it was in front' and for 3 'it clearly looked like it was in front'. We adopted the rating paradigm from Palmer and Brooks (2008)to get a richer subjective report. A new trial started after the rating was given. Participants performed 192 such trials.

4.3.2 Results

We began by standardizing the participants' responses. Each rating response (ranging from 0 to 3) was multiplied by either +1 or -1 depending on whether the participant's response in a given trial was in the direction of our hypothesis or not, respectively. That is, if participants saw a relatively slower flickering half of the square as being in front their rating response was multiplied by +1, if it was the opposite their rating response was multiplied by -1. Then for each participant, we averaged these scores separately for each flicker frequency pair. This gave us scores for six different flicker frequency difference conditions. A one-way repeated measures ANOVA was then performed on these scores with flicker frequency differences as a variable. Our results showed a significant main effect of flicker frequency differences on these scores ($F(1, 23) = 31.2$, $p< .001$, $\eta2 = 0.57$). Showing that increasing flicker frequency differences meant that participants saw slower flicker regions more 'clearly' as being the figure (i.e., in front; see Figure 4.2). A trend analysis also confirmed this by showing a significant linear relationship (β= .13, p < 0.001, R2 = .34).

The results for Experiment 1 were similar to earlier findings, showing that regions with flicker at lower temporal frequencies are most often seen, as the figure (Klymenko & Weisstein, 1989; Klymenko et al., 1989; Wong & Weisstein, 1987). It should be noted though, while our results are consistent with earlier findings, there are some differences in the methodology. Here, the design used a brief presentation (1.5 seconds, compared to 15–30 seconds in previous studies; see Klymenko and Weisstein (1989) and Klymenko et al. (1989)). We also employed no spatial frequency differences and employed flickers on both figure and ground regions, to show that it is relative differences in flicker frequency which matters.

4.4 Experiment 2

In experiment 2, we were interested in seeing a reciprocal temporal correspondence in parsing a percept as foreground and background. In the previous experiment, we found that slower flickering regions were seen as figural. If there is a temporal correspondence between the timing of figure-ground segregation and temporal experiences of figure-ground, then we expected a change in a temporal property of experience when a region was viewed as figure vs. background. To test this prediction, we conducted experiment 2. We showed participants a Rubin's face-vase drawing and asked them to see the image as a face or vase in separate blocks. While participants viewed the central region as a vase or as a background (in the case of seeing the drawing as faces), they were asked to judge the order of briefly flashing dots. We expected that they would be better at doing this when they viewed the central region as figural compared to background. This prediction followed from the previous experiment where we found that seeing a region as figural was related with relatively slower flicker frequencies, hence we expected a corresponding poorer temporal resolution when seeing a region as figure.

4.4.1 Methods

4.4.1.1 Participants

Sample size was calculated apriori using a conservative effect size from a previously unpublished study (Cohen's $d = 0.5$, with a power of 0.8). This gave us a sample size of 29. Overall, 30 participants (14 females, mean age = 25.2 years) voluntarily participated in the experiment, and were compensated for their time.

4.4.1.2 Apparatus and Stimuli

A drawing of Rubin's face-vase figure was used as the stimuli. The drawing was outlined in black on a completely white background. Two dots were displayed on this drawing with varying stimulus onset times (0, 10, 30, 50, 70, 90 and 110ms). The size of figure was 9.5° in visual angle, and the dots were 1° in visual angle. The experiment was run on a 24' inch LED monitor with a 100Hz refresh rate.

4.4.1.3 Procedure

In this experiment, we ran a temporal order judgement (TOJ) task in two different blocks. Participants were presented with a figure of Rubin's face vase illusion at the beginning of each trial. They were told to press a key when they could see the face or vase (depending on the block) to self-initiate a trial. Soon after they pressed the key, two dots appeared one after the other (above and below the fixation cross). Participants were asked to report which dot came first, the one at the top or bottom (the Figure 4.3 depicts the trial structure). The dots had varying stimulus onset times (0, 10, 30, 50, 70, 90 or 110ms). There were 30 trials for each stimulus onset condition (15 where the dot comes above the fixation first and 15 where the dot appears first below the fixation). Participants performed a total of 360 trials.

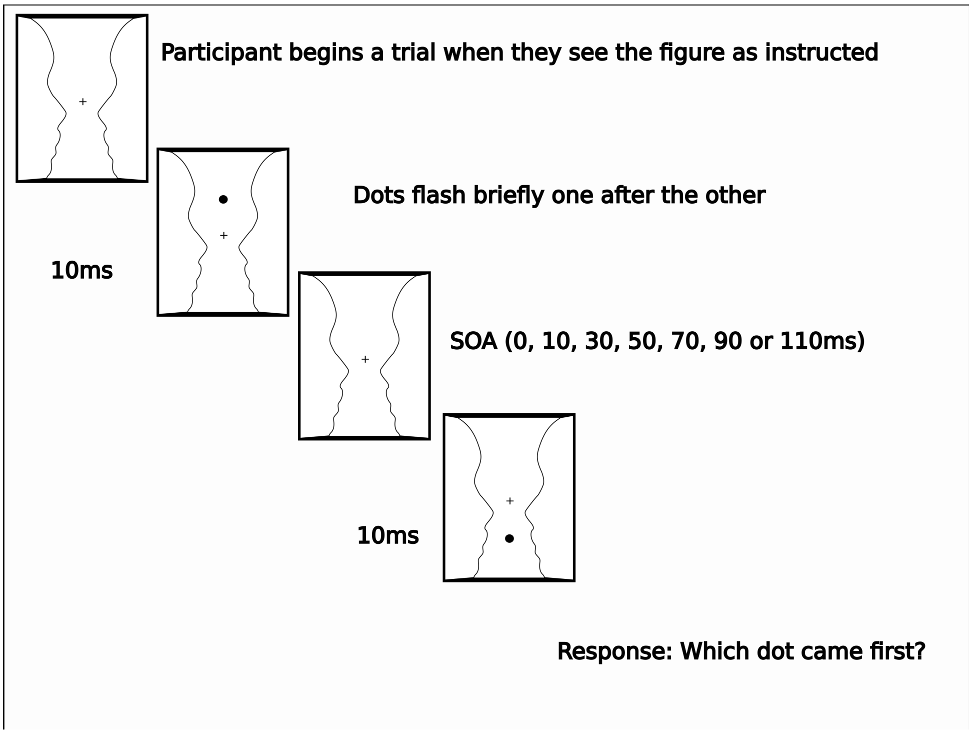

FIGURE 4.3: The figure shows the experimental procedure for the TOJ task. Participants initiate a trial when they can see the face/vase (based on instruction in the block). Two dots flash above and below the fixation cross (in random order) with variable delays. Participants are asked to report the order of the flashed dots.

4.4.2 Results

Participants responses in the Temporal Order Judgment (TOJ) task were fit to a psychometric function $(1 - \exp(-(\frac{x^\beta}{a})))$ using the curve fitting toolbox in MATLAB. This was done to compare slope (β) and threshold (a) values for the figure and ground conditions, to investigate if there were differences in temporal sensitivity between these conditions. A non-parametric Wilcoxon test was performed since the data violated normality assumptions.

We found a significant difference in slopes, with participants having higher slopes when they performed the task while viewing the central region as the background compared to when they saw it as the figure ($W(29) = 338.5$, $p = 0.03$, rank biserial correlation= 0.46). There was no difference between thresholds for the same comparison of conditions. These findings are illustrated by plotting the means of slopes and thresholds, along with their confidence intervals, in Figure 4.4.

We also used another model based curve fitting analysis to look for additional support in temporal sensitivity differences. We used an independent channel model (Garcıa-Pérez &

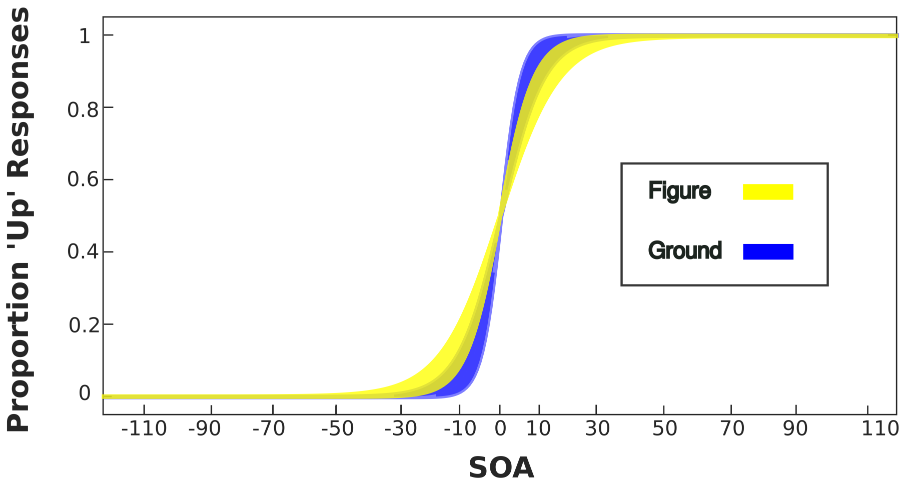

FIGURE 4.4: Results of the experiment 2. The plot shows psychometric curves plotted with 95% confidence intervals for the two conditions; figure (in yellow) and ground (in blue). The plot illustrates the result of a finer temporal resolution when a region is viewed as a ground.

Alcalá-Quintana, 2012, 2015, 2018). The model was developed to separately out effects of resolution, bias, and guessing parameters while participants perform temporal order judgement tasks. Our motivations behind fitting our data with this model were twofold. One, to rule out confounds in our data due to guessing or biases, and second, to show that the differences we observed were primarily driven by changes in temporal precision. We fit the data using the publicly available MATLAB scripts (Alcalá-Quintana & García-Pérez, 2013). We compared differences in TOJ performance between figure and ground conditions on temporal resolution, bias and guessing parameters. We found differences only for resolution parameter, with participants having a finer temporal resolution in the ground condition compared to the figure condition, $t(24) = 2.15$, $p = 0.04$, $d = 0.38$.

4.5 General Discussion

Our aim in this study was to empirically demonstrate a temporal correspondence for visual representations, and the results of the two experiments offer support for this correspondence. In particular, the argument for the correspondence is built via a reciprocal correspondence between the role of flicker frequency and temporal resolution in figure-ground segregation. We show that relative differences in flicker frequency influenced figure-ground segregation. Correspondingly, the flicker frequency relationship systematically carried over to temporal resolution differences.

4.5.1 Demonstrating Temporal Correspondence

There have been similar demonstrations of temporal correspondence in the past. For instance, studies have shown that mental representations have temporal properties in the form of representational momentum (Hubbard, 2005). This entails that changing aspects of a perceptual object are dynamically represented in their next expected state (Hubbard, 2005). Even though a perceptual object may disappear at a time point (t) in state (s), people usually report it as having disappeared at being in the state of its next time point ($t + 1$). Examples of this are participant reports of moving objects disappearing at a later location than where they actually disappeared (Hubbard, 2005). This is also true at a conceptual level, where changes in object features are represented. For instance, participants report logs being more burnt or ice cubes being more melted than they were while they viewed a video (Hafri et al., 2022) showing that perceptual representations of dynamic scenes and objects anticipate the forward dynamics of their states. This is true for both perceptual features like motion but also conceptual features (Hubbard, 2019). Such results have been used to argue for inherent temporality in mental representations in both perceiving and remembering perceptual scenes and objects (Hubbard, 2019). In terms of our hierarchy from the previous chapter, temporal momentum is a property of both the intermediate and retentional levels. Here, however, the temporal correspondence is predicted only for the intermediate level. Not for the slow-updating concepts at the retentional level. Therefore, a prediction that follows here is that a reciprocal link for representational momentum may be found for perceptual representational momentum but not those like in Hafri et al. (2022).

As discussed in the previous chapter and in the beginning of this one, demonstrations of temporal correspondence (two-way relationship) are needed to show strong support to the hypothesis that visual representations represent temporal properties by themselves being dynamic. Even though other studies may not have explicitly tested the existence of a temporal correspondence, findings across timing literature can be pooled to argue for it. For instance, there is evidence of a prior entry effect for stimuli presented on the foreground compared to background (Lester et al., 2009). This study demonstrated that targets appearing on figures were processed earlier than targets appearing on the background, with a prior entry benefit of almost 10 milliseconds. Correspondingly, Kandil and Fahle (2001) showed that figural regions could be segregated from the background with only a temporal delay in their flicker (using phase as a cue). This segregation could be done with delays as little as 10 ms. If interpreted under the glass of our framework and the present study, these prior studies show a temporal correspondence in figure-ground processing prioritization when put together.

4.5.2 Two channel theories of temporal correspondence

My aim here was not to test the neural basis or plausible mechanisms of temporal correspondence. Nevertheless, a large part of the studies that motivated this experiment come from a tradition of two-channel theories. Where a spatio-temporal correspondence and trade-off are built into the perceptual pathway that carry perceptual information across perceptual systems. Even though we did not explicitly test a two-channel hypothesis, our results can be discussed as being parsimonious with previous studies. Firstly, our results are parsimonious with previous studies showing a role of flicker-frequency as a cue for figure-ground segregation (Klymenko et al., 1989; Palmer & Brooks, 2008). The results from our temporal order judgement experiment are also in agreement of similar findings with prior entry and simultaneity judgment tasks (Hecht & Vecera, 2014; Lester et al., 2009). Both these lines of investigation (i.e., studying flicker as a figural cue and temporal resolution differences in figure-ground perception) employ a magno/parvo cellular pathway or activity based explanation (Hecht & Vecera, 2014; Klymenko et al., 1989; Weisstein et al., 1992) to explain potential tradeoffs in temporal sensitivity and spatial selectivity, including figure-ground segregation. The magnocellular pathway is believed to have poorer spatial resolution but higher temporal resolution, whereas vice versa holds true for the parvocellular pathway. The tuning of the parvocellular pathway to slower temporal frequencies, but higher spatial frequencies have previously been exploited to show why slow flickering regions are seen as figural (Klymenko & Weisstein, 1989), and why figural regions have poorer temporal resolution than regions viewed as backgrounds (Hecht & Vecera, 2014). Figure-ground assignment activity has been hypothesized to be based on relative activation differences between the parvo and magno pathways for each region, with the region with the relatively greater parvo-magno differential activation being assigned figural status (Weisstein et al., 1992).

4.6 Conclusion

Overall, we answer the question whether perceptual representations possess temporal properties in the positive, showing temporal correspondence with visual representations. Specifically, we show that flicker-frequency can be used to induce figure-ground segregation in ambiguous displays. Moreover, segregating a region as figure or background, changes one's temporal resolution for that region. These results, over two experiments, offer support for a temporal mirroring based view of visual representations.

Chapter 5

Structure-Matching of Duration Perception: A Necker Cube Study

In this chapter, we take a look at an empirical test of the structure-matching thesis of duration perception. As a quick recap, for there to be a way to combine and unite (1) time perception and (2) timing of cognition, there must exist a structure matching thesis. That is, the perception of time must be intricately linked to how our experiences themselves change in time. This chapter discusses our empirical efforts for elucidating evidence for this to hold true (for the published version, please see Singhal and Srinivasan (2022b)).

5.1 Background

A running theme of this thesis is to scoop out the factors that make 'time' special. In the previous chapter, we established a temporal correspondence between temporal sensitivity to flicker frequencies and temporal resolution in figure-ground perception. In this chapter, we look at temporal mirroring hypothesis for duration perception.

5.1.1 Do existing models of time perception take into account temporal mirroring?

The question we are faced with is the following: how do we estimate the duration of brief events? For more than a century, psychological and neurological studies have been looking for dedicated timers in the form of 'clocks' in the brain[1]. The dogma in time perception literature has been set by the pacemaker-accumulator and comparator model of time, or simply the clock model. The idea behind the model is fairly simple. An incessantly beating clock emits pulses at an approximately constant rate. These pulses are gathered by an accumulator and fed into a comparator for translating into units of judged duration. Classically, this internal clock model has been used to explain how felt duration is altered by changes in complexity, information, arousal or attentional resources allocated to an event or stimulus. The credo of the clock model disallows it from being affected by the contents of our experience. It is only that the rate of this clock or the gating mechanisms between components of the clock that are altered. This alteration can happen due to arousal or attentional resource allocation (Matthews & Meck, 2014).

Recent extensions of these models also place felt duration to be a function of temporal markers (separate from the temporality of experiences). Take, for example, felt duration being a directly proportional product of activity in perceptual classification networks (Grossman et al., 2019) or parsing of perceived events as chunks in memory (Kurby & Zacks, 2008).

On the other hand, state-dependent and intrinsic models of time perception that identify dynamics of underlying neural activity to perceived time (Ivry & Schlerf, 2008; Karmarkar & Buonomano, 2007) are founded on the temporal mirroring view (Nishida & Johnston, 2002). These models directly equate perceived duration to activity within a neural network without an intermediate clock or counter, with the duration and amplitude of neural activity predicting perceived time (Ivry & Schlerf, 2008). If we recap from the previous chapter, the same two representational format systems can be used to classify dedicated and intrinsic models of time perception into temporal marking and temporal mirroring. The extension being made here is of 'structure matching' between timing of cognition and time perception. Specifically, that the felt duration of an event structurally matches the dynamics underlying its experience.

5.2 Present Study

If our experiences are indeed temporally structured, then understanding its dynamics could offer ways to simultaneously link both timing of cognition and time perception under a

[1]The hunt for an 'organ' that senses time or psychological timekeeping has isolated the research in time perception from the rest of the study of the mind. The assumption that time is like any other sensory feature fails to appreciate its fundamentally different nature. I have written about this in detail elsewhere, see Singhal (2021)

common approach of time consciousness (see Chapter 3). A prominent phenomenon that has been used to study the temporal structure of our experiences are bistable figures. The time duration period of maintaining a particular percept while viewing such images is called dwell time (for detailed reviews on bistability, see Kornmeier and Bach (2012) and Long and Toppino (2004).

Dwell times have been equated with the temporal extension of our experiences also called the psychological 'now' (Pöppel, 1997) and also to model the relationship between different timescales of perceptual experiences (Atmanspacher et al., 2004; Pöppel, 1997)[2]. The underlying dynamics of bi-stability have been investigated also to understand the rhythmic and quasi-periodic nature of our experiences and the continuity between them (Doesburg et al., 2009; Madl et al., 2011; Van Leeuwen, 2007; Varela, 1999). One prominent finding from these studies is of correlated periods of fronto-parietal theta-gamma phase-locking while participants view bi-stable figures (Alipour et al., 2016; Başar-Eroglu et al., 1996; Doesburg et al., 2009; Kruse et al., 1996). Crucially, these periods of phase-locking are thought to be correlated with visual awareness of a percept while viewing bi-stable images (Doesburg et al., 2009; Madl et al., 2011; Van Leeuwen, 2007). These findings allow one to speculate that even though perceptual switches seem instantaneous to us while looking at a bistable image, the process of perceptual switching takes some time (Alipour et al., 2016; Başar-Eroglu et al., 1996; Doesburg et al., 2009; Kruse et al., 1996; Nakatani & Van Leeuwen, 2006; Varela, 1999). Thus, it is possible that there is a brief moment during a perceptual switch that is not perceived (Van Leeuwen, 2007). For our investigation of structure matching, this was the ideal premise.

It would allow us to investigate whether a single perceptual switch (without any changes in the stimulus per se) would alter perceived time. Our premise based on previous findings entails that if perceived time is a function of conscious experience, then trials with perceptual switches would be estimated to last for a shorter duration. This is because there would be a brief moment of absence of visual content at the time of a perceptual switch.

This stands in direct contrast to the simple pacemaker-accumulator models of time perception (Matell & Meck, 2004; Miall, 1989; Treisman, 1963), which would predict no differences in perceived durations for an interval with and without a perceptual switch. This is because there is nothing to alter the rate at which the internal clock ticks and accumulates pulses. This applies to all models of time perception based on the principle of temporal markers, where information about the duration of a stimulus is represented

[2]These accounts of 'present moment' consciousness based on dwell times are not without critiques c.f. P. White (2017)

independently of conscious experience of the same stimulus, either as magnitude representations (Walsh, 2003) or abstract memory representations (Van Wassenhove, 2009).

Variants of such models such as cognitive timers that equate perceived time proportionally with the amount of attentional resources engaged (Mattes & Ulrich, 1998; Zakay & Block, 1995), amount of information processing (Allman et al., 2014; Ornstein, 1969a) or the number of perceptual classifications (Roseboom et al., 2019) to be timed in an interval would predict lengthening of felt time[3] in trials that contain a perceptual switch. This follows from the idea that an interval with a perceptual switch draws more attention, has more information, or is more complex than an interval without a perceptual switch.

However, these models do not take into account the underlying dynamics that realize our conscious experiences, such as those linking intrinsic temporality in state dependent networks for perceived time (Ivry & Schlerf, 2008). Drawing out predictions from theories based on temporal mirroring would lead one to predict that trials in which a perceptual switch occurs would be perceived as shorter than trials with no switch. This is based on the correlations of theta-gamma phase-locking and phase resetting observed at the time of perceptual switching between two perceptual states (Doesburg et al., 2009; Madl et al., 2011; Van Leeuwen, 2007). In Chapter 3 our formalization of this link (Singhal & Srinivasan, 2021) between experience in time and experience of time (specifically duration perception here) makes explicit this prediction as a test for the structure matching thesis in experience (i.e., the possibility of temporal isomorphism between our experiences and their contents).

To test these predictions, we conducted three experiments. In the first two experiments, the occurrence of a perceptual switch was induced by allowing a rod to pass through the cube in a certain way. This rod either violated or maintained the perceived 3D orientation of a Necker cube as it passed across the screen (see figure 5.1). The violation of geometry was expected to produce a switch in a reasonable number of trials. We hypothesized that trials in which a switch occurs would be perceived as shorter than trials in which it does not. In experiment 1, we asked participants to estimate the duration of an interval and explicitly report if a switch occurred during this interval in the way that they saw the cube. In experiment 2, we asked participants to report only the perceived presentation duration of the rod (assuming that enough trials in which the geometry was violated led to perceptual switches). Experiment 3 was carried out as a free viewing paradigm with no perceptual switch inducer (i.e., moving rod), allowing us to rule out confounds

[3]Dr. Roseboom disagrees with this interpretation. Over a personal communication, he suggested testing this claim empirically.

from a moving secondary object. We expected that trials with a reported perceptual switch would be judged as lasting for a lesser time than trials with no reported perceptual switch. Finally, we supplemented these empirical investigations with a phenomenological demonstration to support our claims.

5.3 Methods: Experiments 1 & 2

The first two experiments in this study were nearly identical, except for differences in what the participants were asked to report.

5.3.1 Participants

Both experiment 1 and 2 had the same number of participants (N = 23). The age and gender distributions were similar in both experiments (Experiment 1: 12 females, median age = 23 years; Experiment 2: 11 females, median age = 22.5 years). The sample size was calculated apriori for a main effect of switch on perceived time (η = 0.1, Power = 0.85, α = 0.05; required N = 23).

5.3.2 Apparatus and Stimuli

The stimuli were brief clips presented on a CRT monitor. The participants sat approximately 55 cm away from the screen. The clips depicted a Necker cube (13°visual angle) and a bar-like object (10°visual angle).

5.3.3 Procedure

A Necker cube was presented at the center of the screen, and participants were instructed to view it as facing up or down in separate blocks. When they were able to see it in the instructed perspective and ready to begin a trial, they pressed a key. Each trial was self-initiated. As soon as they pressed the key, the bar-like object passed across the screen. In doing so, the object either maintained or violated the geometry of the Necker cube perspective being seen by the participants. By passing 'above' or 'below' the cube (see figures and video for reference). This allowed us to induce a perceptual switch or maintain the stability of the perception of the cube (see Figure 5.1 for a depiction). The

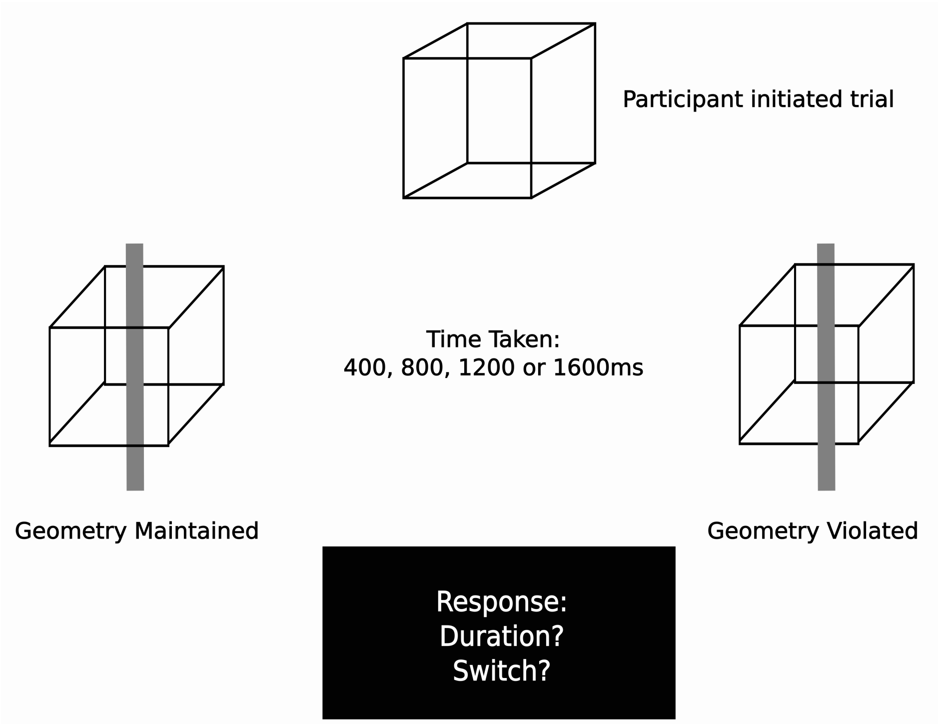

FIGURE 5.1: Schematic of the procedure of experiments 1 and 2. Experiment 2 had no report of perceptual switches.

bar object could take four different duration intervals to pass across the screen (400, 800, 1200 or 1600 milliseconds). At the end of this duration, the bar, and Necker cube disappeared from the screen. In experiment 1, participants were required to estimate the duration interval from keypress to disappearance of the cube and also whether they experienced a perceptual switch. The only difference between the two experiments was that in experiment 2, participants were supposed to only report the duration of the bar object.

In both experiments, the same experimental parameters were used. They both had 320 trials (80 trials per duration). Half the trials had geometry violations, while the other half were to maintain the geometry of the percept of the Necker cube. The experiment took approximately 40 minutes to complete. Before participants ran the main experiment, they were provided a training block of 24 trials. The training block was used to familiarize participants with the four durations and the task of estimating duration intervals. The training task was done only a moving bar (no cube was present). Participants' training data was used to see if they could discriminate the four different duration intervals.

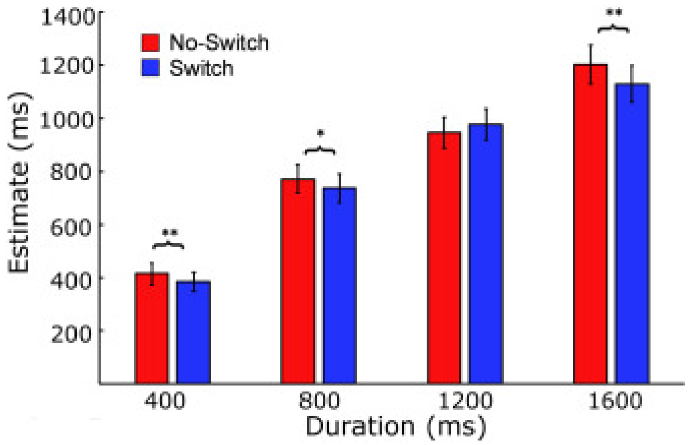

FIGURE 5.2: Results of Experiment 1. Comparing duration estimates in trials where participants reported a switch (blue) or no perceptual switch (red). The error bars show the standard-error of means. The y-axis plots the duration interval estimate.

5.3.4 Data Analysis

Responses of duration estimates were log transformed for both the experiments to avoid violations of normality. The responses were then averaged for each duration and condition. Subsequently, a two-way repeated-measures ANOVA was performed.

5.3.5 Results

For both the experiments, we found a main effect of duration intervals. Essentially indicating that the participants could differentiate between the lengths of different intervals, in experiment 1 ($F(3, 66) = 107.35$, $p < .001$, $\eta 2 = 0.83$) and experiment 2 ($F(3, 66) =$ 146.73, p¡.001, $\eta 2 = 0.87$).

Both experiments also showed a main effect of perceptual switches. The main effect indicated that trials with reported perceptual switches (experiment 1) and trials with geometric violations (experiment 2) were reported as lasting for shorter a duration than trials with no perceptual switches or geometry violations (refer to Figures 5.2 and 5.3, $F(1, 22) = 14.32$, $p = .001$, $\eta 2 = 0.39$ and $F(1, 22) = 6.20$, $p = .021$, $\eta 2 = 0.22$, respectively. Another commonality between the two experiments was also a significant interaction effect (Experiment 1: $F(3, 22) = 5.07$, $p = .008$, $\eta 2 = 0.19$; Experiment 2 $F(3, 66) = 4.08$, $p =$ .010, $\eta 2 = 0.156$; see Tables 5.1 and 5.2 for post-hoc comparisons).

TABLE 5.1: Experiment 1: Post-hoc comparisons for the interaction between duration and reported perceptual switch

Duration Interval	t statistic	p value	Cohen's d
400	3.46	0.002	0.72
800	2.17	0.041	0.41
1200	1.56	0.133	0.32
1600	3.22	0.004	0.67

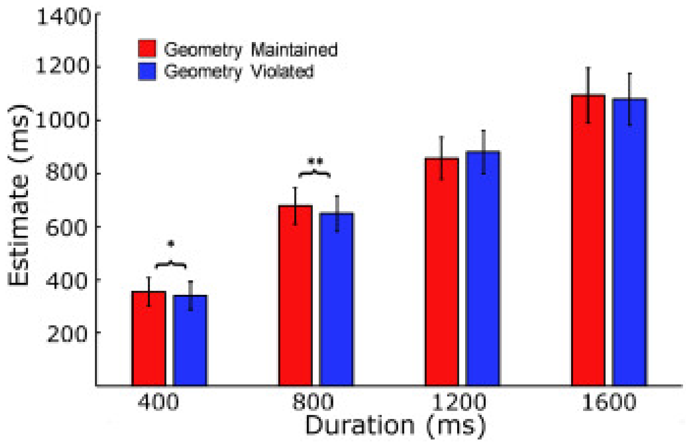

FIGURE 5.3: Results of Experiment 2. Comparing duration estimates in trials with and without a geometric violation. Here, participants only reported how long the bar took to go across the screen. Trials were split into geometric violated (blue) or geometry maintained (red) as proxies for perceptual switches.

TABLE 5.2: Experiment 2: Post-hoc comparisons for the interaction between duration and geometry

Duration Interval	t statistic	p value	Cohen's d
400	2.55	0.018	0.53
800	3.09	0.005	0.64
1200	1.65	0.112	0.35
1600	0.29	0.77	0.04

5.3.6 Discussion

The two experiments allowed us to demonstrate that trials with perceptual switches are indeed perceived as shorter than trials with no perceptual switches. The results are in line with predictions from the temporal mirroring representations formats. This is because, perceived time is a function of perceived contents. It was possible that our results in experiment 1 are because of a split of attentional resources between reporting perceptual switches and judging duration intervals. One could argue that the contraction of perceived time is due to distractions of the perceptual switch. To rule this out, we did experiment 2 where participants performed only a single task (duration judgements). We assumed that trials with geometric violations would most likely lead to perceptual switches, and trials where the geometry was maintained would most likely ensure that no perceptual switches occur. Not only did we replicate our results in experiment 2, but we found no difference in overall duration judgements. If our results are solely due to attentional effects, then reducing task-requirements would have led to a general difference in estimates of duration. We did not see this in our results. Together, these help us rule out the possibility that our results were due to attentional demands. In the next half of this chapter, we rule out additional confounds and create a phenomenological illusion to further strengthen our claims.

5.4 Experiment 3

The first two experiments used a secondary object (bar) to induce perceptual switches. It is possible that our results were confounded by demands of attending to a moving object, speed of this moving object and or motion itself. To rule out these possible confounds, we performed experiment 3. We chose to now use a free-viewing paradigm where only the Necker cube would be presented. To mark duration intervals which participants would later estimate, we changed the colour of the Necker cube for variable time intervals (600, 800, 1000, or 1200ms). Our prediction remained the same, that trials in which a switch occurs would be reported as having a briefer presentation. However, now we expected to demonstrate this with a stronger effect size, having now removed the distraction of a moving bar.

5.4.1 Methods

5.4.2 Participants

We recruited a total of 26 participants (10 females, median age = 26 years, age range = 23–31 years). Out of these, data from two participants were excluded for having insufficient number of trials with a perceptual switch for any duration interval (exclusion criterion: less than 25% trials with a perceptual switch.).

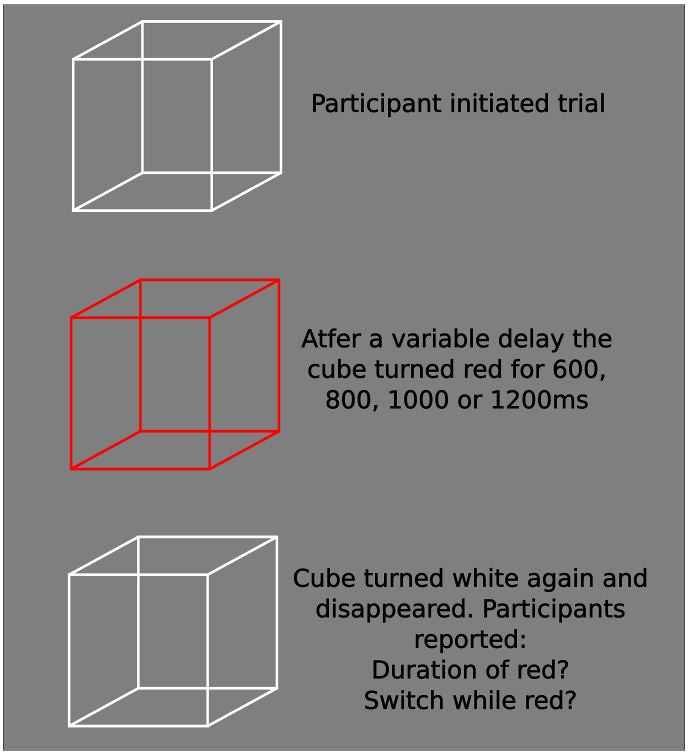

FIGURE 5.4: Schematic of the procedure of experiment 3 of Study 2

5.4.3 Apparatus

The size of the cube was the same (13°visual angle). The experiment was conducted on a 24' inch LED monitor. The participants sat at a distance of approximately 55 cm away from the screen.

5.4.4 Procedure

The procedure for experiment 3 was similar to experiment 1. Participants were asked to report both perceptual switches and duration estimates. The major change here was that perceptual switches were not induced. A Necker cube was presented centrally with its outline drawn in the colour white. After a certain delay, the lines drawing the Necker cube turned red for a fixed duration picked from 600, 800, 1000 or 1200ms. The cube remained in red for this duration and returned back to white afterwards. Participants were asked to report if they experienced a perceptual switch while the cube was red and how long the cube was red (see Figure 5.4).

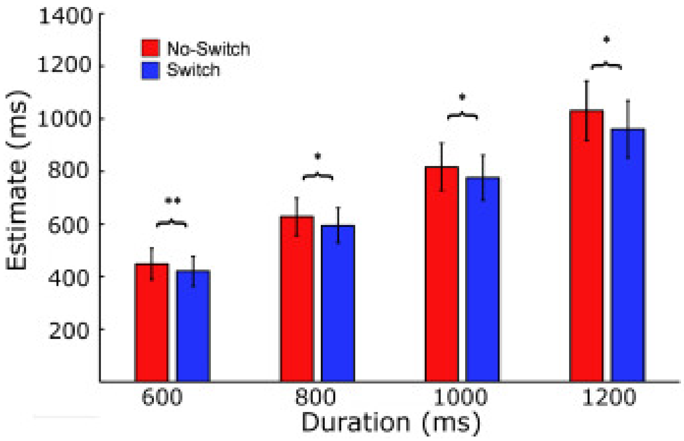

FIGURE 5.5: Results of Experiment 3. Comparing duration estimates between trials with and without a perceptual switch.

5.4.5 Results

Before running the duration estimate analysis, we checked to see if we had sufficient number of trials for each participant in which they reported a perceptual switch. On average, participants reported a perceptual switch in 42% of the trials across the four duration conditions. This left us with a balanced split between the switch and no-switch trials.

Once again we performed a two-way repeated measures ANOVA with reported perceptual switches (yes/no) and duration (600ms, 800ms, 1000ms, and 1200ms) as the two factors. Participants could differentiate the duration intervals, indicated by a main effect of duration, with estimates of time increasing with duration $F(3, 69) = 50.9$, $p < .001$, $\eta 2 = 0.66$. More crucially, consistent with the results from experiments 1 and 2, we found a main effect of perceptual switching on perceived time $F(1, 23) = 15.94$, $p < .001$, $\eta 2 = 0.41$. In agreement with the first two experiments, participants again estimated trials with perceptual switches to last for a shorter duration. This was the case for all duration intervals (see Figure 5.5 and Table 5.3). We also found a larger effect size in this experiment. We did not find a significant interaction effect between duration and reported perceptual switches, $F(3, 69) = 1.18$, $p = .32$, $\eta 2 = 0.04$.

5.5 General Discussion

In this study, we investigated whether there is evidence in favour of representational format where duration intervals of time are their own representation. Specifically, whether

Table 5.3: Experiment 3: Post-hoc comparisons for the interaction between duration interval and reported perceptual switches

Duration Interval	t statistic	p value	Cohen's d
600	2.55	0.018	0.53
800	3.09	0.005	0.64
1000	1.65	0.112	0.35
1200	0.29	0.77	0.04

we could empirically offer support for the assumption that how we experience time is isomorphic to the timing of those experiences. We did this by examining participants' reports of felt time in intervals with and without a perceptual switch. We assumed that if our experiences are temporally structured, then breaks in visual experience over time (periods of perceptual switching) would co-occur with loss of felt time. Our results here are concordant with predictions from such extensional models (Droege, 2009; Madl et al., 2011; Singhal & Srinivasan, 2021; Van Leeuwen, 2007), wherein perceived time is a function of consciously experienced content. We proposed that trials in which a perceptual switch occurs are perceived as lasting for shorter durations (compared to trials without a switch) since there is a brief gap at the moment of a perceptual switch where there is an absence of visual awareness even though switches seem instantaneous. Over three experiments, we showed that this purported gap in content over time (perceptual switch) alters our perception of time. Our study and results together offer support to the thesis of temporal isomorphism (Fekete et al., 2018; Moutoussis & Zeki, 1997a; Phillips, 2014b; Singhal & Srinivasan, 2021) and the inexorable link between consciously experienced content and time perception.

Models of time perception based on the number of perceptual classifications or information processed (Grossman et al., 2019; Roseboom et al., 2019) or abstractions from memory (Van Wassenhove, 2009) cannot account for our results. Since for our design, they would predict that perceptual switches would dilate felt time. Similarly, temporal marker-based models also cannot account for our results, as their temporal mechanisms do not allow contents of conscious experience to concurrently alter perceived time (Arstila, 2017; Johnston & Nishida, 2001; Nishida & Johnston, 2002). For alternate explanations of our results, we next consider ideas from attention and time, and event segmentation theory.

5.5.1 Alternative Explanations

It could be that a perceptual switch in experience draws attention away from the timing tasks, and thus trials with a perceptual switch are perceived as shorter than trials that do not have a distracting perceptual switch. Thus, it could be that our results were confounded by divided attention and can be explained using "inattention to time" due to limited attentional resources (Brown, 2008, 2010; Zakay & Block, 1995). While this is possible and cannot be completely excluded as an alternative explanation, comparing the results from the first two experiments makes it less likely. Our results remain the same even after asking participants to perform a single task of only reporting duration in experiment 2. Moreover, there was no difference in overall duration estimates between the two experiments (a Bayesian independent t-test provided strong evidence in favour of this null hypothesis, BF = 5.85). These two empirical findings weaken the top-down resource limitation based 'inattention to time' explanation.

It is quite possible that the change in visual experience captures attention (somewhat akin to bottom-up attentional capture) such that it forces "inattention to time" leading to reduced duration estimates in a switch trial. The current study cannot rule out this potential possibility, and further experiments would be needed to clearly establish the role of such an attentional capture on time perception.

Results from all three of our experiments can be also explained via event-segmentation theories. Models according to which perceived duration is a function of abstract representations from memories based on event segmentation (Kurby & Zacks, 2008; Liverence & Scholl, 2012) could potentially accommodate our results. This is despite these models positing a temporal marker based representational format. These models propose that continuous streams of experience are segmented into discrete events to make sense of and remember what we see (Bangert et al., 2020; Yousif & Scholl, 2019).

Here, the theory would argue that a perceptual switch segments the stream of Necker cube into two halves with a fuzzy overlapping event boundary (moment of the switch), thus this duration is remembered (instead of perceived) as lasting for a lesser duration than the same interval without a switch (and also without an intermediate event boundary). If this holds, it remains unclear whether trials with perceptual switches are judged/remembered to be shorter or actually perceived to be shorter (an illustration of this is done in Figure 5.6). One possible way to break this deadlock is proposed in Singhal and Srinivasan (2021), where we argue for a phenomenological contrast in settling such debates (see also Siegel (2007)).

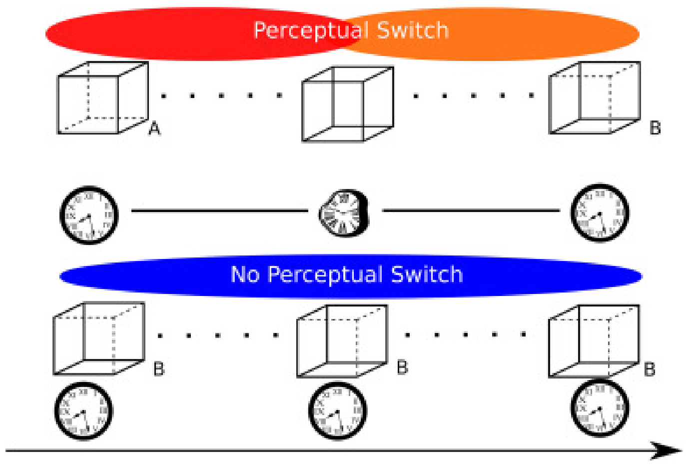

FIGURE 5.6: A schematic to show two competing explanations of the *wrinkle* in time of duration with a perceptual switch.

5.5.2 A phenomenological demo to differentiate temporal mirroring and event segmentation during perceptual switches

Singhal and Srinivasan (2021) conceptualized temporal evolution of conscious experiences in terms of three interconnected hierarchical levels (see also Chapter 3). Going by the hierarchy, if the Necker cube perceptual switch is extended in time, that is, both experience of and in time are absent at the moment of a switch, then there should be a putative "blink" in visual awareness at the time of a perceptual switch. However, if the switch just leads to an interval being remembered as lasting for a shorter duration, then there should be no such phenomenological change. To put it another way, people's visual awareness of the content of Necker cube would blink along with a perceptual switch if the structure matching these is true.

Here we present a small video clip to demonstrate that it is indeed phenomenologically true that a perceptual switch leads to a blink in visual awareness at the moment of a switch, and it is this 'wrinkle in time' which leads to contraction of felt time. Please open the video clip on your computer to experience the demo. The clip loops over a repeated presentation of a number sequence (1–2–3-4) inside a Necker cube. To demonstrate for yourself this 'blink', we recommend you sit at a comfortable distance away from your computer screen while squinting in a manner such that the whole cube and the number stream are simultaneously visible. You will notice that at the time the Necker cube switches, you would miss seeing one of the numbers in the repeating number sequence. A repetition stream might look something like this 1–2-switch-4, where one might miss out on seeing '3' entirely if the switch occurs around the time. Participants from experiment 3 were shown this clip on a loop and asked to report if they thought they missed a number at the time of a perceptual switch. Most of them (17/24) did report this 'blink'. The demo can be improved in the future with tighter empirical controls.

5.6 Conclusion

Collectively, we illustrate here a link between duration of experience and experience of duration. In three experiments, we show how models of time perception, which are unhitched to timing of cognition, are unable to predict changes in felt time driven by a single perceptual switch. Similarly, models that predicate amount of stimulus complexity and information processing make predictions in the wrong direction when they are not linked to underlying dynamics of visual experience. Finally, we strengthen our empirical results by backing them up with a phenomenological demonstration that exemplifies the link between experiences in and of time and rules out alternate abstract memory and representation-based theories of time perception.

We conclude here by proposing a need for the study and theories of time perception to hook up with the larger and broader study of temporality in consciousness for a unified understanding of temporal experiences(Arstila, 2017; Singhal & Srinivasan, 2021).

Chapter 6

Multi Timescale (D)Evolution of Experience

This is the final empirical chapter of this monolith. Here, we discuss a study done to test the temporal property of consciousness, which states that experience evolves and devolves over multiple timescales. This property forms a key tenet in the theoretical developments behind this thesis and our proposed framework of hierarchical temporality.

6.1 Introduction

How do contents of our visual perception unfold over time? Most theories of consciousness propose singular timescales over which we become aware of visual contents of perception (Kent & Wittmann, 2021). The ersatz"time" of present-day consciousness research is that of "early vs. late"[1] realization of experience. The theories clubbed into the early camp estimate that it takes somewhere between 100–200 milliseconds to consciously perceive a stimulus, whereas the late camp argues for a duration of 300–450 milliseconds (Förster et al., 2020). Nevertheless, they are in agreement that conscious experience evolves over a single timescale. Even theories that champion a phenomenology-first approach (for e.g., Integrated Information theory), fail to extend experience beyond a singular timescale (see Singhal et al. (2022) for a criticism).

[1]This line of thinking also has a cousin with an ersatz neuroscience of consciousness of "back vs. front" of the brain.

In parallel to these theories, there are attempts to demonstrate that experience unfolds over multiple timescales. We reviewed some of this work in Chapters 2 and 3 when we discussed models of timing of cognition. There are models and frameworks of dynamics of cognitive processes that look at clustering of various temporal regularities across experiments and disciplines of cognitive science and neuroscience to point at the fact that our minds work over different temporal scales. Prominent and pioneering examples of these over the last three decades includes works of Pöppel (1997), Varela (1999), Atmanspacher et al. (2008), Kent (2019), Wittmann and Van Wassenhove (2009) and many others. The running theme across these papers is that different perceptual processes unfold at different timescales.

In our own work we have tried to collate this understanding and extend it to understanding the timing of processes involved in awareness along with temporal phenomenology and its underlying neural dynamics (Singhal & Srinivasan, 2021). Over the last three chapters, much of this work has been detailed. Here, in the penultimate chapter of the thesis, we introduce you to a novel way of studying multiple timescales in visual awareness. So far, the evidence for multiple timescales have come from pooling large amount of empirical studies or using neuroimaging methods where neural signatures with different latencies or regularities are jointly correlated with an experimental task. In this chapter, we introduce the reader to a novel experimental paradigm where multiple timescales of how experiences evolve and devolve can also be studied. For this, we develop a new variant of the Continuous Flash Suppression (CFS) paradigm called the perturbatory Continuous Flash Suppression (pCFS).

6.2 Continuous flash suppression

CFS is a masking technique that employs a binocular rivalry setup. It involves presenting different inputs to each eye of a person. For instance, one eye could be shown a flickering noise mask (for e.g., mondrians, circles or scrambled images) and the other eye is presented with a target image of interest (see Figure 6.1). When viewed under an optimal binocular rivalry apparatus, participants see a fused binocular image of the two stimuli presented. These overlap entirely in a participants' perception. As the presentation goes on, the flickering noise mask attempts to hide the target image from appearing into awareness. Participants initially report seeing only the noise-mask, but slowly over a couple of seconds, the target image breaks-through into awareness. Since its formulation two decades ago (Tsuchiya & Koch, 2004), CFS has become a popular tool to investigate various aspects of visual awareness (Stein, 2019). The CFS paradigm is typically employed to investigate

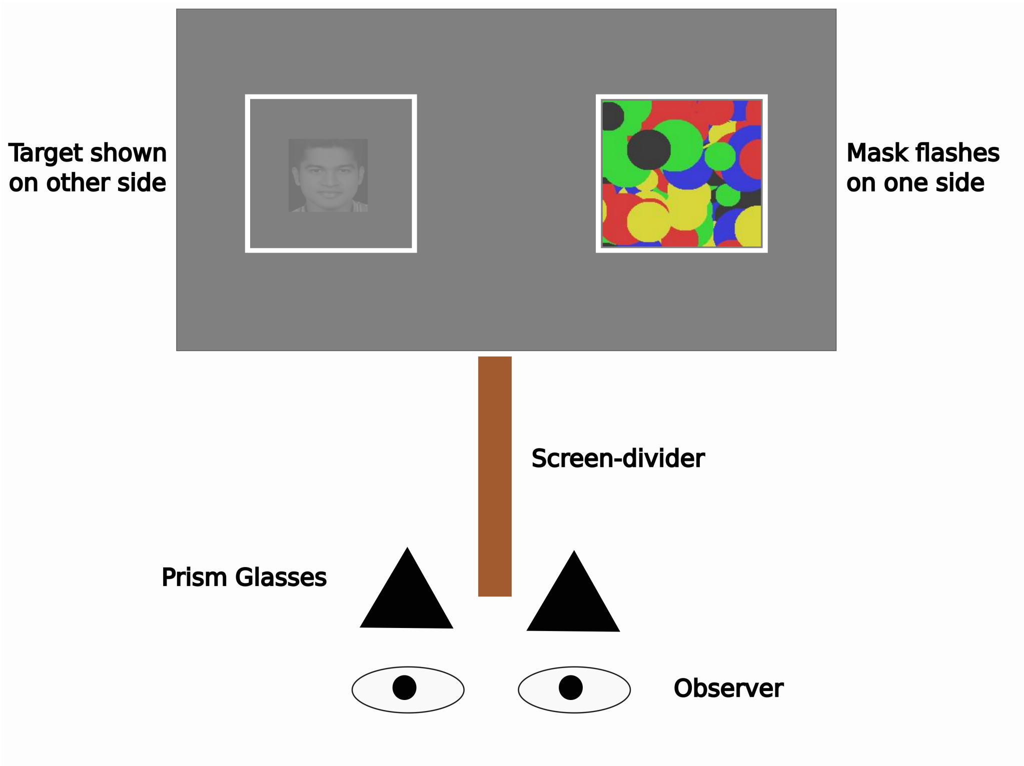

FIGURE 6.1: Schematic of the setup used for the CFS experiments throughout this study.For the real lab setup and stimuli samples, click on the this link.

(i) whether and which perceptual processes occur before stimuli break into awareness or in the absence of awareness, and (ii) whether and which perceptual properties are prioritized for an expedited entry into awareness.

Investigations of the paradigm itself, that looked into mechanisms responsible for suppression, have highlighted the role of spatial and temporal frequencies employed within the flickering mask. Specifically, masking strength (in terms of proportion and duration of suppression) has shown to be influenced by the choice of temporo-spatial characteristics of the mask. Several studies have shown that breakthrough duration of stimuli are much longer when the temporal frequency of the mask is lower than 10 Hz[2]. For instance, peak suppression varying as a result of flicker frequency, reportedly in the range of 1-7 Hz (Drewes et al., 2018a; Han et al., 2018a; Zhu et al., 2016). Whereas these studies have looked at flicker frequency as a variable for optimal suppression, they have not looked at systematically varying them as a function of the phenomenological nature of a task. These studies were largely motivated to study mechanisms of suppression in CFS and the CFS paradigm itself. These studies did not look to test multiple timescales of visual awareness.

[2]The default flicker frequency in CFS paradigms has been and continues to be 10Hz, despite the recent evidence that it may not be the most effective.

Here, we devise a new variant of CFS to use it to investigate different flicker frequencies sui generis. Our aim being to investigate whether specific flicker frequencies exclusively perturb specific kinds of tasks.

6.3 Present Study

The logic behind the present study comes from the same deductions involved in showing a double dissociation in neuropsychology. Lesions (or temporary perturbations) are used to functionally dissociate two different brain regions by showing mutually exclusive performance deficits on two different tasks. A classic example of a double dissociation in neuroscience is of independent language deficits by damage to the Broca's and Wernicke's areas. Here, the damage to the former affects language production but not language comprehension, whereas damage to the latter affects language comprehension but not language production. How does this logic apply to our present efforts here?

We start by assuming that the flicker rate of the mask in our CFS can lesion the workings of a perceptual process operating in a timescale close to that of the flicker. Thereafter, we can use a set of flicker frequencies and a set of perceptual tasks. Then, if we can show that one particular flicker frequency (from the larger set) maximally inhibits one particular perceptual task (again from the larger set) but not other flicker frequencies and not other tasks, then a demonstration of a temporal double dissociation would be complete. This is exactly our attempt here.

We set out to show that (i) different flicker frequencies maximally hinder different kinds of behavioural tasks, (ii) where these flicker frequencies ranges map onto the temporal hierarchy we developed (see Chapter 3) and correspondingly, (iii) the phenomenological nature of these different behavioural tasks also maps onto the phenomenology of each of the three levels of the temporal hierarchy.

To demonstrate this tripartite link, we conducted four experiments. Each experiment used a CFS paradigm with the same set of flicker frequencies (1Hz, 4Hz, 10Hz and 25Hz). We used these flicker frequencies to approximate the timescales proposed in our temporal hierarchy (1, 4 and 25 Hz) and to compare it with the standard paradigm (10Hz). All four experiments employed prism glasses and a screen separator to implement the CFS setup (see Figure 6.2).

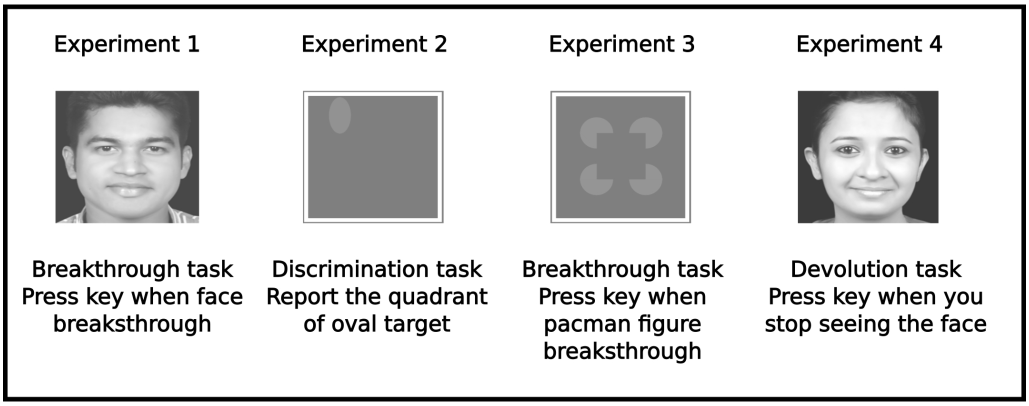

FIGURE 6.2: The four tasks used in four different CFS experiments.

6.4 Experiment 1

6.4.1 Participants

We recruited 12 participants (4 females, mean age = 25.6 years) based on an apriori sample size calculation. Sample sizes were based on conservative estimates of effect size calculations from a previous study done by Han et al. (2016). All participants were tested for visual acuity before they did the experiment. Participants were compensated for their time.

6.4.2 Apparatus

All four experiments reported in this chapter used the same apparatus and setup. A 21' inch LED monitor with a refresh rate of 100Hz was used. The monitor was split for viewing into two equal halves by a wooden screen. This wooden screen extended from the screen to a chin rest placed on the other end of the table (total distance 120 cm). Participants sat with their heads placed on a chin rest. To converge the split display binocularly, a parallel projection was required. For this, a custom prism glass was used (dioptre 10; base out). When viewed through these glasses, the projections from either side of the screen hit the eyes in parallel (please refer back to Figure 6.1).

6.4.3 Procedure

On entering the lab, participants were first tested for visual acuity. After this, participants were seated in front of a screen and asked to place their heads on a fixed chin rest. They were asked to wear prism glasses and look at the monitor. Before we began the experiment, participants were asked to report if they could see a single square drawn on the screen (a merged overlapping image of two squares). This was done to ensure that the CFS setup offered optimal convergence for each participant. After this, the main experiment began. Participants were asked to self-initiate each trial. They were told that some colourful flashing circles would be presented on one side of the screen and a picture of a face would be shown on another side of the screen. They were told to expect to initially only see the flashing circles, and that slowly the image of the face would appear. They were asked to press the space-bar on the keyboard as soon as they saw the face. Participants were also told that on some trials they would not be able to see a face because it may not break suppression, or because there was no face on that trial at all. In such cases, they were asked not to press any key.

Each trial of the experiment began with an initial period of blank flickering. That is, for the 500ms, only the noise mask was presented on either side of the screen. It flickered at one of four flicker frequencies (1, 4, 10 or 25 Hertz). After 500ms, a face was presented on the other side of the screen. The contrast of the face was ramped up in equal steps split over 100ms to avoid abrupt onset effects. The contrast of the target picture ramped up to 60% and stayed at the value. The mask continued to flicker along with the target on the other side until the participant pressed a key, or if a trial timed out (after 10 seconds). The target and mask locations were counterbalanced between trials. A male and female face were used as targets. Each face was presented 14 times for each flicker frequency (14×4) on either side of the screen ($14 \times 4 \times 2$) making for a total of 112 trials. The breakthrough suppression duration were averaged across different flicker frequency trials (28 trials for each) for only target present trials. There were additionally 15% trials added as catch trials. In the catch trials, no face appeared at all during a trial. Participants were instructed to not press the response key if they did not see a face. These catch trials were used to make sure participants followed instructions and did not just press the response key arbitrarily. If a participant had more than a 20% error rate for catch trials, they were to be excluded. However, no participant failed this exclusion criterion.

6.4.4 Results Experiment 1

We averaged breakthrough times for target present trials separately for each of the four different flicker frequencies. Almost all participants performed at nearly a 100% hit rate (only 4 participants missed a target, with a maximum miss rate of $\sim$3%). A one-way repeated measures ANOVA was performed on averaged breakthrough times with flicker

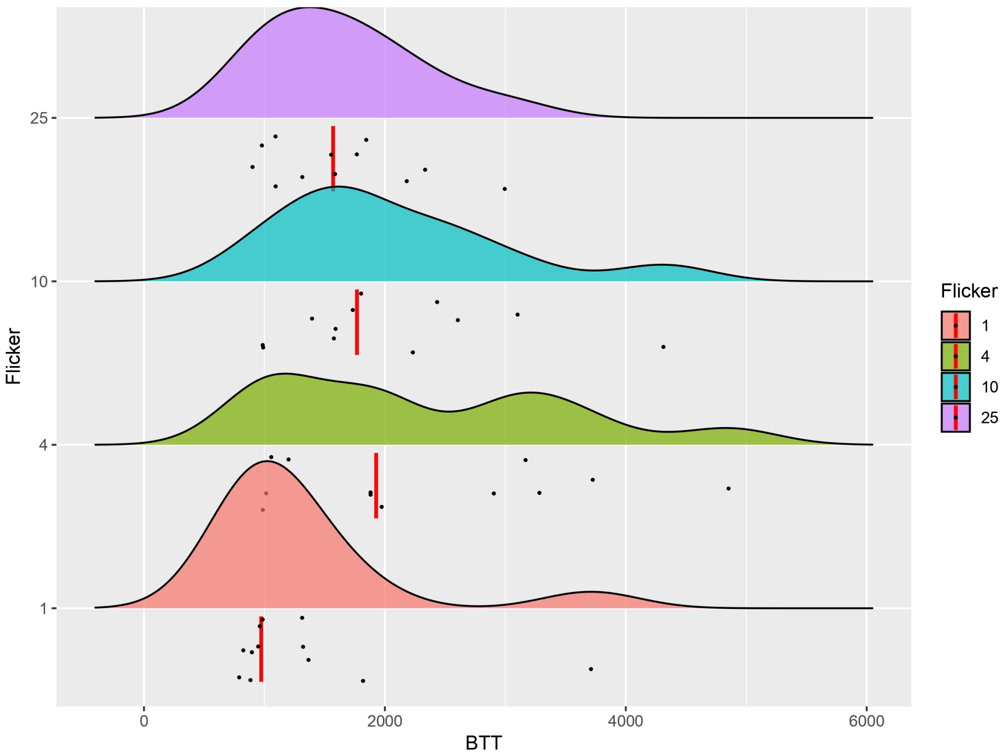

FIGURE 6.3: Results of CFS Experiment 1. Dots represent individual participant data, the red bar marks the mean. The density plots are generated using Gaussian kernel density estimation, uniquely for each flicker frequency (marked in different colors).

TABLE 6.1: Results from CFS Experiment 1

4Hz flicker compared	t statistic	Holm corrected p value	Cohen's d
1Hz	5.75	<0.001	1.66
10Hz	1.5	0.15	0.44
25Hz	3.94	0.002	1.14

frequency as the independent variable. Our results showed a significant main effect of flicker frequency on breakthrough times, ($F(3, 33) = 13.1$, $p < .001$, $\eta 2 = 0.54$). Post-hoc tests revealed that participants reported that the target face broke slowest into their awareness when the mask flickered at 4 Hz (see Table 6.1 and Figure 6.3).

6.5 Experiment 2

6.5.1 Participants

The same number of participants (N = 12) were again recruited for experiment 2 (3 females, mean age = 27.7 years). All participants were once again tested for normal visual acuity and were compensated for their time.

6.5.2 Apparatus

Same as in experiment 1.

6.5.3 Procedure

Experiment 2 also had self-initiated trials. Each trial began with a blank period of 500ms where only the noise-mask flickered on any one side of the screen. Over a period of 1000ms, an oval appeared on the other side of the screen. The contrast of the oval was ramped up in equal steps over this interval. The oval appeared close to one of the four edges of the square. In each trial, the position of the oval was slightly jittered (1°) to avoid adaptation effects. Participants were asked to indicate by a keypress which quadrant the oval appeared in. If they did not respond within 10 seconds, the trial timed out. There were no catch trials. There were a total of 144 trials (4 locations x 4 flicker frequencies x 2 sides of the screen x 4 repeats).

6.5.4 Results Experiment 2

To compare the independent variable of interest (Flicker frequency of the mask), we averaged response times across participants separately for each flicker frequency. A repeated measures one-way ANOVA was performed on these averaged values. The results showed a main effect of flicker frequency, ($F(3, 33) = 23.2$, $p < .001$, $\eta 2 = 0.68$). Post-hoc comparisons showed that participants were slowest to identify the location of the hidden oval target in trials with a 10Hz flicker (see Table 6.2).

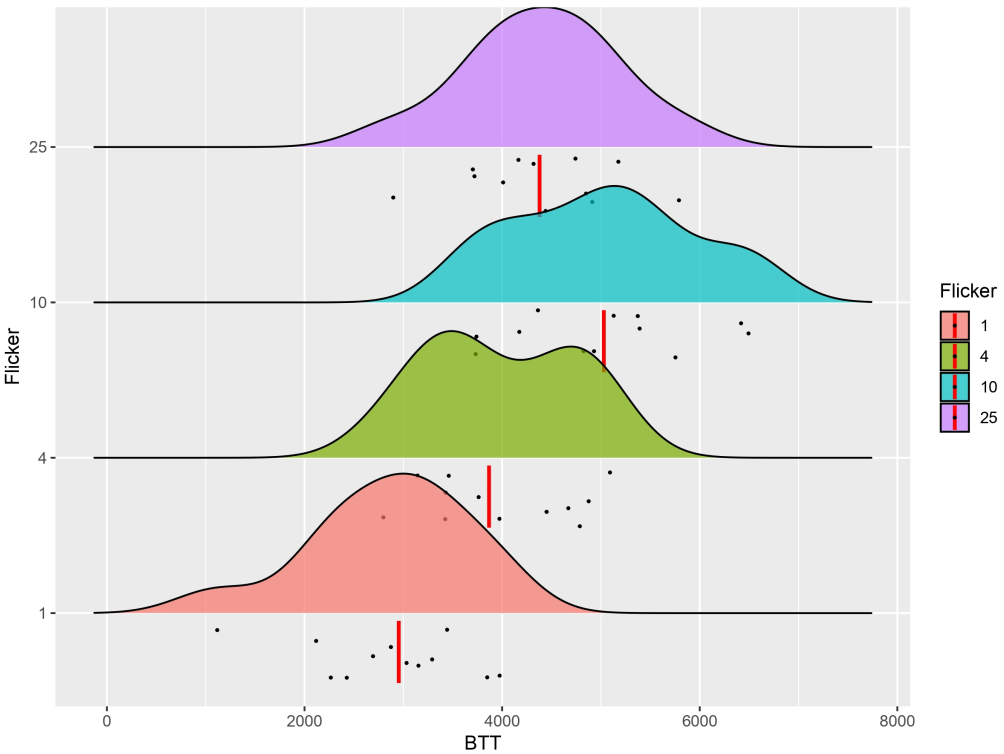

FIGURE 6.4: Results of CFS Experiment 2. Dots represent individual participant data, the red bar marks the mean. The density plots are generated using Gaussian kernel density estimation, uniquely for each flicker frequency (marked in different colors)

TABLE 6.2: Results from CFS Experiment 2

10Hz flicker compared to	t statistic	Holm corrected p value	Cohen's d
1Hz	8.11	<0.001	2.34
4Hz	3.88	0.001	1.12
25Hz	2.36	0.04	0.68

6.6 Experiment 3

6.6.1 Participants

Yet again, we recruited a set of 12 participants for the experiment (5 females, mean age = 25.6 years).

6.6.2 Apparatus

Same

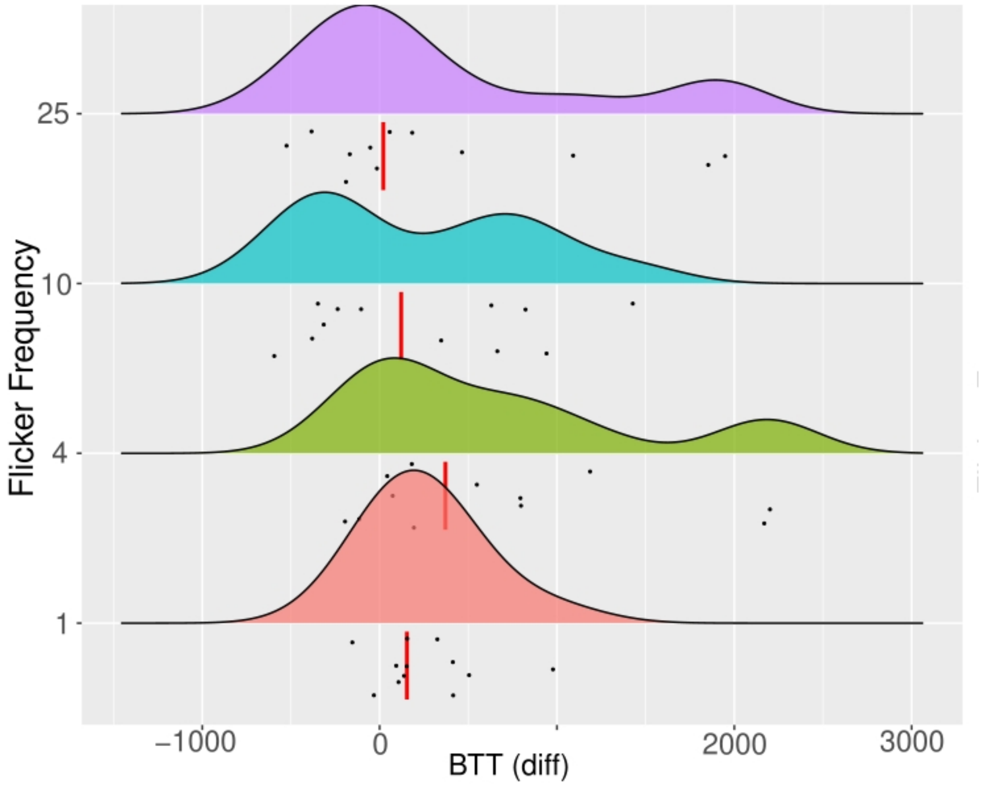

FIGURE 6.5: Results of CFS Experiment 3. The plot shows the difference in breakthrough times between the two conditions (randomly aligned − aligned to form a Kanizsa).

6.6.3 Procedure

This experiment was similar to experiment 1. Participants were asked to press a key as soon as a target broke through into their awareness. Instead of faces, we used geometric shapes here (specifically, pacman-like circular figures). Two sets of geometric shapes were used. One set formed an illusory Kanizsa square, whereas the other set did not. Participants began each trial with a keypress. After a blank period of 500ms, the image of the geometric set ramped up. The image remained on the screen for 10 seconds, while the flash continued flickering. A trial ended when participants reported the broke-through. Otherwise, in the absence of a keypress, the trial timed out after 10 seconds. There were a total of 16 catch trials where no image was displayed, these acted as tests for false alarms and arbitrary responding.

Table 6.3: Results from CFS Experiment 3. Effect size given as Rank Biserial Correlation (RBC).

Configuration (Random > Kanizsa)	W	Holm corrected p value	RBC
1Hz	71	0.009	0.82
4Hz	69	<0.001	0.77
10Hz	54	0.15	0.39
25Hz	49	0.002	0.26

6.6.4 Results Experiment 3

We compared the difference in the break through times between the trials in which the geometric set formed a Kanizsa square and trials in which it did not. This comparison was done separately for each flicker frequency. Our expectation was that this difference would reduce as the flicker frequency increased. Our results were consistent with this expectation. Firstly, a significant break-through benefit for the illusory Kanizsa square was present only when the mask flickered at 1Hz and 4Hz (see Table 6.3 for details). Moreover, the effect size for these differences reduced with increasing flicker frequency, with the smallest effect size for the fastest flickering trials (see Table 6.3). We also sought support in favour of the null hypothesis that trials in which the mask flickered at 25Hz offered no advantage to the illusory Kanizsa square. A Bayesian paired t-test showed that there was moderate evidence to support this null hypothesis (Bayes' Factor in favour of null = 2.7).

6.7 Experiment 4

6.7.1 Participants

Another pool of 12 participants were recruited for the experiment.

6.7.2 Apparatus

Same

6.7.3 Procedure

This experiment was a modification to experiment 1. Instead of reporting breakthroughs, participants were asked to press a key as soon as a target broke away from their awareness.

Table 6.4: Results from CFS Experiment 4

1Hz flicker compared to	t statistic	Holm corrected p value	Cohen's d
4Hz	4.27	<0.001	1.23
10Hz	5.34	<0.001	1.56
25Hz	2.35	0.07	0.67

A face was presented on the screen, that was initially visible to the participant and over time would be suppressed by the flickering circles on the other side of the screen. The face was presented from the beginning at 60% contrast for 2 seconds and then was ramped down in contrast (reduction in 10% contrast every second). Participants were asked to press a key as soon as the face disappeared from their awareness. The trial timed out after a total duration of 10 seconds (2+ 6+ 2 seconds blank). To ensure that participants were not randomly responding, 16 catch trials were used where the face never disappeared from the screen. Along with 96 main trials (24 trials per flicker frequency), this added up to a total of 112 trials.

6.7.4 Results Experiment 4

We compared, here, the disappearance times across different flicker frequencies using a one-way repeated measures ANOVA. The results showed a main effect of flicker-frequency, ($F(3, 33) = 11.18$, $p < .001$, $\eta 2 = 0.50$). We hypothesized here that the flicker at 1 Hz would result in the slowest disappearance times. Our results supported this hypothesis (see Table 6.4).

6.8 Discussion

In this study, we set out to demonstrate that different aspects of our visual experience evolve and devolve at different timescales. To show this, we used a perturbation in the form of flicker frequencies in a CFS paradigm. We wanted to link different flicker frequencies to perturbations in different tasks. In experiment 1, we showed that visual contents broke into awareness slower in trials when the CFS flickered at 4 Hz compared to the other three flicker frequencies. Similarly, in experiment 2, we saw that a flicker of 10Hz maximally perturbed the search for the spatial location of a target. Orthogonally, experiment 3 showed that breakthrough benefits of perceptual organization of illusory contours were reduced most at faster-flicker frequencies of 25Hz. Finally, we also investigated the timescale of content devolving away from awareness in a reverse CFS task where participants reported

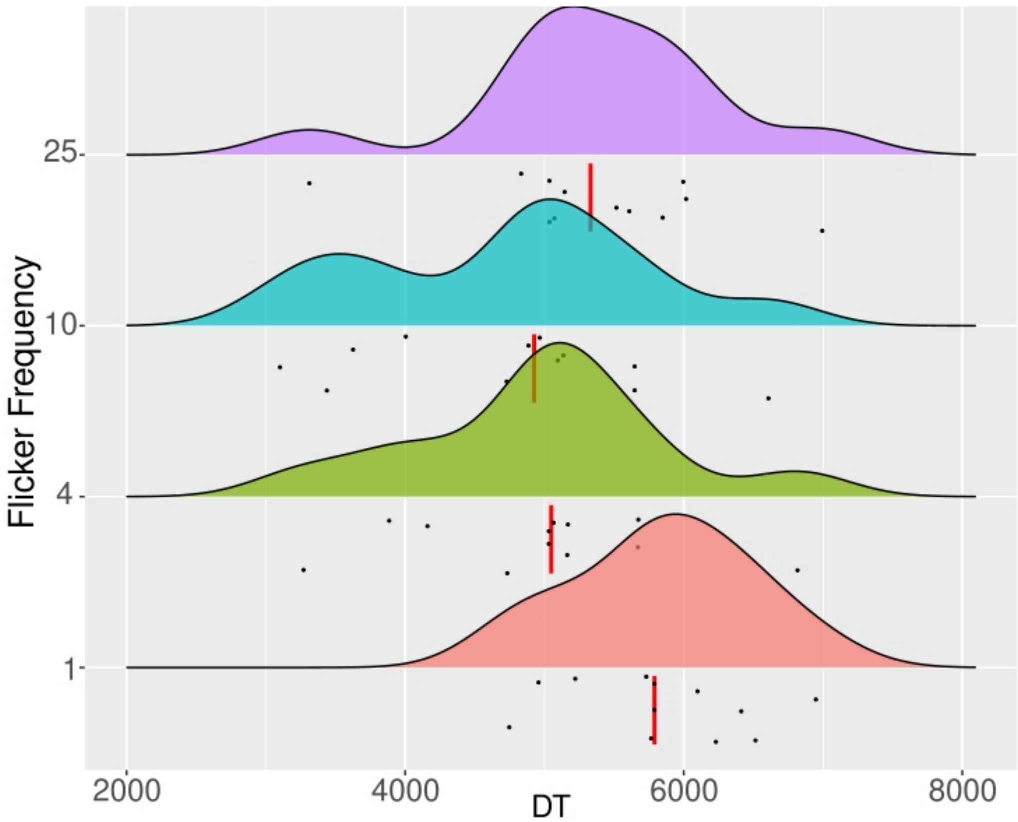

Figure 6.6: Results from Experiment 4. The results show disappearance time (DT), indicating how long it took for a target image to fade away from participants' visual awareness.

disappearance of targets. We found that contents disappeared slowest when the CFS mask flicker at the slowest frequency (1Hz).

6.8.1 Recommendations for flicker frequency choice in CFS experiments

Along the same lines as previous studies (Drewes et al., 2018a; Han et al., 2018a; Zhu et al., 2016), we too find that the standard flicker frequency of 10Hz currently employed as a default in CFS paradigms is not optimal. However, our suggestions differ from previous studies. In this study, we demonstrate that choice of flicker frequency must depend on the particular paradigm being employed. For instance, when using a simple breakthrough task, our recommendation is of using flicker frequencies close to 4Hz, since it best tracks the temporal regularity of contents breaking into awareness. If investigators are interested in maximally suppressing targets when the perceptual aspect of interest is related to early visual organization (grouping, contrast effects, brightness and so on), faster flicker frequencies in the range of 25 Hz may offer better suppression. Similarly, very slow flickering

Mondrians can be used to deploy decay and devolution of content from visual awareness. In this study, we used the nested hierarchical framework of time proposed by us (Singhal & Srinivasan, 2021) to make predictions regarding which flicker frequency would maximally inhibit which aspect of our visual experience. Future studies can also use the same framework as a tool in picking flicker frequencies for various CFS tasks.

6.8.2 Evidence of multiple timescales of experience

One of the core tenets of the framework we discussed in Chapter 3 was that our experience evolves and devolves over multiple timescales. We postulated a framework where temporal events too fast to be grasped in our experience and having no temporal extent evolve over ranges of 30–50 milliseconds (20-30 Hz). Similarly, we argued that experienced content persists and endures with a temporal extent in our experience at a temporal regularity of 300-500 ms (2-4 Hz). In the third level of our framework, we postulated that mental content has retentional aspects that are echoed in our experience over a regularity of 3–5 seconds (0.2-0.3 Hz). To approximate these levels, in this study we chose flicker frequencies of 1, 4, and 25 Hz. We also chose a flicker frequency of 10 Hz. This is because it remains the standard flicker frequency employed in CFS tasks and is argued to disrupt discrete rhythmic sampling of attention and perception in the alpha oscillation range (see Discussion in Zhu et al. (2016)). The task choices we made to investigate these regularities followed strictly from these predictions of regularities and their nature.

We had derived the values for temporal extension (300–500 ms) of the intermediate level of the framework from empirical data investigating time taken for a stimulus to persist in conscious awareness (Atmanspacher et al., 2008; Dainton, 2008a; Sergent et al., 2005) and upper limits of integration cycles within conscious experiences (Herzog et al., 2016). To maximally inhibit the temporal regularity of extensional aspects of our experience, we hypothesized in experiment 1 that a face would breakthrough in participants' awareness slowest at a flicker frequency of 4Hz. Results from experiment 1 supported this prediction. Not only did the range of flicker frequency match the purported oscillatory mechanisms in updating of extended visual contents (Doesburg et al., 2009), but also the estimates from the hierarchical framework. We are also not the only study to show that breakthrough times of images are largest in this range (see Zhu et al. (2016) for comparable results).

The standard flicker rate used in CFS of 10Hz was also used as one of the flicker frequencies in our study. This mainly had two reasons, one to have a bench-marked comparison across tasks and flicker frequencies and two to investigate whether we could find a task which got maximally perturbed at the standard flicker rate. Our results from Experiment 2 showed that this was the case when participants had to locate a dim target in one of four possible locations. In fact, the target also shared feature similarity with the flickering CFS mask (the target being oval and the mask being made up of circles). We found that participants were slowest to perform this task when the CFS mask flickered at 10 Hz. A reason for this could be the implication of rhythmic attentional sampling in this frequency range (Landau & Fries, 2012).

Similarly, in our framework, we had assigned a cinematic-like phenomenological mode to the fast-updating level with a temporal regularity between 30–50 milliseconds. In experiment 2 of this study, we showed that when this level is disrupted with a flicker frequency within this range (25Hz), the stimulus advantage of illusory contours breaking through faster is lost. Another study done by Kaunitz et al. (2014) showed that brighter targets broke out faster. However, in their study, this effect reduced and disappeared when the flicker frequency was increased to 28.5 Hz. Given that previous studies which have shown that illusorily grouped contours break out faster from suppression in CFS (Wang et al., 2012) because the illusory contour has a higher perceived brightness, these two studies are compatible with our results. Similar to contrast effects disappearing at fast flickering frequencies (Kaunitz et al., 2014), it stands to reason that an early perceptual grouping effect which leads to perceiving an illusory surface as brighter than a background would also lose its advantage in the same flicker frequency range. Our work here helps to reconcile the results across these three findings.

In experiment 4, we looked at how content exits visual awareness. Estimates of specious presents and psychological nows have been in the range of a few seconds, where it is argued that this is the duration over which experienced content is immediately accessible before fading away or being encoded into memory (Dainton, 2010). Firstly, all breakthrough times across experiments fall roughly within the estimated ranges of the specious present (∼3-5seconds). These results are comparable to dwell times in binocular rivalry and bi-stable perception (Pöppel, 1997). More importantly, however, we were interested in how a seen target would devolve out of visual awareness as a function of flicker frequency. Given this was a reverse CFS task, we expected that the frequency closest in temporal regularity to the retentional level would delay the exit of the face from awareness. This is what we reported in the results of experiment 4. A possible reason for this is that the slower flicker frequency acts as an entraining anchor for the visual content over time.

6.8.3 Conclusion

In this study, we set out to offer support to a third temporal property of consciousness; multi timescale evolution and devolution of experience. We modified a common paradigm used in consciousness research to create a new variant of continuous flash suppression. Using the logic of a double dissociation, we showed that four different flickering frequencies inhibited performances in four different tasks of visual awareness. In Experiment 1 we showed that flicker frequencies of 4Hz maximally perturbed content breaking into awareness. Whereas, in Experiment 2 we found that performance in sampling the location of a dimly presented target was slowed down by CFS masks flickering at 10Hz. Continuing into Experiment 3, we demonstrated that the benefit of perceptually grouped illusory contours breaking into awareness disappears at fast-flicker rates (25Hz). Finally, we showed that a slow flicker of the CFS mask at 1Hz maximally delayed the devolution of visual contents from awareness. Together, in four experiments, we showed how visual contents evolve and devolve out of our awareness simultaneously over multiple timescales.

Chapter 7

General Discussion

7.1 Putting everything together

So far, we saw the contributions of the thesis in terms of a nested hierarchical framework for timing of cognition and time-consciousness (see Chapter 3). We also saw properties of temporal experience that we can extract from this framework. To recap, Chapter 4 discussed empirical evidence for a temporal correspondence between temporal organization of figure-ground segregation and reciprocal interactions with temporal sensitivity. Meanwhile, Chapter 5 showed a structure-matching between the duration of structure and visual contents while participants viewed bistable figures. Finally, Chapter 6 covered evidence from a novel CFS setup in support of multiple timescales of evolution and devolution of visual contents. Together, the theoretical and empirical arsenal of this thesis is used to ultimately argue for temporal properties of consciousness that can be used for understanding experience. One serious limitation of this work, however, is that much of it is limited to vision. All empirical studies of this thesis are largely vision based, and much of the theoretical framework from Chapter 3 comes from vision science too. In extending this work beyond vision, first, we would need non-cinematic metaphors of perceptual experience. Moreover, we would need to specifically look for similarities and differences between the temporal organizations of different modalities of perceptual experience. This work, at present, can only demonstrate through visual experience that such endeavors may be possible across experienced modalities.

In this chapter, we demonstrate the utility of this endeavor. Specifically, in the next sections, we discuss how the findings of this thesis reconcile with the fields of time perception, timing of cognition, and time-consciousness. We also elucidate, how the temporal properties discussed in this thesis can add to the knowledge of the nature of mental representations. Along similar lines, the framework proposed in this thesis is briefly discussed as a candidate to also unify 6 prominent theories of consciousness. Finally, brief discussions of the future scope of the findings from this thesis are speculated.

7.2 Reconciling the thesis with studies of time

One of the contributions of the thesis to the general study of mental time is to offer new platforms for discussions and debates. For instance, there exist persistent debates about the nature of conscious content and its unfolding in time. Are our experiences frame-like and discrete, or do they unfold continuously in time? These debates have divided philosophical schools over millennia, split approaches to cognitive science, led to postulations that our experience may be an illusion and even led to revisions of how we understand neural mechanisms. This thesis argues that these positions can be reconciled under a nested hierarchy. Specifically, the phenomenological modes of frame-like and extendedness co-exist at different timescales, representing different aspects of our experience as it unfolds in time.

Another contribution of the thesis is uniting disparate inquiries of mental time. Before the work done in this thesis, there existed no model or framework that could systematically allow one to link the timing of visual awareness with how our experience unfolds in time. Moreover, the framework and the empirical results presented in this thesis are demonstrations of how cross-modal predictions about timing and temporality can be made. We showed how perceptual organizations were sensitive to temporal manipulations, and reciprocally related to changes in temporal resolution (see Chapter 4). Similarly, how extended representations of conscious content matched the duration estimates within an interval (see Chapter 5). These two inversions show that it is possible to make headway in forming a general theory of mental time where timing of experiences and experiences of time can be thought of as two sides of the same coin.

An important facet of this work that I would like to point out here is that while the framework allows making cross-modal predictions and also allows one to make predictions across subfields of cognitive science, it does so systematically. What do I mean by systematically here? What I mean is that the framework allows one to ascribe both timescales and phenomenological kinds when making predictions. I hope to have emphasized this facet for the reader in all the empirical chapters. In Chapter 4, when we predicted and tested the temporal correspondence in figure-ground segregation, we not only predicted the timescales over which this correspondence would occur but also its phenomenological nature (specifically temporal resolution). Similarly, in Chapter 5, when we were stuck in deciding whether Necker cube switches contracted felt time because of memory abstractions or a phenomenological absence of visual content at the time of a perceptual switch, we again employed a systematic analysis. Specifically, we designed a demo to phenomenologically settle this dispute. And this phenomenological prediction followed from the framework. Lastly, in Chapter 6, when we discussed that the content of experience evolves (and devolves) over multiple timescales, we did not just assign different temporal regularities. Instead, we apriori tied each timescale to a phenomenological kind and had predictions specific to those in different tasks.

This thesis offers constraints on how the research of mental time can move forward. These constraints can be thought of as a scaffolding to be used in furthering a research inquiry into time. We show how three seemingly disparate fields of study can come together. Namely, the study of temporal phenomenology, time perception, and the timing of cognition. By illustrating a nested hierarchical framework that unfolds both in and over time, we open a new avenue for theorizing about the dynamics of experience. But how do we extend the temporal properties discussed in this thesis to representational systems in cognitive and consciousness science?

7.3 *Ersatz* time in cognitive science

The time in representations of cognitive science is an *ersatz time′*. A time′ tied to no experience and a time′ of no consequence. For the last five decades and more, time has been kept outside of the predicates of mental representations. These might seem like severe and perhaps unfounded accusations. But a closer look may make you realize that the situation is grimmer than you think. A survey of the foundational literature on representational systems in cognitive science would show you that there is no place for time (Freyd, 1987). To illustrate a few examples for you, here, Pylyshyn (1979) argued that the timing of cognitive processes was a fallout of the implementation limitations of a system. It had no bearing on the kinds of cognitive tasks being performed algorithmically, nor were the measurements of these times′ informative about a cognitive process or human experience. Similarly, Dennett and Kinsbourne (1992) argued that time′ was represented like any other sensory property, with no isomorphism between the content and vehicles[1]

[1] For present purposes, 'vehicle' can be read as structure.

of representation. For Dennett and Kinsbourne (1992), not only were there any temporal properties assigned to mental representations, but they also argued that there was no correspondence between the timing of neural processes and our experience.

I would like to draw the reader to consider the framework and the empirical findings presented in this thesis in the larger context of mental representations. If we use the grounding offered by Palmer (1978), mental representation systems in the past and present-day cognitive science do not consider time to be either an intrinsic or a necessary property. By and large, as we repeatedly hinted at or considered in all of the chapters in the thesis, that time′ is treated as a pointer, tag, or marker in cognitive science. It is no more dynamic than a date stamp on your WhatsApp chat, and offers no more constraints than temporal order. Moreover, given there is no temporal nature assigned to representations, there is no talk of their unfolding nor the timescales over which they unfold. Thus, they are completely out of sync or inexorably locked away from the dynamics of experience.

Perhaps I can convince you further with an example from neuroscience. A ubiquitous tool in neuroscience, is spike rate coding. Tuning curves are considered the gold standard for deciphering a neuron's sensitivity to a particular psychological feature. However, spike rate coding is only applicable inside an economy where the currency is the spike rate per second. There is no way for this representational system to instantaneously represent content or match in structure and correspondence (á la Chapters 4 and 5) to how our experience unfolds. Such representational systems resort to an illusionist stance about the temporal phenomenology of our experience to defend their timeless mechanisms.

Consider yet another example from this dogma. Neural peaks of activity. Upon registering a novel stimulus, the baseline neural activity rises to a peak and subsequently returns to baseline. Let us say we present a picture for someone to recognize. But say we present it for a relatively long duration. Let us say that this picture is shown for 15 seconds to an observer, while we record some neural activity (or its proxy) over time. We would observe perhaps a deviation from baseline activity over the first few hundred milliseconds. And then a subsequent return to baseline over the next few seconds. However, the observer continues to "see" the image displayed on the screen for still some time. If our representational system of deviation from baseline activity = conscious experience is true, then the observer should not experience the image anymore. However, such a representational dogma cannot account for such discrepancies. Largely because they are unidimensional when it comes to timescales and because they are representational systems that have the nature of temporal tagging or event marking. Not those of dynamical evolution. Because they are not isomorphic to our experience, they can come apart and out of sync in time with them. So, our experience can persist, while the neural markers responsible for them do not persist in time. Even representational systems where the structure of conscious experience is supposedly axiomatically isomorphic to its representational structure (integrated information theory, see (Tononi, 2015)) do not account for temporal regularities (see Singhal et al. (2022) for a criticism). It would be unfair to not present to the reader alternative representational systems that do try to take into account such issues (for instance, see works of Fingelkurts et al. (2010), Fries (2015), Jirsa and Müller (2013), Rabuffo et al. (2022), and Vishne et al. (2023), amongst many others).

Surely, though, the picture in consciousness research would be better? A research field that specifically takes into consideration our experience both as an explanandum and explanans, surely here time would be taken seriously? The answer, sadly, is no. I will briefly go over the status of time in present day theories of consciousness in the next subsection. Though, instead of a pessimistic critique, I hope to be able to offer the reader a *collective* show of the strength of consciousness theories. How present day theories of consciousness can *together* account for temporal properties of experience.

7.4 Better now than never: Unifying theories of consciousness

Time in consciousness science is also an *ersatz* time′. Almost all theories of consciousness postulate mechanisms on a single timescale and fail to account for temporal phenomenology (see Kent and Wittmann (2021)). Such is the state that even phenomenology-first theories, like integrated information theory, grant only an illusionist view of mental time (see Singhal et al. (2022)). The time′ of consciousness science is limited to answering the questions of whether consciousness occurs early vs. late [2]. However, there is a way out. Unlike Kent and Wittmann (2021), who argue that none of the theories of consciousness capture temporal properties of experience, I want to show you here how each of them captures one unique property. And how, together, each of these theories can contribute to a greater understanding of temporal phenomenology.

I will employ six prominent theories of consciousness to demonstrate to the reader that not only do these theories capture non-overlapping properties of time, but that when combined, they look very much like the framework we proposed in Chapter 3. Let me first list out the prominent facets of our temporal framework, and I will then tie them to the

[2] Also having an ersatz neuroscience cousin of front vs. back

six theories of consciousness. In formulating the framework, we posited it to (1) be nested, (2) constrain the evolution of content from faster updating to slower updating levels, (3) recurrently constrain the evolution of faster-updating content from slower-updating levels, (4) anchor a moment of a psychological now, (5) have a definitive temporal expanse, and regularity, and (6) unfold in tandem.

The next step involves tying each of these properties uniquely to a theory of consciousness. There is only one prominent theory of consciousness which lists temporal nestedness as a necessary property of experience and is developed keeping in mind this aspect of experience. The theory is temporo-spatial theory of consciousness (Northoff & Huang, 2017). Similarly, integrated information theory is explicitly concerned with mechanisms that define the temporal extent of an experience (Tononi, 2015). Although, they do this over a single timescale, revisions of this theory to differentially calculate the maximal time extent of different aspects of our experience can allow it to pin down the timescales of different levels in the hierarchy. Next, global workspace theories are founded on a blackboard architectural view of the mind, where local hubs communicate with each other by broadcasting their contents to a shared blackboard (Baars, 2005). This broadcasting can be thought of as the communication of content from a fast-updating level to one that extends over time. And two different kinds of bottlenecks can be postulated at the intersections of the three levels.

7.5 Revising theories of consciousness

It is possible that not everyone is looking to unify theories of consciousness. Some may choose to be interested in the implications of the findings from this dissertation for a particular theory of consciousness. Here, I will give a gist of what the work from this thesis can contribute to the same six theories we discussed in the previous section. I will list these possible implications in light of each theory's own boundary conditions. Unlike the previous section, here, I will not look for a common ground.

I will begin with the integrated information theory. A reader familiar with the literature would know that this theory has generated a lot of conversation. Whether this comes from empirical data, adversarial collaborations, ambitious predictions, testability, and merit. However, I want to focus on a very limited aspect of the theory. At its foundation, integrated information theory is a phenomenology-first theory (Tononi, 2015). At least, from its proclamations, it aims to derive a mathematical structure that matches that

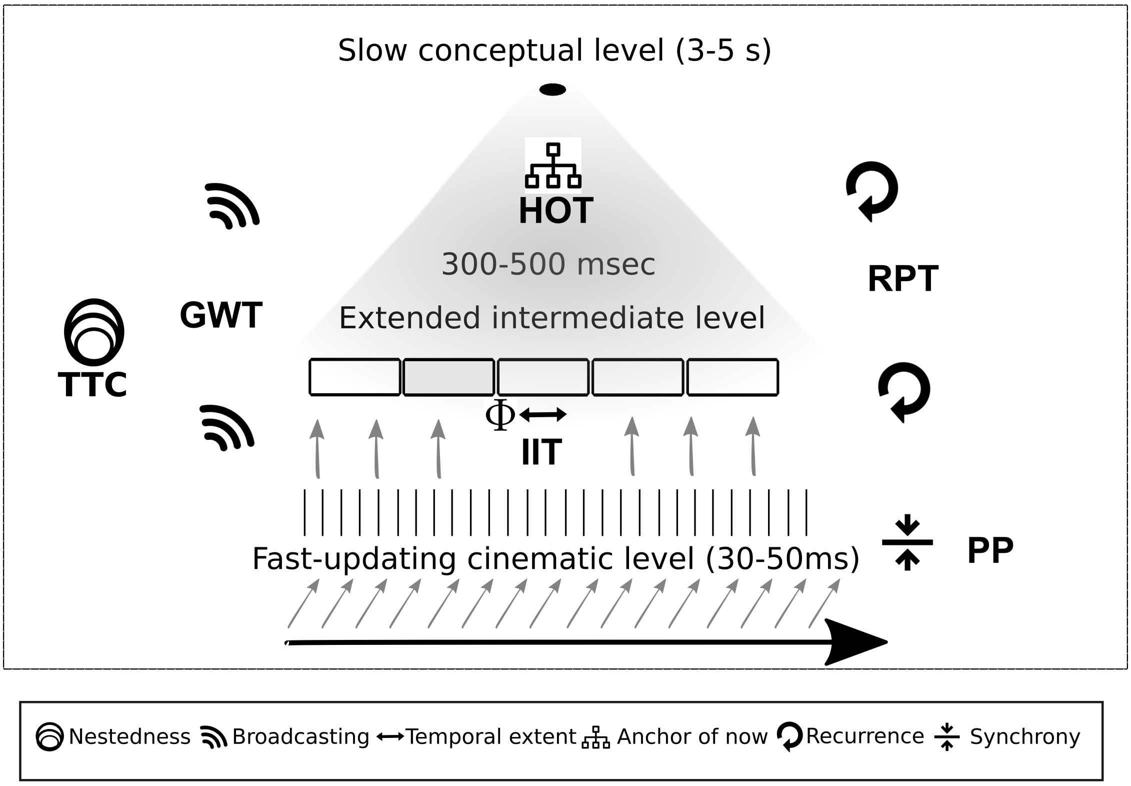

FIGURE 7.1: An illustration of how the proposed nested hierarchical framework can accommodate 6 prominent theories of consciousness. Each theory's essential temporal properties are used for this, see text for more details.

of experience. The theory does it through five constraints that are common between experience and its structure (termed 'axioms'). We argued elsewhere ((Singhal et al., 2022), that in its current conception, the aspects of temporal experience are missing from its mathematical structure. Thus, a straightforward suggestion for revision is to adopt a time-based axiom. In our opinion, employing a time-based axiom would enrich the structure behind integrated information theory to better capture the dynamics of our experience. One that the theory currently claims is illusory, contrary to its very own foundation (see Singhal et al. (2022)). Adoption of the 'realness' of temporal experience would open the theory to massive revisions (multiple timescales of evolution, nestedness, and asymmetry, for example).Our suggested axiom from Singhal et al. (2022) is quoted below:

> Time Axiom: Consciousness is such that experience occurs to us as a temporal whole; i.e., experience always has an extension, is continuous, and has an inherent direction that is asymmetric.

Moving onto theories of global workspace and recurrent processing, both require hierarchical interactions of feed-forward and feed-back interactions. Currently, their interactions are not distinguished based on timescales or temporal phenomenology. As an example, consider the broadcast of contents from the cinematic to the intermediate level and from the intermediate level to the slow-retentional level. The nature and timescale of these two 'broadcasts' would be remarkably different (as we discussed in Chapter 3). The same holds true for theories of recurrent processing.

Predictive processing theories, on the other hand, may be the only set of theories that have been actively tried to co-opt aspects of time-consciousness (for examples see Grush (2005), Hogendoorn (2021), and Wiese (2017)). The only suggestion my work can offer to this camp is to consider different phenomenological modes of experience. For instance, most of the work in predictive processing is focused on anticipatory and retentional aspects of experience. These models have failed to find common ground with phenomenological modes of temporal extent, mirroring, and structure-matching. If the work presented in this dissertation holds true, then predictive processing theories still have more temporal properties of consciousness that must be accounted for in future revisions.

The last theory I consider here is the temporo-spatial theory of consciousness (Northoff & Huang, 2017). This theory also adopts several temporal properties of consciousness discussed here, for instance, those of temporal nestedness and distinct timescales. The theory extends these properties as markers of wakefulness, in essence arguing that both of these properties are necessary properties of conscious experience (or at least wakefulness). However, the tenets of these theories have not been extended to how content unfolds in our experience nor to the incredibly large data pool of empirical findings where time is either a dependent or independent variable. If proponents of this theory are looking to extend its scope beyond states of consciousness to contents of conscious experience, they would find some readily available suggestions in this dissertation.

7.6 Future Scope

This section is *especially* conjectural and speculative. The future directions I can envisage here do not necessarily lie in the area of my expertise. However, I am aware that it is customary to end theses with such conjectures. One avenue that I feel is ideal for extending the work here is in comparative cognition. The reason for this follows from this train of thought: if time is a minimal unifying property of consciousness, it follows that it pervades across experiences and individuals. Would it, then, also pervade species? Most studies looking at ways to identify markers of conscious experience in non-human species have done it via neurocentric theories. Does an organism possess a complex neural architecture to experience something similar to a human? This seems a common benchmark for the search for sentience, pain, and reasoning experiences in non-human species. However, looking at temporal regularities of psychological nows for different species and understanding species specific temporal regularities would offer promising insights into the structural properties of non-human experience. Just like how structural regularities allow us to bypass the issue of content equivalence between individuals, it may allow us to bypass the issue of content equivalence between species.

Another open avenue, of course, is to look at disorganization of the temporal properties discussed in this thesis. The thesis postulates certain structural properties of experience, both in and of time. What happens to experience when this temporal structure breaks down? As an example, would distortions in the workings of the framework be able to describe the phenomenology of patients suffering from schizophrenia? Similarly, would the framework allow for a better description in general of essential time-based alterations and psychopathology like anxiety, depression, panic, mania, and so on? I think one of the biggest contributions of phenomenology in diagnostics is pain research. Given the phenomenological nature of pain and its descriptions,[3] help immensely in doctors being able to diagnose a disease, it may follow that better descriptions of temporal phenomenology may aid a better understanding of experience.

One hope is that having an understanding of a temporal structure may aid in studying aspects of the mind considered entirely private. An example of this is mental imagery. Pinning down a general temporal structure of the mind can help us ask questions of such private experiences. For instance, what is the temporal resolution of the field of imagery? How long do imagined mental contents persist? And what are the phenomenological modes of imagined content?

The most immediate course of future work along the lines of this thesis is to extend its unifying capabilities to consciousness theories. As we discussed in the previous section, a common construct is the need of the hour for theories of consciousness. Alongside this monolith, I have been engaged in writing an extension of the nested hierarchical framework to theories of consciousness. My hope is that it can provide a platform to break the silos that are currently becoming popular.

[3]Think stinging, burning, rising, churning, pinching, persisting, pulsating etc. as qualities of pain.

There are some who consider experience to be idiosyncratic. For them, the nature of our experience is such that a regularity for it cannot be drawn out. Their claim is that experience is too unique and random for the possibility of drawing out commonalities. Or the other worry is that the contents of consciousness cannot be conveyed. Thus, a scientific study of consciousness is not possible because either the contents wary randomly or are not accessible. In my opinion, a science of consciousness can be done through structuralist constraints. We have bypassed these issues repeatedly in the past by identifying regularities of experience. My hope is that these now limit the theoretical space for explaining and understanding conscious experience. The biggest promise of this work is offering temporal constraints. The three temporal properties of experience that we identify and test can ultimately offer useful constraints on how we think about mental representations.

Chapter 8

Conclusion

8.1 Summary of contributions

The primary contribution of this monolith and its associated work is of elucidating a law-like temporal structure of experience. The hierarchical nested framework, experiments, and phenomenological demonstrations described in this thesis were performed to show how conscious experience persists, evolves, switches, organises, and devolves. The work behind this thesis entertains the possibility of revolutionising the way representational systems are formulated in cognitive and consciousness sciences. It aims to offer temporal properties that apply to both content and structures of experience. At its best, this dissertation comes from a motivation of shattering the content/vehicle distinction present in the study of mind. The endeavour of mind sciences to look for necessary and intrinsic properties of mental representations has been going on for nearly 200 years, we throw in the midst the candidacy of time as one such property. Our contention is that a temporal structure of experience can allow a unified study of the mind. In winding down this dissertation, I enumerate below the key contributions made.

1. Reconciling phenomenological modes of experience under a common nested hierarchical framework of time-consciousness in Chapter 3.

2. A framework that allows predictions about temporal distortions over specific timescales and their phenomenological type in Chapter 3.

3. An empirical and phenomenological test of the temporal-mirroring between the timing of cognition and time perception in Chapter 4.

4. Demonstrating a structure-matching between the duration of the persistence of an experience and the structure underlying that experience in Chapter 5

5. A novel paradigm variant of CFS and an empirical test to show that the contents of our experience evolve and devolve over multiple timescales in Chapter 6

6. Putting to use the temporal properties derived in this dissertation to enrich representational systems in cognitive science in Chapter 7.

7. Arguing how a time-based minimal model of consciousness proposed in this thesis can be used as a construct to break the boundaries of six prominent theories of consciousness, in Chapter 7

8.2 Epilogue

Jorge Luis Borges ends his essay, *A New Refutation of Time*, by quoting a German poet and priest, Angelus Silesius. Borges lays down this quote at the end of his essay as an invitation, perhaps for a reply, extension, or refutation of his own work. A call to arms, perchance, for another individual interested in the study and experience of time. I close this writing, having laid bare my thoughts on time, with the same quote. I hope that you will also become your writing.

Freund, es ist auch genug. Im Fall du mehr willst lesen, So geh und werde selbst die Schrift und selbst das Wesen [Friend, this is enough. Should you wish to read more, Go and yourself become the writing, yourself the essence.]

Angelus Silesius

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