Exploring the Impact of Visual and Haptic Feedback on Eye-Hand Coordination and Embodiment in Virtual Reality

by

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Abstract

Virtual Reality (VR) has emerged as a powerful tool for investigating human perception, cognition, and behavior. The ability to create immersive and interactive environments provides researchers with the opportunity to study human behavior in controlled and repeatable conditions. In recent years, there has been a growing interest in using VR to study human motor control and embodiment, which has led to the development of various VR systems for motor control studies.

The aim of this PhD thesis is to investigate the impact of visual feedback, haptic feedback, and their combination on embodiment and eye-hand coordination in VR. To achieve this, we conducted three studies that explored different aspects of VR object interaction.

The first study, described in depth in Chapter 2, investigated the effect of visual feedback on movements and embodiment in VR. We compared two VR object interaction conditions in which participants saw either a virtual replica of the controllers they held or a set of dynamic human-like limbs. Our results indicated that participants felt more embodied in VR when they saw the virtual limbs, compared to the virtual replica of the controllers. And, we found that participants who reported higher levels of ownership over their virtual limbs actually moved their bodies more differently between the two conditions, suggesting that body movement could be used as an objective measure for embodiment in VR environments.

In Chapter 3, we describe the second study, an investigation of the similarities and differences in eye-hand coordination during an object interaction task in VR and the real world. In short, we compared eye-hand coordination in a real-world task to the same task in controller-mediated VR. Our findings showed that participants visually fixated the object to be manipulated approximately the same amount of time in advance to their hand arriving at the object in VR and the real world. But, VR participants moved much slower, and spent more time visually fixated on their hand after the object was picked up, and after it had been released. We hypothesize that this is due to the limited haptic feedback provided in controller-mediated VR.

Finally, the third study is detailed in Chapter 4, where we investigated the impact of haptic feedback on embodiment and eye-hand coordination in VR. We used a set of VR gloves that tracked the location and orientation of participants' hands and fingers as they interacted with objects in VR. We compared two VR object interaction conditions in which participants either received no haptic feedback or felt the actual real-world version of the virtual object they were seeing. Our results showed that participants were more embodied when they felt the objects in VR, and also exhibited eye-hand coordination behaviours closer to the real world dataset.

Overall, this PhD thesis provides new insights into how different VR object interaction conditions affect embodiment and eye-hand coordination. Our findings have implications for the continued study of embodiment, the design of VR systems for motor control studies, and have the potential to inform the development of more effective VR-based interventions for motor rehabilitation.

Preface

This thesis is an original work by Ewen Lavoie. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Action and Attention in Virtual Reality Using EEG, Eye and Motion Tracking”, No. Pro00085257, October 29, 2018.

Chapter 2 of this thesis has been published as: Lavoie, E.B., & Chapman, C.S. (2021). What’s limbs got to do with it? Real-world movement correlates with feelings of ownership over virtual arms during object interactions in virtual reality. *Neuroscience of Consciousness*. This work is presented here with minor changes to acronyms for consistency. I designed this experiment, collected (with Garett Motley) and analyzed the data, and wrote the manuscript. Dr. Craig Chapman created visualizations and edited this manuscript.

Chapter 3 of this thesis has not yet been published, but is in the revision stage as: Lavoie, E.B., Hebert, J.S., & Chapman, C.S. (2023). How real is virtual reality? Comparing eye-hand coordination in virtual reality and real world object interactions. *Journal of Vision*. As well, many versions of this content have been presented at international, peer-reviewed conferences. This work is presented here with minor changes to acronyms for consistency. The real-world dataset used in this study was previously collected as part of the Hand Proprioception and Touch Interfaces (HAPTIX) project sponsored by the Defense Advanced Research Projects Agency (DARPA) BTO under the auspices of Dr. Doug Weber through the DARPA Contracts Management Office Grant/Contract No. N66001-15-C-4015. All procedures were approved by the University of Alberta Health Research Ethics Board, the Department of the Navy Human Research Protection Program (DON-HRPP) and SSC-Pacific Human Research Protection Office (SSCPAC HRPO). Dr. Jacqueline Hebert was the lead investigator at the University of Alberta, with co-investigators: Drs. Craig Chapman, Patrick Pilarski, and Albert Vette. I designed this experiment, collected and analyzed the data, and wrote the manuscript. Dr. Craig Chapman created visualizations and edited this manuscript, and Dr. Jacqueline Hebert edited the manuscript.

Chapter 4 of this thesis has not yet been published. A version of this chapter has been presented at the 2023 Canadian Association for Neuroscience Annual Meeting as Lavoie, E.B., Hebert, J.S., & Chapman, C.S. (2023). How real is virtual reality? Comparing eye-hand coordination between VR and real world object interactions. I instructed the design of this experiment to Riley Dawson, who programmed it. I collected and analyzed the data, and wrote the manuscript. Dr. Craig Chapman created visualizations and edited this manuscript.

Dedication

I’ve been immensely fortunate in my life to have support, encouragement, and love from so many people. I have been selflessly helped in both small and great ways over the course of my life, and any achievement or reward I receive is but a reflection of how fortunate I’ve been to know so many wonderful people. Ariana, you’re such a light in my life. You’re caring, kind, smart, and hilariously funny, and you lift me up all the time. Being with you is such a consistent joy that I didn’t think was possible. Special thanks to Dr. Michael Grace and Rose Carter, for their unwavering support and encouragement, without which this work would not have been possible.

To echo words that I’ve previously written, I can pursue academics because I stand on the shoulders of giants. My giants are not scientists from previous generations, but rather my remarkable family. Growing up, I was blessed to know all four of my grandparents, all of whom I wish I’d had more time with. They taught me, and still teach me, many important lessons for life. It’s not a feasible task to put into words all that I’ve learned from them, but some small life lessons that come to mind are: have faith, persevere, take responsibility, and work hard.

As I age I understand more everyday how much effort, time, and sacrifice my parents, Mitch and Cecilia, put in for my siblings and I to be able to pursue endeavours that we found meaningful. My parents not only provided me with all the love and support necessary for me to succeed in any arena of my choosing, but they believed in my potential when I did not. They have modeled so many positive attributes for me all the while providing me with immense opportunity in life. There’s no words that can do justice to the gratitude that I have for them. Thank you as well to my siblings, Malcolm, Callum, and Maura, who have each supported and encouraged me throughout my life, often in times when I was struggling the most. I am indebted to you all more than you know.

Acknowledgements

Accepting the opportunity to continue working with Drs. Craig Chapman and Jacqueline Hebert for my PhD was a rather easy decision to make. Dr. Chapman mixes patience, encouragement, curiosity, and guidance in a way that not many mentors can to teach his students. Our great working relationship has grown into a friendship, in which Dr. Chapman and I discuss science fiction, hockey, space travel, and the deeper questions of life and existence. This combination has made working together enjoyable, challenging, and formative. Dr. Hebert has a way of challenging her students while also encouraging and advising them. Our conversations during my candidacy exam preparations were quite impactful on my chosen career path. Thank you both for your effort and support over the years.

I also wish to acknowledge the financial support I've received from the Natural Sciences and Engineering Research Council of Canada, TD Bank Financial Group, the Canadian Association for Neuroscience, Campus Alberta Neuroscience, and the University of Alberta, without which this work would not have been possible.

Finally, great thanks go to my colleagues and mentors past and present, including but not limited to: Riley Dawson, Quinn Boser, Dr. Aida Valevicius, Dr. Nathan Wispinski, Dr. Jennifer Bertrand, Dr. Scott Stone, Dr. Jeff Sawalha, Dr. Ahmed Shehata, Alex Ouellette Zuk, Dr. Brea Chouinard, Dr. Patrick Pilarski, Dr. Dave Collins, Dr. Kelvin Jones, and Dr. Brian Maraj.

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1 - Introduction

At the center of this thesis is the concept of embodiment. This term is notoriously difficult to define, but includes the idea that the way a person acts and experiences the world is inextricably linked to their body. After all, we use our bodies quite literally every second of our lives. Some believe our bodies are all we are (Armstrong, 2022), while others argue that our bodies are a part of us, with our minds distinct, and the two connecting in a variety of ways (Descartes, 1984). Many opinions exist, including those in which our minds extend into the physical world outside our skulls (Clark & Chalmers, 1998), but whatever your theory of mind, most agree that we share the feeling of being inside a body (Clark, 2010). Whether we are lying on the couch or climbing up a mountain, we know that our body is tightly linked to our conscious experience, and is ready to sense and act in the world. In fact, by using intracranial electrical stimulation on the brains of awake surgical patients, it's been shown that the closer a brain area is to sensorimotor structures, the more influential it is on a person's conscious experience (Koch, 2020). Understanding the mechanisms that create this feeling of embodiment are not only important for philosophical discussions about the possible origins of consciousness (Glasgow, 2018; Longo et al., 2008; Seth et al., 2011), but also for designing better medical treatments for those experiencing physical disorders like amputation and Parkinson's disease, and mental health disorders like body identity integrity disorder and schizophrenia (Giummarra et al., 2008).

It can be argued that embodiment is also central to evolution. Having a body that reliably senses and acts in the world has been postulated as the foundation for the evolutionary process (Cisek, 2019; Cisek & Hayden, 2022). In this framing, every organism along its evolutionary path up to and including modern day humans was able to sense its environment and act in it based on that sensory input to sustain itself long enough to reproduce. Single-celled organisms with one photoreceptor were able to use the information from that photoreceptor to make a successful action (e.g. light on the photoreceptor initiates movements of flagella to push the organism towards it). The signal of whether an action was a success or failure relies upon some reward for the organism. In the above example, movement towards the light increases chances of finding food, with ingestion of food being the reward. The fulfillment of this type of relationship with the environment requires the organism to have a "body", and it has been argued that this is the foundation for the development of conscious awareness (Glasgow, 2018). In Minimal Selfhood and the Origins of Consciousness, Rupert Glasgow argues that organisms, even as small as a single cell, can experience what he terms "minimal selfhood" if they are able to self-maintain, self-reproduce, and self-contain (Glasgow, 2018). He asserts that the minimum requirements for what one could call a “sentient” organism are these three intrinsic reflexivities. When a boundary with the outer world (that also has the ability to interact with this outer world) contains behaviours to maintain itself and reproduce, the foundations of consciousness are met. He provides evidence that these foundational requirements are seen in many types of lower organisms, and up the phylogenetic tree to primates and humans. Every behaviour over the course of evolution has been selected for by sensory input, computation, and motor output with the caveat that the result will help an organism self-maintain (survive and find food), self-reproduce, and self-contain (protect the “body”). This is not all that is required for human-level consciousness, but rather the foundation of which higher consciousness is built (Glasgow, 2018). The argument is that our ability to sense and act in the world from the confines of our own contained “body”, although not unique to humans, is the foundation upon which our beautiful conscious experience is built, at least from an evolutionary perspective.

Over the course of evolution to modern humans, increased ability to act in the world, especially with end effectors like hands, begot increasingly more complex inner computation as is evidenced by the increase in primate brain size with increased dexterity (Heldstab et al., 2016). I assert that as affordances in the environment increased, computational power also increased to exploit these new affordances and achieve greater rewards to increase the probability of survival and reproduction. At the same time, these increased abilities to interact with the world could have been the driver for the development of our unique human self awareness. As a result, it can be argued that the human condition of being situated within a body with the ability to interact with the world is deeply ingrained in what we are on an existential level.

I want to pause to make the important caveat that many individual humans experience impairment of their ability to sense and act in the world. I must stress therefore that I make the previous argument from a theoretical, evolutionary perspective, and by no means believe or argue that any individual is more, or less “conscious” as a result of their specific abilities. In fact, it could very well be that human level consciousness has now, in some ways, transcended any specific bodily boundary. As mentioned above, evolution has driven humans toward complex internal calculations which some theorize are associated with richly populated internal models of the world. It may very well be that this has allowed us to dissociate our experiences from any specific type of embodiment, despite the evolutionary pressures that led to our species.

Given this, while embodiment may not be necessary for our consciousness, it is at minimum a crucial factor in how we experience the world. This speaks to the major question of this thesis - if you alter a person's experience of embodiment, how does it impact their behaviour? This question of course raises at least two more: how can you alter embodiment and, if you can, what tasks and behaviours should you measure? Regarding the first, here we take the approach that an embodied agent is not just a blind actor in the world, but rather one who is fundamentally, intelligently guided by sensory feedback. That is, our ability to interact with our environment is not a one-way street, but rather a dynamic multi-directional highway where each sensory stream influences motor outputs, and vice versa. When we reach out to pick an apple off a tree, not only do we observe visually our body moving through and changing the environment, but we also sense haptic and proprioceptive changes on and in our body. Alterations in sensory feedback are therefore one way to change the experience of embodiment, and in this thesis I explore changing both visual and haptic feedback.

Modulating sensory information received from and about one's body and the environment is not scientifically novel, but until relatively recently, it was impossible to completely control the visual information people receive as they move and interact in the world. This has dramatically changed with new virtual reality (VR) technology, which has been gaining momentum in gaming and entertainment for over a decade, and more recently breaking into industrial training and healthcare fields (Freeman et al., 2017; Laver et al., 2017; Phelan et al., 2015). Promises of a revolution in the way we train firefighters, doctors, astronauts, and heavy equipment operators along with how we diagnose and treat diseases, as well as rehabilitate patients, have become ubiquitous. However, to fully realize the benefits of VR and its potential impacts on the future of humanity, we need a better understanding of how the technology interacts with our bodies, changes our feelings of embodiment, and alters our behaviour. For example, while it has been shown time and again that haptic feedback, the sense of touch, is a major contributing factor to the creation of embodiment (Longo et al., 2008), the impact of full haptic feedback on behaviour in VR is still not well understood. It is imperative that, as VR is deployed in our everyday lives, we understand what differs between VR and the real world. This will allow us to catalogue the sensory modalities that contribute most to an optimally-immersive embodied VR experience. More importantly, predicting the possible changes that humans may undergo as VR technology infiltrates more of our everyday lives will help us maximize positive outcomes and minimize negative ones.

If VR presents the opportunity to manipulate a sense of embodiment by changing visual and haptic feedback, for the purpose of this thesis, that still leaves the question of what task to have people perform and what aspects of their behaviour to measure. Conveniently, the example of apple picking also hints at an answer to this question. Tasks requiring direct manipulation of the environment seem excellent candidates for this kind of study. Object interactions like apple picking firmly situate a sensing agent in a manipulable world, accentuating their embodiment. Regarding measurement, as we have shown previously (Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018), metrics detailing the timing and location of eye-hand coordination provide exquisite sensitivity during object interaction tasks. After all, eye-hand coordination is a fundamental aspect of human behaviour and is essential for everyday modern activities like grasping objects, typing on a keyboard, and playing sports. In fact, as mentioned earlier and will be discussed again later, evolutionary evidence suggests primates' brains grew to control increasingly dexterous hands (Heldstab et al., 2016). Given humans' particular aptitude for coordinating our eyes and hands to perform complex tasks, these behaviours are excellent candidates to be tightly linked with our sense of embodiment.

Putting this all together we arrive at a succinct description of what I did in this thesis: I tested eye-hand coordination as people moved objects in virtual reality (VR) under varying levels of haptic and visual feedback. Arriving at this description parallels my personal academic journey to arrive here. While completing my Master’s thesis, in which I explored the eye-hand coordination patterns of humans during everyday object interactions, I helped explore these patterns in those using upper-limb prostheses. Upon discussing with prosthesis-users their experiences and feelings about carrying out object interactions, I learned that there are not only changes in eye-hand coordination patterns when interacting with a prosthesis, but also differences in how people feel about their device. More specifically, some feel as though their device is a part of their body, while others feel as though it is a tool or object that is separate from their bodily self (Cheng et al., 2023; Zbinden et al., 2022; Zopf et al., 2018). My curiosity about differences in eye-hand coordination took hold, especially with respect to how it might change under various forms of feedback to the user and I sought out tools to manipulate visual and haptic feedback in a controlled manner. I was overwhelmed to see how advanced new VR technology had become. VR, AR, XR, spatial computing, whatever you want to call it, is going to impact our future in unimaginable ways. It has evolved into an immensely important psychological tool for many reasons, not the least of which is that it allows experimenters to precisely control the exact visual feedback participants receive. But, it is also undeniable that these technologies are altering our embodied experience at a fundamental level. As such, we have to learn how similar, and different, our behaviours are when doing them in VR as opposed to in the real world. Thus, the goal of this thesis, again, is to elucidate the behavioural changes that occur when people interact with objects in VR with varying degrees of visual and haptic feedback, compared to the exact same task in the real world. To do this, I used an object interaction task that had been tested on many participants in the real world, and recreated it in VR. In a step by step approach using VR, I was able to modify visual representations of participants' virtual bodies, as well as haptic feedback received in the virtual world, to elucidate the role that each plays in embodiment of a virtual body and eye-hand coordination during object interactions.

To situate the reader and provide some of the necessary background to contextualize this work, the following sections of this introduction outline the previous literature from three main fields of study: visuomotor behaviour, embodiment, and virtual reality. This is followed by a detailed explanation of the motivations and hypotheses for this current research stream which makes up the three main chapters of this thesis. A short conclusion integrates the findings of all three studies, highlights several limitations, hypothesizes possible unexplored phenomena, and explores potential future areas of study.

1.1 - Visuomotor Behaviour

"Why does a bias toward vision occur?" (Posner et al., 1976)

As I walk through the forest I hear the ocean only a few hundred feet away. I feel the crunch of dead leaves under my feet and I smell the flowers and bark mixed into the ocean breeze. Out of the corner of my eye I spot what might be a ripe blackberry. I stop and fixate closely to confirm that it is, in fact, a plump, juicy blackberry. I reach out to pick it, carefully avoiding the plant's thorny defences, and transport the treat into my mouth. I savour the flavour for a few moments before carrying on my way down the path. This series of actions is so much more complicated than it first may seem. If I'm walking down the path to the ocean, how am I also able to have my attention taken by something in my peripheral vision? Why do I need to look more closely at the blackberry to gain more information about it? How am I possibly able to navigate my hand and fingers around thorns to access my intended target, and how do I even know when my hand has arrived there? The quote above comes from a review of literature up to the time of publication describing the way in which visual information seemed to dominate our other senses, how this may have developed, and its implications (Posner et al., 1976). The authors understood that vision takes hold of our attention in most situations over other senses, but that our brains seamlessly shift attention away from vision to other senses in order to achieve each specific goal. In this section I explore the relevant visuomotor behaviour literature concerning the coordination of eyes and hands for successful object interactions. I look first at the evidence for the theory that visuomotor behaviour was a critical driver of evolution, highlighting studies that showcase the path evolution took resulting in the human visual system. I then discuss the way in which interactable objects are perceived by the brain's visual system, and explain how visually fixating an object primes the brain to act upon it. Moving outward from the brain, I explore the role the visual system plays in feedback for the motor system, explain the complex interplay that occurs between the eyes and hands when carrying out object interactions, and finally introduce the visuomotor behavioural differences that result from limited haptic feedback during object interactions. Our brains and bodies are the product of billions of years of sensation and action in an environment. Starting from an evolutionary lens and connecting the human brain to its environment through action is necessary to explain the link between visuomotor behaviour and embodiment.

1.1.1 Visuomotor behaviour as evolutionary driver

"... consciousness is a Darwinian adaptation and that as such it confers an advantage upon those organisms that happen to be endowed with it: in concrete terms, the advantage of being able to propel oneself in a direction that is aligned with one's interests rather than just remaining motionless or moving at random. This ability to align self-caused self-movement with self-interest is what consciousness, in this primitive sense, is. Of course, functions may morph over time, just as the feathers that originally played a role in thermoregulation subsequently gave rise to the possibility of flight. In this way, what initially enabled a motile organism to move itself in the direction of some nutritious feature of its environment has now transformed itself (in humans) into an ability not only to procure and ingest a meal but to remember, plan, share and generally reflect upon the process." (Glasgow, 2018)

How we move and act is fundamental to the human experience. Glasgow asserts that an organism's ability to be self-contained while also being able to sense and act in its environment is a necessary component of minimal selfhood. Putting the development of consciousness aside, however, both Glasgow, Cisek, and others have asserted that the visual system may have been the driver for the evolution of complex organisms we see today (Cisek, 2019; Glasgow, 2018; Goodale, 1996). The first neurons appeared on the outer layer of multi-celled organisms approximately 800 million years ago and served both sensory and motor functions (Brunet & Arendt, 2016). Over time, some neurons responded to mechanical pressure, which would then lead to a contraction at the opposing side of the organism, while other neurons produced chemical changes in response to the activation of photoreceptors. As time passed, even more specialization occurred leading to cells with specific functions for motor and sensory information, and even those for organizing signals across the organism. Although touch receptors on the surfaces of organisms provide vast amounts of information, this information is necessarily spatially situated in direct proximity to the organism itself. Photoreceptors provided information from further distances from the organism, and likely gave more information about an environment allowing these organisms to move to achieve some sort of reward.

Fastforwarding along the evolutionary lineage of early vertebrates to roughly 540 million years ago, the Cambrian explosion produced changes from one to two photosensitive patches that migrated to either side of the “head”. The split is thought to enable organisms to see shadows of approaching predators, and quickly react (Erwin et al., 2011). If a shadow fell on the left side, the signal was sent directly to the right side of the primordial brain initiating a motor response to turn to the right before swimming away. Jumping a couple hundred million years into the future, around 385 million years ago, the first fish were evolving into four-legged animals that could take on terrestrial locomotion. This change in light refraction from water to land increased the volume able to be sensed by an immense margin (MacIver et al., 2017). This increased the opportunity for advances in locomotion through navigation, and also opened the door for the ability to plan movements further in advance (Cisek & Hayden, 2022). Before the extinction of the dinosaurs 66 million years ago, early mammals were small, nocturnal, and adapted to dim light by having forward-facing eyes, thus relying more on olfactory (Rowe & Shepherd, 2016), auditory (Frost & Masterton, 1994), and tactile information from whiskers and body hair (Muchlinski, 2010). Along with the shift of eyes to the front of the face, early primates saw an expansion in the dorsal visual stream, the widely accepted visual processing stream for actions, as opposed to the ventral visual stream (see section 1.1.2), known more for allowing perception of the environment (Kaas et al., 2022).

In addition to changes in the visual system, primates evolved in other important ways. Dexterous hand movements are a primitive motor capacity linked to the evolutionary development of the primate brain (Cisek, 2022; Heldstab et al., 2016). Heldstab and colleagues showed a strong correlation between primate brain size and the complex forelimb manipulations that were necessary for each species’ survival (Heldstab et al., 2016). Even more, increase in brain size was disproportionately concentrated in the neocortex, leading to the assumption that the ability to complete complex upper-limb manipulations was made possible by areas associated with cognition (Heldstab et al., 2016). Not surprisingly, out of the 36 species in the study, humans scored atop the scale of complex dexterity, even more than one would expect based on brain size. This study provides more evidence to the theory that the impressive cognitive abilities of humans were a result of ecological factors pressuring the development of evermore dexterous hand movements (Heldstab et al., 2016). The ability to effectively carry out dexterous hand movements is an important aspect of stereotypical human behaviour, but, of course, dexterous hand movements don't occur in isolation - instead, relying on the aforementioned visual system and carefully coordinated eye movements to guide them in their precision. The evolutionary history of the development of the human visuomotor system is much more complex than what has been outlined here. In the interests of brevity, I'll direct interested parties to the reference list and discuss the human brain's dorsal and ventral visual streams in the next section.

1.1.2 Human vision and action are inextricably linked

"Vision did not evolve to enable animals to see the world; it evolved to provide distal control of their movements within it. Conscious sight is a relative newcomer on the evolutionary stage." (Goodale, 1996)

Vision is an incredible ability that is used for a variety of purposes. Right now vision is allowing me to look at this computer screen and read the words I'd previously typed. Yesterday vision let me track a frisbee as it flew past my outstretched hand. Tonight I'll be able to sit on the porch and see the smiles of my loved ones as we share memories, while reliably reaching my hand to a glass of beer. Vision is obviously not a one-dimensional function for humans. We view art, grab tools, drive cars, gain information, and even share memories with others using vision. With all these different uses, one must wonder how our brains differentiate between them all. Is our vision different when we are searching for a tool to pick-up and when we are enjoying a beautiful painting? Here I discuss one way in which our visual pathways are differentiated in the brain, the two visual streams hypothesis (Goodale & Milner, 1992).

As mentioned above, non-human primates share visuomotor circuits of the brainstem and midbrain with lower vertebrates, but have evolved more control over their eye movements through modulation by the cerebral cortex (Goodale & Milner, 2013). The cortex is responsible for many higher order, non-motor, mental functions, including cognition, decision-making, planning, reasoning, while also functions like reaching and grasping that are obviously directly linked to motor function (Goodale, 2011). In short, the primate, and more specifically, the human visual system evolved two distinct neural pathways (Goodale & Milner, 1992). The vision-for-action pathway, the dorsal stream, receives visual input originally from the retina via the primary visual cortex (V1), and through a series of neural connections, transmits signals dorsally in the brain to the posterior parietal cortex. The vision-for-action pathway controls actions related to objects, and is mostly thought to be controlled in real-time imperceptibly. The vision-for-perception pathway (ventral stream) also takes information from V1 but transmits signals ventrally in the brain to the inferotemporal cortex. The vision-for-perception stream creates awareness of objects and the environment, and could possibly be the foundation to an organism's conscious experience. Figure 1.1 depicts both streams, and has been duplicated from Goodale's 2011 review paper, *Transforming vision into action* (Goodale, 2011). The dorsal stream "is designed to operate in real time and is not normally engaged unless the target object is visible during the programming phase, when (bottom-up) visual information can be immediately converted into the appropriate motor commands" (Goodale, 2011). The ventral stream, on the other hand, "plays a fundamental role in constructing our perceptual representations of the world – but is not essential for the programming and online control of visually guided actions [to] goal objects that [it] has helped identify" (Goodale, 2011).

Much of the early evidence for the two visual streams hypothesis in humans was based on neuroanatomical findings in non-human primates (Mishkin & Ungerleider, 1982). More direct evidence has been found in people living with neurological damage in specific brain regions. Patients with damage to the posterior parietal cortex have trouble reaching and grasping objects they're looking at, while having no difficulty touching specified parts of their own body (Goodale, Meenan, et al., 1994; Holmes, 1918; Jakobson et al., 1991). Intriguingly, these same patients, while being unable to reach and grasp objects, are able to describe the position, size, shape, and orientation of these same objects (Perenin & Vighetto, 1988), and even direct their gaze accurately towards them (Ratcliff & Davies-Jones, 1972). More recently, visuomotor changes to patients with ventral stream damage have come to light, the most famous of whom was documented starting in the early 1990's (Goodale et al., 1991; Milner et al., 1991). The patient, who goes by her initials, DF, had suffered lesions in the lateral occipital cortex, a brain region later shown to be instrumental in recognizing the shapes of objects and to be part of the ventral stream through fMRI (James et al., 2003). DF could not recognize faces of loved ones or even state the shape of a common object by looking at it, but she was fully able to correctly recognize loved ones via their voices, and also accurately identify an object by holding it in her hands. Surprisingly, DF was able to reach out and pick up objects without problem, with the same appropriately-sized grip aperture and orientation of someone without neurological damage (Goodale et al., 1994). Another patient, who had similar damage to the ventral stream via a stroke exhibited nearly identical behaviour to DF (Karnath et al., 2009).

So, patients with damage to the dorsal stream are fully able to perceive the position, size, shape, and orientation of objects, while not being able to reach out and grasp them, while patients with damage to the ventral stream have the reverse detriment, being able to reach out and grasp objects unhindered while not being able to perceive them fully. This distinction pushed the original anatomical definition of the two visual stream hypothesis to be a functional one: an action-perception framework, asserting that vision and action are inextricably linked (Goodale, 2011). Focusing on vision-for-action, in the next section I begin to explore how humans use visual information to initiate and guide reaching actions.

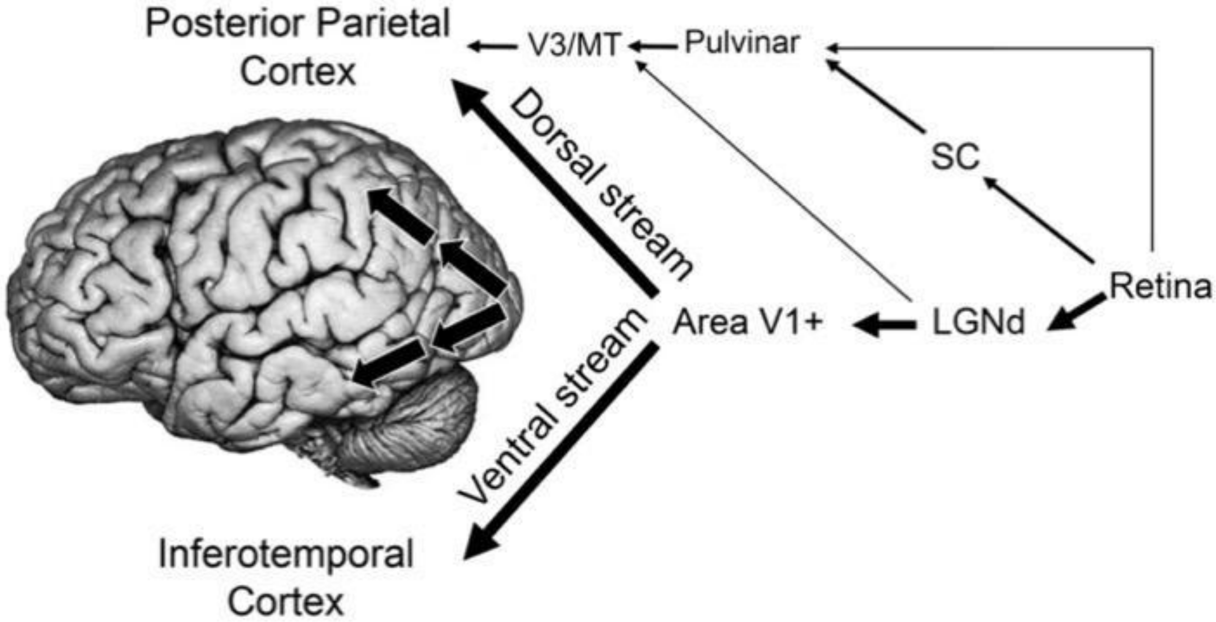

Figure 1.1: A visualization of the Two Visual Stream Hypothesis: the Dorsal Stream (vision-for-action), and the Ventral Stream (vision-for-perception). Duplicated from *Transforming vision into action* (Goodale, 2011).

1.1.3 Visual system as action planner

“Everyone knows what attention is. It is taking possession of the mind, in clear and vivid form, of one out of what seems several simultaneously possible objects or trains of thought. Focalization, concentration of consciousness are of its essence. It implies a withdrawal from some things in order to deal effectively with others.” (James, 1890)

The end goal for this thesis is to understand how visual information is acquired through eye movements to guide object interactions, and the relationship this process has with embodiment and new VR technology. Having discussed how visual information is split into two streams in the brain, here I move further along the flow of sensory information within the brain and discuss the key components of visual attention in relation to object interactions.

The amount of sensory information the visual system delivers increased markedly over the evolutionary path to modern humans, and it makes sense that there had to be a mechanism to select what information was important at any given moment, and what wasn’t. Our ability to control our attention is undoubtedly an important aspect of being human. When I’m driving my car, how am I able to choose which objects to look at and which to ignore in order to arrive safely at my destination? There is some mechanism that allows us to decide what stimulus is amplified in our conscious experience at any given moment, and what is dampened. This mechanism is known as “attention”.

Attention is a massive topic in and of itself, with a wealth of visual attention literature, including theories arguing top-down, bottom-up, saliency models, and combinations of these. For the purpose of this document, here I focus on visual attention with respect to action with the knowledge that both the ventral and dorsal visual streams seem to share one attentional mechanism (Deubel & Schneider, 1996). Although famously stated over a hundred years ago, the William James quote to begin this subsection runs into difficulties when one tries to define attention in an objective, rather than subjective manner. Individually, we all know what attention is, while objectively we don’t, which has led to many psychology researchers lobbying for the dismissal of the term (Hommel et al., 2019). These authors argue that “attention” may not be mutually exclusive to “intention” to act, especially when considering the overlap of the two concepts in the posterior parietal cortex (the brain region connected to vision-for-action) (Culham & Kanwisher, 2001), and conclude that “attention” and “intention” should be integrated (Hommel et al., 2019). With this in mind, I use the term “visual attention” with respect to how vision affects action from a functional standpoint, akin to the premotor theory of attention. That is, shifting attention is triggered by foveal saccades in order to plan actions (Rizzolatti et al., 1987). Next, I explain how visual attention is specifically thought to be deployed in the lead up to an action.

One way to separate the sensory information coming into our eyes is that which falls on the fovea (the location on the retina with the highest acuity) and that which does not (peripheral vision). It’s been shown that humans can attend to objects in their peripheral vision without shifting their foveal fixation to that object (Posner, 1980). For example, as I type this sentence, I am able to keep my eyes fixated on the computer screen in front of me, while shifting my attention to the coffee mug beside the screen. This shift in attention without shifting of the eyes is called ‘covert attention’. Using the same example, if I shift my eye gaze to the coffee mug so that an image of it lands on the fovea of my retina, and my attention along with it, I am said to be shifting ‘overt attention’ (Posner, 1980).

Numerous studies have shown that, although humans have the ability to shift covert attention to different regions in their field of view while their fixation is maintained, covert attention will involuntarily shift to the target location of a saccade immediately before the saccade occurs (Deubel & Schneider, 1996; Henderson, 1992; Kowler et al., 1995). In one study, participants were asked to discriminate between two images as one appeared on a screen before the eyes made a saccade but after the signal to make this saccade was given (Deubel & Schneider, 1996). Participants had greater success discriminating when the images appeared at the target location of the upcoming saccade, meaning that participants shifted their covert attention just before the saccade took place. This has been elaborated on to show that even when a third distractor stimuli appears after the 'go' signal, but before the eyes make a saccade, covert attention will shift to this distractor stimuli before shifting to the target location of the saccade only if the eyes also fixate on this distractor before arriving at the target (Peterson et al., 2004). Another study found that as a shift of visual fixation occurs, subjects are unable to attend to a location that is not the target saccade location (Hoffman & Subramaniam, 1995). This is all evidence for a tight coupling of covert attention location and upcoming saccade location, and what follows covert attention at the location of a saccade, then, necessarily, is overt attention, at least briefly.

So, overt attention relies on covert attention. In this way, it is possible that we can orient covert attention to an object, and not overt attention, but, we cannot orient overt attention without first having oriented covert attention. The premotor theory of attention also argues that covert attention is a necessary preceding step to overt attention as its purpose is to plan for an upcoming saccade of the eyes (Rizzolatti et al., 1987). Further research has found more evidence for this connection, showing substantial overlap in the brain regions associated with covert attentional processing and eye movements (Corbetta et al., 1998; de Haan et al., 2008). Moreover, a study combining electroencephalography and head-mounted eye-tracking showed similarities in the neural responses of covert and overt attentional shifts with slightly larger measurements in the frontal brain areas during covert attentional shifting that was hypothesized to be due to the inhibition of saccades (Kulke et al., 2016). In other words, covert attention may have evolved as a preparation mechanism for an overt attentional shift, and active inhibition is required to stop a visual saccade from occurring. The premotor theory of attention has been extended to preparation of movements other than the eyes, including studies providing evidence for a common generator of attentional shifts of eyes and motor outputs of the hands (Gherri & Forster, 2012). Coupling all this with previously mentioned evidence that primate brain size correlates with increased manual dexterity (Heldstab et al., 2016) yields even greater cause to suggest brain size, manual dexterity, and visual attention are, perhaps, related to the evolution of our human-level conscious awareness.

Given the above, it’s no surprise that overt attention aids accuracy during reaching and grasping (Bekkering et al., 1995; Johansson & Flanagan, 2001), and a line of research shows that covert attention plays an important role too. When planning a goal-directed movement towards a target or object, before the eyes overtly fixate the target of action, covert attention shifts to both the hand immediately before the onset of movement (Eimer et al., 2006; van Velzen et al., 2006) and to the target of the upcoming action (Baldauf & Deubel, 2009). This provides yet more evidence that covert attention is part of visual preparation of an upcoming movement. What’s more is that covert attention splits to more than one upcoming target during multi-step reaching movements in a divisible manner. In an important study, participants were asked to keep their visual fixation on a central cross while making rapid reaches to up to three targets in their peripheral vision (Baldauf et al., 2006). Participants were cued with an arrow to the target they were to point to first on the screen in front of them, and were to continue to the next clockwise target after touching with their index finger. Participants were then cued with an auditory signal. Covert visual attention at the peripheral targets was assessed with a secondary symbol discrimination task where, after the auditory cue but before the onset of movement, letters or numbers would be shown for 50 ms at each of the peripheral targets. Up to three of the peripheral targets would flash with symbols, and participants were instructed to indicate after the trial if they were the same or different from one another. Participants were more successful at discriminating symbols at areas of upcoming movement targets compared to areas irrelevant to the upcoming movement task. Interestingly, participants split their covert attention in a descending manner from first to third target before movement onset. That is, when completing three sequential manual reaching tasks, before the onset of movement, the greatest magnitude of covert attention is dedicated to the first target, the next highest level to the second target, and the lowest level of covert attention is given to the third target in the sequence. In subsequent studies, the authors were able to increase covert attention at the second target of action by increasing the movement complexity at this target by increasing movement delay and removing the visualization of the target (Baldauf & Deubel, 2008a). Another study showed that during goal-directed bimanual reaching movements, participants will also divide their covert attention equally to targets that are of equal distance from each hand, and that more covert attentional resources will be dedicated to targets that are placed further from the hand that will reach to it (Baldauf & Deubel, 2008b). Figure 1.2 illustrates this series of studies.

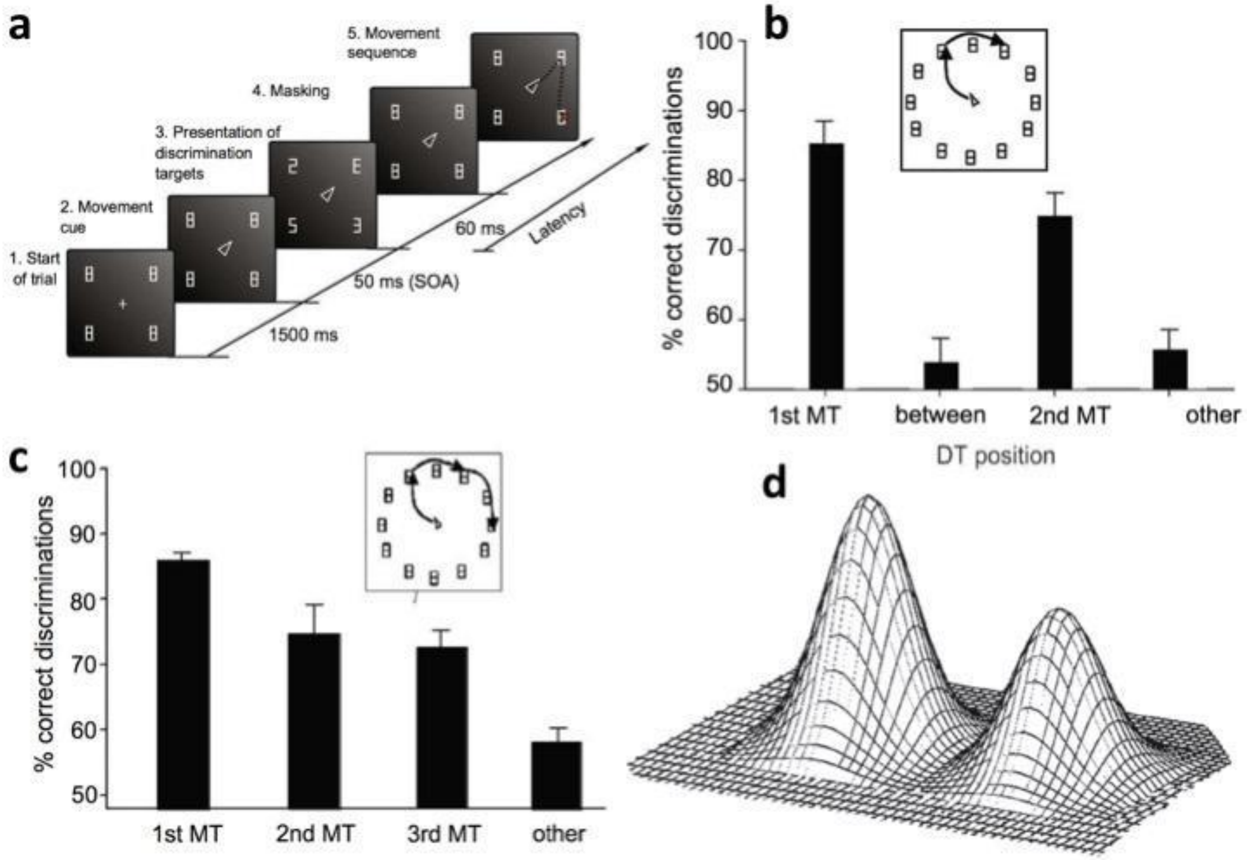

Figure 1.2: a) Timeline of a trial to test for strength of covert attention at areas of future manual action. b) Participants discriminate letters better at locations of future sequential manual actions than at irrelevant locations. c) Percentage of correct discriminations at three future locations of manual action. d) Illustration of an attentional landscape divided unequally between two locations. All from (Baldauf & Deubel, 2010).

To summarize, covert attention helps plan upcoming hand movements in a differentially divisible manner based on the accuracy needs of the movement goal, the time of the upcoming movements, the number of goals of the movement, and the distance between the hand and said goal. But, the influence of the visual system during goal-directed movement doesn't stop once an action begins, but rather continues to influence motor output as a feedback mechanism in real-time which is explored in the next section.

1.1.4 Visual system as real-time feedback for action

"Skilled motor behaviour relies on the brain learning both to control the body and predict the consequences of this control. Prediction turns motor commands into expected sensory consequences, whereas control turns desired consequences into motor commands." (Flanagan et al., 2003)

The world doesn't freeze around us once we begin acting, and obviously, our bodies don't either. It is important to have information about the actions we are going to make and a plan to do them, but, once we've decided to initiate a movement, how do we control it in real-time in a dynamic environment? Of course, proprioceptive and tactile information play a role and will be discussed later, but here I discuss the role the visual system plays in controlling movement.

We take for granted the complex nature of coordinating many degrees of freedom to achieve a goal-directed movement. The human upper-limb, for example, has 3 joints (without considering those involved in the hand). Each of these joints is controlled by multiple muscles and can move in several different spatial planes. Feedforward planning models of movement put emphasis on advanced calculation of joint angles and muscle activation to move the limb in a specific trajectory. Not only would it be incredibly computationally-intense to calculate all of this in advance of every movement, but the outcome likely would not be as smooth and accurate as human movements actually are (Franklin & Wolpert, 2011; Morasso, 1981; Todorov & Jordan, 1998). As well, goal-directed human movements are reliable and repeatable, but with considerable variability in their path to success when repeated (Harris & Wolpert, 1998). That is, if I were to repeatedly reach out and grasp a coffee cup, I would reliably get my hand to the location effectively each time, but with differences in the joint angles of my arm each time. Moreover, the fact that humans will respond to visual perturbations in under 100 ms after a movement has already been initiated provides further evidence that online visual feedback of movement is at play (Soechting & Lacquaniti, 1983). From these observations, a new theory for motor coordination has been proposed (Todorov & Jordan, 2002). Optimal feedback control relies on error signals calculated from the difference between actual and predicted movement to generate a corrective action to minimize this error. In other words, for optimal feedback control to work, an estimate of the state of the body is required. This estimate is calculated from the outgoing (efferent) motor signals and the incoming (afferent) sensory signals (Wolpert et al., 1995). The quote at the start of this section summarizes this well. Optimal feedback control requires both effective control over the body, and also reliable sensory prediction of that control (Flanagan et al., 2003).

In fact, the reason that humans may have large variance in joint angles and trajectories during repeated reaches is that the desired outcome of the hand reaching the target is constructed from an inverse internal model (Kalaska et al., 1997; Wolpert & Kawato, 1998). In other words, a spatial goal or trajectory of the hand is converted into specific motor patterns. Not only are there multiple arm joints to account for, but we are constantly changing body and head positions, even if we think we are sitting still at a table participating in an experiment. Our evolutionary path accounted for this constant change, using the end goal of a movement as the primary input, and ultimately allowing for noise in most degrees of freedom to arrive at that end goal. This could be the reason why neural activity in the primary motor cortex encodes functional muscle synergies (Holdefer & Miller, 2002) rather than encoding individual muscle activation. The information being sent to the primary motor cortex may originally be derived from a desire to move to a certain spatial location. The specific motor patterns can be different each time and result in the same outcome of the hand arriving at the desired spatial location. In the same vein, errors that are irrelevant to the goal of the action are not used in the prediction error calculation, as this would require unnecessary effort and would necessarily increase the noise in the system. This minimal intervention principle has been shown experimentally as reaches that are perturbed towards more narrow targets are corrected while those to wider targets are not (Nashed et al., 2012). In essence, to some extent we use the desired result of our movement to form our movement plan, including the necessary accuracy of the movement.

With the previously-discussed knowledge that primate brain size and hand dexterity evolved together (Heldstab et al., 2016), it's not surprising to find that we possess visuomotor feedback mechanisms that treat our own hands in an exceptional category when compared to objects or distractors in our environment. For optimal feedback control to be possible in dynamic environments that change spatially and temporally, humans have developed an efficient mechanism that links visual information about the hands and their targets and filters out distractions (Reichenbach et al., 2014). Specifically, these authors showed that visual distractions at the hand are more efficiently filtered out than at the target, providing evidence for a link of hand representation between the motor and visual systems (Reichenbach et al., 2014). Interestingly, the ability of humans to correct errors in trajectory of hand movements using peripheral vision has been found to be highest when the hand is moving towards the gaze location - even higher than when the eyes are fixated on nearby locations (de Brouwer et al., 2018). We do not perceive our hands as just objects in our environment that we can wield, but rather special entities we know to be a part of us.

Some assert that humans have evolved a predictive coding system of motor control, going as far as saying that motor commands are signals to minimize the error between predicted sensory information and actual sensory information (Adams et al., 2013). In brief, the authors assert that we are constantly calculating an error between the actual sensory information we receive and the predicted sensory information with the aim of minimizing the prediction error through motor outputs (Adams et al., 2013). This theory of active inference takes into account prior beliefs about the sensory consequences of desired limb trajectories (Friston, 2011). Whatever the case, there seems to be consensus that online control of motor commands is made possible, in part, by the minimization of error between visual sensory feedback and some calculated internal state of the body in relation to a goal. Therefore, measuring eye gaze, especially with respect to hand position during object interactions will provide insight into how these sensory and motor streams are coordinated (see section 1.1.6). Of course, the human body receives other streams of sensory information that are integrated to aid in a host of functions. In the next section, I discuss the role that haptic feedback plays in successful motor control during object interactions.

1.1.5 Haptic feedback in object interactions

“... peripheral neurons in the touch-processing pathway, as with peripheral neurons in the visual-processing pathway, perform feature extraction computations that are typically attributed to neurons in the cerebral cortex.” (Pruszynski & Johansson, 2014)

Even though this section is putatively about visuomotor behaviours, this thesis is about embodiment. And, at the boundary point between these two is haptic feedback. Specifically when we move our body, guided by vision, to interact with the world, we interface with our environment through the sense of touch. Therefore, as we continue the journey along the path of sensory information from inside of an embodied agent outward, in this section I explore the role haptic feedback plays in visuomotor behaviour during object interactions. Computational processing occurs outside the brain in the individual tactile neurons of human fingertips (Johansson & Flanagan, 2009; Pruszynski & Johansson, 2014). Coupling this with the knowledge that computation also occurs in retinal neurons before transmission of visual information to the visual cortex (Gollisch & Meister, 2010), it’s important to state, at the very least, that the brain is not the sole proprietor of the hardware for sensory integration, but that even first-order peripheral neurons have a role to play. Although not necessarily answered in this document, this knowledge elicits several questions. What other computation occurs in our periphery before arriving centrally? Should there be such a hard distinction between the central and peripheral nervous systems? What is to be said about the idea that our brain is the centre of our conscious experience if such parts of that conscious experience rely on what’s peripheral to it? Notions of embodied cognition in humans are, for some reason, still considered controversial in the academic community. Co-authors and I highlighted the importance that these theories are considered when pursuing research aiming to understand human behaviour

(Lavoie et al., 2018). But, those questions are outside the scope of this thesis, so here I focus on the more relevant topic of the value that haptic information provides to successful object interactions, the impact that haptic information has on visual behaviour during interactions, and how humans balance between using haptic and visual information over the course of an object interaction.

It seems an obvious statement to say that haptic feedback makes interacting with objects easier. But, what specifically does haptic feedback provide that vision doesn't, or vice versa? Information about an object can be received visually, but much of that information can still be gained through haptic feedback alone. Spatial location and size of the object can be deduced from the central nervous system by using the proprioceptive inputs of the arm and hand and tactile feedback provided to the fingertips (Berryman et al., 2006; Edin & Johansson, 1995). Of course we are able to grasp objects without seeing them, but if the only information about an object that we have is haptic (ie. we can feel the object with one hand while we perform a grasp with the other), we are still able to successfully interact with it. In fact, while doing this, it's been shown that the grip aperture scales with the size of the object (Westwood & Goodale, 2003), but not quite in the same way as it does when the object is visualized (Chieffi & Gentilucci, 1993; Pettypiece et al., 2010). Westwood and Goodale used a size-contrast illusion to show that haptic object processing can be separated into one stream for action and another for perception (2003). Participants used their hands to feel objects without seeing them with a set of object illusions in place to manipulate incoming haptic information. The authors showed that size perception of the target object would change with the illusion, while participants' grip aperture did not, relying solely on the information from the target object, and teasing the possibility that "direct transformation of somatosensory signals into motor commands could occur within a distributed network of dorsal brain regions, without contribution from ventral brain regions that are responsible for constructing perceptual object representations" (Westwood & Goodale, 2003). Although grip aperture scales with just haptic information, maximum grip aperture is wider and movements take longer than with vision alone, and interestingly, when participants are provided both haptic and visual information, movements resemble those when only vision is available (Pettypiece et al., 2010). This seems a counterintuitive finding, and has been argued that, in these studies, the reason haptic information seemed to provide little advantage to participants is that the hand and object were hidden, providing little confirmation that haptic and visual feedback were coming from the same object (Camponogara & Volcic, 2019). In this instance, haptic information may have been ignored in favour of visual information.

In light of the fact that many studies have found haptic feedback to be important in successful goal-directed object interactions (Bingham et al., 2007; Bozzacchi et al., 2014; Coats et al., 2008; Weigelt & Bock, 2007; Whitwell et al., 2016), Camponogara and Volcic compared reach to grasp movements on objects where participants received haptic only, visual only, and combined visuo-haptic information (2019). The authors collected movement duration, maximum grip aperture, and maximum wrist velocity and deceleration on each of the three conditions shown in Figure 1.3. The results of this study clearly show, unsurprisingly, that having both visual and haptic feedback increases performance, with faster movements and smaller maximum grip apertures. Interestingly though, when participants received haptic feedback alone compared to visual feedback alone, their performance was noticeably worse. In the haptic condition, maximum grip aperture, and both maximum wrist velocity and deceleration occurred much earlier along the movement trajectory indicating that hand preshaping started earlier, fingers opened wider to be more cautious upon grasp, and closed slower around the object (Camponogara & Volcic, 2019). The authors go on to show that differences between the visuo-haptic condition and each of the other two conditions were unique, with grip aperture differing earlier along the movement trajectory between visuo-haptic and visual conditions, differences between visuo-haptic and haptic conditions appearing later. Furthermore, wrist velocity differences appeared earlier between the visuo-haptic and haptic conditions, and those between the visuo-haptic and visual conditions appeared later (Camponogara & Volcic, 2019). These findings support previous work showing that haptic information seems to take the primary feedback position in earlier phases of movement, perhaps due to the fact that the hand is in a position further from the fovea, with visual feedback taking the lead in later phases approaching an object, when real-time visual feedback is necessary (Volcic & Domini, 2016).

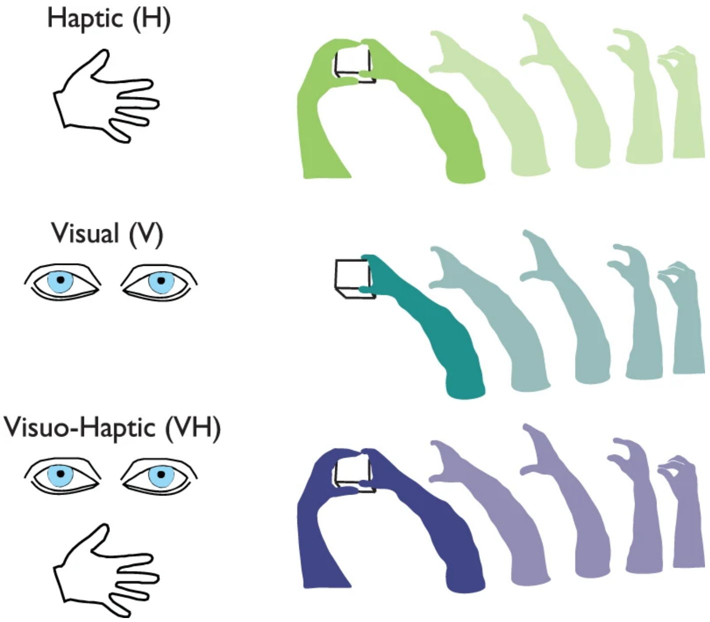

Figure 1.3: Representation of the task under Haptic, Visual and Visuo-Haptic conditions. The grasping action was always performed with the right hand. In H and VH participants were already holding the object with their left hand before the start of the grasping action. Figure borrowed from (Camponogara & Volcic, 2019).

Of course, most everyday object interactions don't stop once the hand arrives at the object and we often do not have ongoing haptic information from one hand as we reach to the object with our other hand. So, how does this interplay progress in more natural, everyday object interactions? Once the hand has arrived at an object for interaction, the haptic information received almost immediately frees the eyes for further information gathering in the environment (Land et al., 1999; Land & Hayhoe, 2001; Lavoie et al., 2018), which is discussed in depth in the next section. The introduction of haptic information from the interacting hand on the object provides enough confidence to the user to allow the visual system to move along. During a reach to grasp movement, when the hand is beginning its reach from a location outside peripheral vision, haptic information about the object from one's other hand provides early preshaping information to the interacting hand. Visual dominance increases as the interacting hand gets closer and closer to the object, allowing for optimal trajectory of reach and grip aperture, right up until the point at which the interacting hand begins to receive haptic information from the object (Land et al., 1999; Land & Hayhoe, 2001; Lavoie et al., 2018; Posner et al., 1976). As long as the eyes are required at another location for a future interaction, the eyes will shift their gaze when a sufficient amount of haptic feedback is received to provide confidence the interaction will be a success.

During natural grasping movements to objects, vision and haptic feedback are integrated (Schenk, 2010). Vision mainly guides the hand and fingers into appropriate grasping positions

(Smeets & Brenner, 1999), while the haptic feedback we receive at the end of a reach gives important information about size and shape and actually corrects any incorrect assumptions about size for future movements (Bingham et al., 2007). It's been proposed that when a reach-to-grasp action is carried out without the expected haptic feedback from the object, engagement of the dorsal, vision-for-action stream is diminished (Whitwell et al., 2014), supporting the notion that for natural reaching and grasping actions to occur, haptic feedback is a requirement (Cuijpers et al., 2008). The main behavioural result of reach-to-grasp actions without haptic feedback seems to be misjudgment of object distance estimation from the participant even after extensive training (Bingham et al., 2007; Bozzacchi et al., 2014; Whitwell et al., 2014). And so, haptic feedback during object interactions not only provides details that can't be predicted based on vision alone (eg. weight), but also allows for fine-tuning correction of distance and depth estimation that vision is unable to reliably provide. Furthermore, previous research has shown that the complex coordination of changing forces during an object movement is aided by the ability to experience tactile sensation of the object on the fingertips (Cheung et al., 2003; Johansson & Flanagan, 2007; Witney et al., 2004). Without being able to feel the full sensation of the object's weight and momentum on the fingertips, appropriate grip force is harder to gauge leading to dropping of the object. In one interesting study, researchers tested grasping behaviour on 20 objects of three people who had permanent loss of tactile and proprioceptive sensory information from the neck down to a control group (Miall et al., 2019). Unsurprisingly, the deafferented participants took longer to complete the grasps, and also had a longer deceleration phase before their hand reached the objects. In agreement with previous work, deafferented individuals had larger and earlier peak grip apertures, along with a wider movement trajectory believed to allow them to maintain visual attention longer as the hand approached the object (Jeannerod et al., 1984; Miall et al., 2019). When grasping objects, the deafferented participants had greater variation in their grasp locations, while maintaining opposition of the thumb and forefinger. All deafferented individuals minimized the degrees of freedom of the hand while grasping, with one describing it as "tucking his ring and little fingers into the palm, or by extending middle, ring, and little fingers, thus restricting active control to a pinch grip between thumb and index finger, or a tripod grip with thumb, index and middle finger" (Miall et al., 2019). Finally, all deafferented participants described using vision to monitor their actions more than controls, which leads to the next topic of discussion where I discuss the way in which visual and haptic sensory feedback is coordinated during naturalistic object interactions. More specifically, how do we use overt visual attention from our eyes to coordinate our hand movements when doing everyday tasks?

1.1.6 Eye and hand movements during object interactions

"... vision is a scarce and valuable resource, and it is disengaged from a particular aspect of an action as soon as another sense is available to take over." (Land & Hayhoe, 2001)

As I sit in a restaurant, I watch intently as a young waiter clears all the used cutlery from his previous guests and places clean ones in their appropriate places for the next group. He has probably done this exact task, at this exact table, thousands of times, and yet, he visually fixates every single time he places an object on the table. As he carries out this task, there's a dance that occurs between his hands and his eyes, an undeniable pattern that's present. Having discussed the function of covert and overt visual attention in movement planning, as well as the role of visual and haptic feedback for online control of movements, now the coordination of visual fixation, body, and hand movements will be explored. In this section I present previous literature studying the way in which eye and hand movements coordinate to achieve smooth goal-directed object interactions. Although a great wealth of important eye movement literature exists that explores free picture viewing (Buswell, 1935), saccade frequency and timing, smooth pursuit, goal-directed scene viewing (Yarbus, 2013), typing (Butsch, 1932), and even piano playing (Weaver, 1943), these experiments constrained participants heads and bodies in an unnatural fashion. Here I focus on studies that allow participants to move their heads and bodies freely. In addition, I focus on research specific to object movement and interactions in everyday tasks. Once again, this is not to discount the importance of other studies, but rather to direct appropriate attention to the purpose of this document.

Technology to measure eye and hand movements during everyday object interactions became more accessible in the 1990s. One of the first studies to do this, now famous in many human behaviour labs, recorded a first-person view, as well as each participants' eye movements using a monocular head-mounted eye-tracker while they made a cup of tea in a kitchen (Land et al., 1999). No directions were given on how to carry out the task, and irrelevant objects were placed in the scene to emulate a real-life scenario. After calibrating the two video feeds, the foveal direction of the eye relative to the head was yielded with 1° accuracy. The authors describe very limited fixation to any objects that were not relevant to the task, and an average of 0.56s of time between the eyes arriving at an object to be interacted with and the hand arriving at the same object (eye-hand latency) (Land et al., 1999). This is the first instance describing the 'just-in-time' phenomenon, which is that visual fixations arrive at objects to be interacted with a minimum amount of time to be processed online. Even for interactions that individuals have done many times, and could be argued to be "automatic", visual attention is still necessary. The authors conclude that “the results of this study clearly show that even automated routine activities require a surprising level of continuous monitoring” (Land et al., 1999). Another landmark study with similar results recorded eye movements while participants made a sandwich while seated (Hayhoe, 2000), and the researchers of these two studies analyzed their results together to define eye movements during object interactions more broadly (Land & Hayhoe, 2001).

Objects were generally fixated for the duration of manipulation, except for some extended tasks like filling the kettle, where the eyes would sometimes fixate irrelevant objects or objects to be used in the future (Land & Hayhoe, 2001). The average of both tasks saw fixation time less than 5% on irrelevant objects. In fact, in a portion of the sandwich trials, the number of irrelevant objects was increased to half of the total number of objects on the table. Before a trial began, fixation on task irrelevant objects was 52%, but once the trial began, this dropped to 18%. The authors hypothesize that this represented a shift from ‘bottom-up, salience-driven’ to ‘top-down, task-driven’ eye behaviour (Land & Hayhoe, 2001). In both tasks, there was strong consistency across participants providing even more evidence that the visual system is strongly influenced by the specific objectives of a task.

Some of the differences between the tea and sandwich tasks were: the eye-hand latency in the sandwich task was shorter (0.09s), there were more, shorter fixations, and more unguided releases of objects in the sandwich task (Land & Hayhoe, 2001). This has been attributed to the closer proximity of objects and the participants being seated in the sandwich task compared to the tea task. The tea task also required participants to turn and walk across the room to retrieve some objects, while the required objects in the sandwich task were laid out in front of the seated participants.

To summarize, the authors agree that when picking up or putting down an object, the hand is rarely fixated as fixation lies on the object, or its target location, respectively (Land & Hayhoe, 2001). Once an object has been reached by the hand, the eyes do not fixate on it. And, when pouring a liquid, fixation lies on the object being filled, rather than the pouring object. These studies show that the idea that unconscious automatic actions do not require feedback while consciously controlled actions do, is not entirely true (Land & Hayhoe, 2001). There are many instances where the eyes are monitoring an action, even actions on objects that have previously been fixated. In fact, the eyes very strongly precede and predict almost every action carried out in these tasks, providing little evidence that the visual system creates a model of the environment while performing these tasks. The required information to successfully complete a manual task seems to be obtained from the visual system every time, suggesting that the visuomotor system solves object interaction problems in real-time (Land & Hayhoe, 2001).

More recent research, the topic of which consumed me for two years as part of my Master's thesis, showed similar findings (Lavoie, 2017). In two different object interaction tasks, participants completed 20 error-free trials moving either a pasta box into and out of a set of shelves, or cups across a table and back. In these tasks, participants wore a head-mounted eye-tracker and motion capture markers on their upper body and were directed to move the objects in a specific order. In both tasks, participants rarely fixate on objects irrelevant to the task, instead fixating objects about to be interacted with well in advance, a minimum of half a second, to their hand arriving there. Little fixation is given to the hand when reaching towards an object, with a very slight increase given to the hand or the object in the hand when it is being transported. In general, once a grasp begins, participants shift their overt attention to the location that the object will be dropped off at, where fixation remains until successful release of the object is imminent. This thesis was adapted for journal publication presenting these results and compiling evidence for a common system that integrates vision and object interactions in humans (Lavoie et al., 2018). These findings provide functional, eye and hand movement evidence for the dorsal, vision-for-action stream of visual information (Goodale, 2011; Goodale & Milner, 1992), and integrates it with the attentional landscapes theory previously discussed (Baldauf et al., 2006; Baldauf & Deubel, 2008a, 2008b, 2009; Deubel & Schneider, 1996). In brief, we describe a fluid landscape of attention (illustrated in Figure 1.4) where, as participants are overtly attending to one relevant location (eg. the cup they are about to pick up), they are simultaneously covertly attending to other areas of relevance (eg. the target the cup will eventually be dropped off at). "As the success of the first movement goal becomes more certain (e.g. the hand-to-object distance is sufficiently small, or proprioceptive feedback is received during a grasp or release), the landscape begins to shift, with the next target of action receiving an increasing amount of attention. At some point, near the onset of object movement, the scales are tipped and the eyes are driven away from the site of current action toward the site of future action" (Lavoie et al., 2018). With greater understanding of normative eye-hand coordination during object interactions, next we explore how eye and hand movements change when haptic feedback is limited.

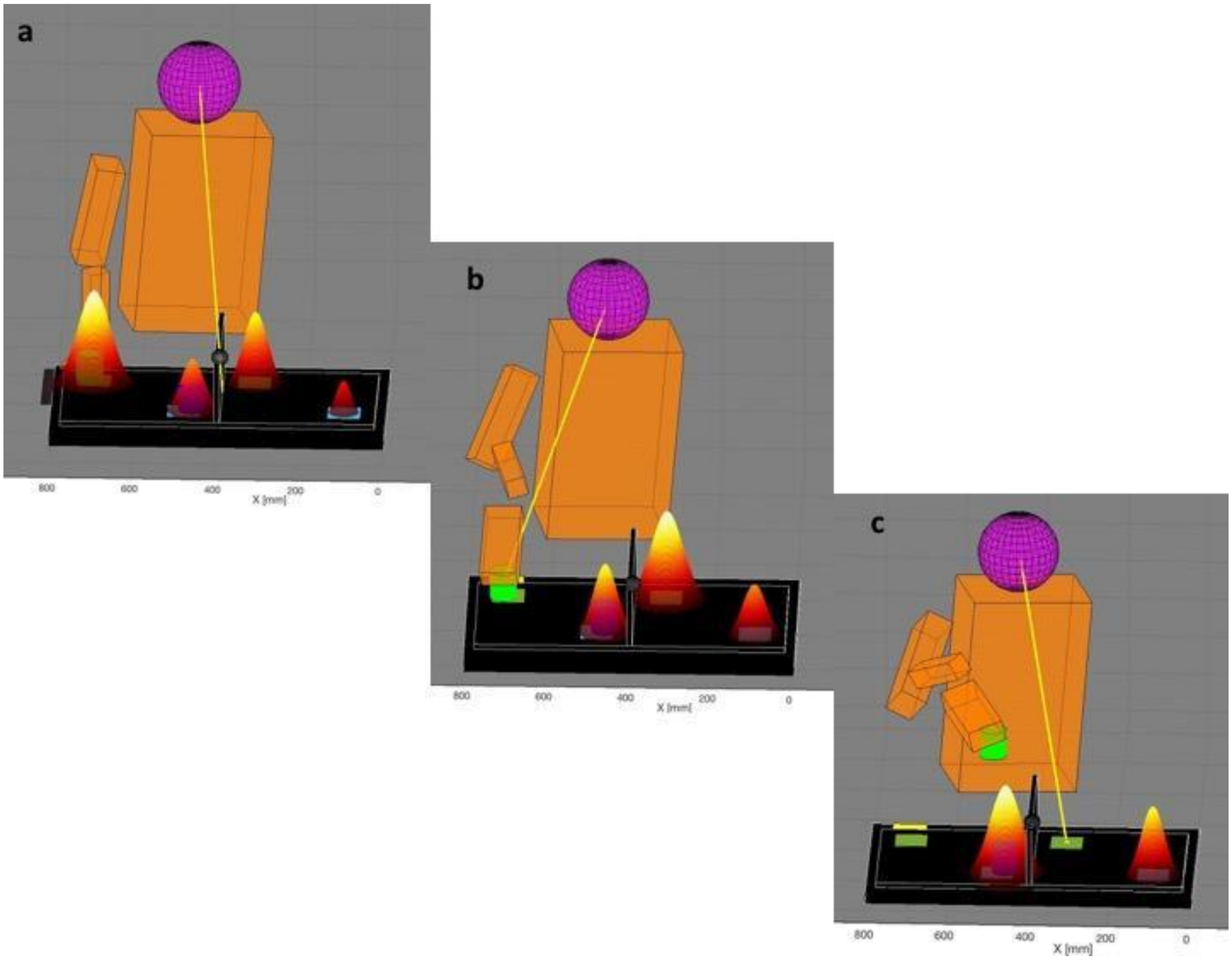

Figure 1.4: A virtual representation of the Attentional Landscape during sequential object movement. a) The participant fixates on the Neutral eye position, with covert attention dedicated to three areas decreasing sequentially in the order in which the hand will act on them. b) As the participant fixates on the Green cup, covert attention increases at its eventual drop-off location and at the next cup to be grasped and its drop-off location; c) The participant fixates on the Green cup drop-off location, with continued increased covert attention on the next cup, and its drop-off location. (Lavoie, 2017).

1.1.7 Eye movements during object interactions with limited haptic feedback

"... disruption to eye-hand coordination when using a prosthesis is characterized by increased hand-focused gaze strategies and a reduced ability to disengage gaze from object manipulations. This prevents the planning of future task-related movements ahead of time leading to a dependency on the online conscious control of the hand and reduced performance. This type of movement control seems indicative of the exploratory or cognitive stage of learning where learners explicitly test hypotheses and declarative knowledge concerning movement rules is formulated, placing high demands on cognitive resources." (Parr et al., 2018)

If you grew up in a country with cold winters, remember back to when you were at the neighborhood toboggan hill on an especially cold day. You may have brought along a thermos with hot chocolate to keep you going for a few extra hours. Taking off your thick winter gloves on these especially cold days to hold a paper cup was not only uncomfortable, but dangerous if done for too long. Recall how holding that cup with those thick gloves could be a struggle. The gloves, although keeping your hands warm, diminished the tactile information that your fingers could receive from the cup. Without looking at it, you wouldn't know if you were closing too hard on the cup, perhaps crushing it, or if the cup was millimetres away from slipping out of your grasp completely. Both negative outcomes resulted in covering the faux fur of your winter boots in sticky hot chocolate. To protect against this, you'd have to keep the cup, and your hand holding it, in a location easily visualized by your eyes. Here I cover the specific changes in overt visual attention that occur as a result of limited haptic feedback during object interactions.

Prosthesis-using populations vary greatly. Obviously, the part of the body that is being augmented by the prosthesis can be different, but more than that, some individuals may have sustained damage to previously-healthy limbs, while others may have experienced their differences from birth. Focusing on upper-limb devices, some are purely aesthetic, while others have moving parts that have traditionally controlled grip through force applied around a joint. More recently developed devices are controlled by electromyography (Calado et al., 2019; Iqbal et al., 2018), but a major bottleneck for prosthetic device functionality has been the lack of sensory feedback returned to its user. Having described the importance of haptic feedback in previous sections, it's not surprising that, in response to disrupted sensory feedback from the hand during object interactions, visual attention compensates in several ways (Cheng et al., 2023; Hebert et al., 2019; Parr et al., 2018; Sobuh et al., 2014).

When reaching for an object while using a prosthetic upper-limb, participants visually fixate on the device more than do normative populations, and less on the object about to be interacted with (Hebert et al., 2019; Parr et al., 2018; Sobuh et al., 2014). Moreover, upper-limb prosthesis-users fixate for more time on their prosthesis while transporting an object (Hebert et al., 2019; Parr et al., 2018), and make more fixations to their device and the drop-off target when transporting an object, due to feelings of insecure grip (Sobuh et al., 2014). Additionally, when dropping off an object before interacting with another area, prosthesis-users not only take much longer than normative populations, but maintain visual fixation on the object being dropped off for much longer after their prosthesis has released the object (Hebert et al., 2019; Parr et al., 2018). The cause for these changes is the necessity for vision to be used as the only feedback mechanism for action. In normative populations, confidence in haptic feedback increases as an interaction begins to take place, allowing vision to disengage at the area of interaction. This cannot occur for traditional prosthesis-users, but what happens to visuomotor behaviour when this confidence in haptic and proprioceptive feedback is returned to prosthesis-users during object interactions?

An innovative study combined several technologically-advanced improvements to upper-limb prostheses and assessed functional behaviours of two prosthesis-users (Marasco et al., 2021). Participants in this study had undergone muscle reinnervation surgery reconnecting the median, radial, and ulnar nerves that had been severed during amputation, to remaining muscles on each patient's residual limb and torso. When each participant sent a neural signal to move their missing limb, a muscle on their residual limb or torso would contract allowing control of their prosthesis through electromyographic electrodes. Similarly, each participant underwent targeted sensory reinnervation surgery mapping tactile sensation of the missing hand to skin afferents on the residual limb and torso (Marasco et al., 2021; Schofield et al., 2020). By touching this skin area, individuals experience the sensation of touch on their missing limb (Marasco et al., 2011). Each prosthesis was fitted with pressure-sensitive electrodes on the fingertips that translated signals to the appropriate area on the sensory-reinnervated residual limb through mechanical tactors. In this way, when picking up a cup, for example, the pressure on the fingertips of the prosthesis provides the sensory experience of feeling the cup on the fingertips of the user's missing limb (Marasco et al., 2021; Schofield et al., 2020). Each participant also had proprioceptive sensation of their prosthetic hand returned to them through a 90 Hz tactor that vibrated at a pre-identified location in deep reinnervated muscle (Marasco et al., 2018). Figure 1.5 illustrates upper-limb prosthetic integration of haptic, proprioceptive and movement information that each participant was afforded in this study (Marasco et al., 2021).

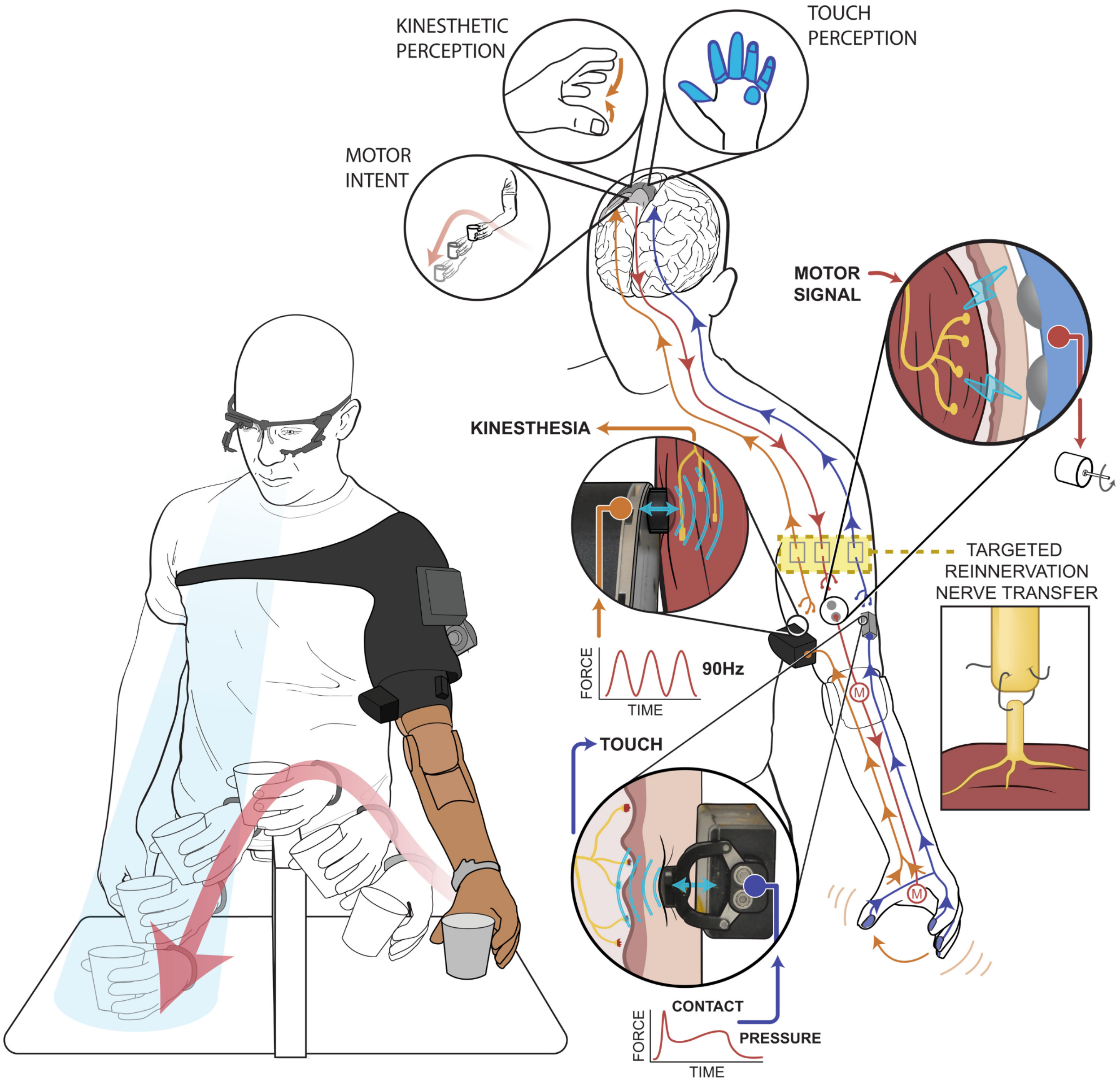

Figure 1.5: A depiction of the added functionality that prosthesis-users are afforded when targeted reinnervation surgeries are coupled with technology that provides kinesthetic and touch feedback to users along with intuitive motor control. Figure borrowed from Marasco et al., 2021.

When participants carried out a cup-transfer task that had been previously published on normative and prosthesis-using populations (Hebert et al., 2019; Lavoie et al., 2018), visuomotor behaviour gravitated towards that of the normative population. In fact, when both touch and kinesthetic sensation were returned to these participants, the results were significantly better than either sensory mode on its own (Marasco et al., 2021). More specifically, prosthesis-using participants with both haptic and proprioceptive sensation returned to them during object interactions spent less time fixating their own limb during reaches and transports and more time fixating the location of upcoming action, and were able to disengage their visual attention from objects they were releasing much earlier. In this way, it's apparent that haptic feedback plays an integral role in efficient visuomotor behaviour during object interactions. An additional component of this study, leading into the next topic of discussion, showed that "multisensory integration is the substrate for incorporating a bionic prosthesis into the user's self-image and providing them with the sense that the limb is part of their body" (Marasco et al., 2021).

1.1.8 Conclusion

Returning sensory feedback and intuitive motor control to prosthesis-users not only enables them to more effectively interact with their environment, but induces feelings that their prosthesis is more a part of their body (Marasco et al., 2021). The next section explores what we know about our sense of embodiment and how the combination of its parts contributes to our spectacular conscious experience.

1.2 - Embodiment

"The world experienced (otherwise called the 'field of consciousness') comes at all times with our body at its center, center of vision, center of action, center of interest. Where the body is is 'here'; when the body acts is 'now'; what the body touches is 'this'; all other things are 'theres' and 'thens' and 'thats'. These words of emphasized position imply a systematization of things with reference to a focus of action and interest which lies in the body; and the systematization is now so instinctive (was it ever not so?) that no developed or active experience exists for us at all except in that ordered form. So far as 'thoughts' and 'feelings' can be active, their activity terminates in the activity of the body, and only through first arousing its activities can they begin to change those of the rest of the world. The body is the storm center, the origin of coordinates, the constant place of stress in all that experience-train. Everything circles round it, and is felt from its point of view." (James, 1905)

Embodiment has been described as the sense of one's own body, and has many synonyms, including, but not limited to, "bodily self-consciousness" (Bermúdez, 2000), and "corporeal awareness" (Berlucchi & Aglioti, 1997). When the term "embodiment" is mentioned, some researchers and scientists scoff at it, claiming it to be a vague, nondescript term. But, as previously mentioned, all humans know the feeling of being inside a body, even if we can't articulate it. Many have tried, including William James, the father of modern psychology, describing the body as the "storm center" of human experience (James, 1905). If we've ever had an out-of-body experience, we take the feeling of being outside our own body as the exception, rather than the norm. Why is this the case, and what are the factors at play in building this experience for us? Going further, we can ask a question that has plagued researchers for decades (Blanke & Metzinger, 2009; de Vignemont, 2011; Gallagher, 2000; Jeannerod, 2003). How are we able to distinguish our body from other people's bodies or objects in the environment?

Our bodies are constantly receiving a flow of information from both the outside world and our position in it: vision, touch, proprioception, smell, taste, sound, and even balance. Our bodies are the only objects that we perceive from the inside and the only objects that submit to our will without some sort of intermediary, giving each and every one of us an exceptional relationship with our body more than anything else (de Vignemont, 2011). The main factor in creating the sense of embodiment is that our different sensory modalities and motor outputs are synchronized close enough in time, allowing our brain to integrate these streams of information (Giummarra et al., 2008). When I'm sitting in the garden and a bumble bee lands on my hand, I both feel and see the touch of its legs on my skin. Two sensory streams, vision and touch, are being received at the same time at a spatial location occupied by my body that a third sensory stream, proprioception, provides. This synchronized information supports the notion that the area the bee is touching is part of my body. When I decide to shake the bee off my arm, I initiate a motor signal while also visualizing my arm moving as I intended it to. Even in this simple example, there are complex phenomena at play. How do I know that my arm is a part of my body? And, if I do know that my arm is mine, what exactly does it mean when "I move my arm"? Finally, how do I know where my arm is and is supposed to be in the environment? In brief, the answer to these questions about embodiment have been separated and studied under three general components: ownership, agency, and self-location (Braun et al., 2018; Longo et al., 2008). 'Ownership' is the feeling of possessing one's body or a part of one's body, 'agency' is the feeling of being in control of an action or an initiation of an action (Braun et al., 2018), and 'self-location' refers to the feeling that one's body is located where one would expect it to be (Longo et al., 2008). This knowledge has allowed researchers to manipulate and test the limits of the sense of embodiment in a variety of ways (Botvinick & Cohen, 1998; Ehrsson, 2007; Kalckert & Ehrsson, 2012; Tsakiris & Haggard, 2005).

1.2.1 Body ownership

"My body is manifested to me in a more primitive form than beliefs or judgments. It is manifested in the form of feelings of ownership. There is something it is like to experience parts of my body

as my own, some kind of non-conceptual intuitive awareness of ownership." (de Vignemont, 2011)

Out in the garden, watching a bumble bee crawl around on my arm, I have no doubts about the fact that my arm is mine, and the extension of this feeling of 'mineness' does not extend to the table when my little friend departs my arm for it. But, how? We take for granted the feeling of ownership we experience over our bodies, and only truly understand that it's there when it's been altered in some way. Overall, the component of ownership with respect to embodiment is "the experience that the body is part of the self" (Ehrsson et al., 2004). Here I discuss research that has explored the limits of our sense of bodily ownership and highlight models of how this feeling seamlessly runs under the radar during our daily lives.

In a groundbreaking study, Botvinick and Cohen discovered that participants could be made to feel as though a fake rubber hand was in fact their own (1998). Participants were seated with their left hand hidden from view and a fake rubber hand placed in an anatomically plausible position in front of them. The experimenter then stroked both the fake hand and the participant's real, hidden hand in synchrony using two paint brushes (control group had their finger stroked with a slight asynchrony to the rubber hand). Ten minutes later, all participants filled out a questionnaire, with results from the experimental group indicating they experienced an illusion where they seemed to feel the touch from the brush through the fake rubber hand in view, and not from their real, hidden hand. In a second experiment, the same procedure of synchronized brush strokes took place, and after different timeframes, participants were asked to indicate, by pointing with their right hand under the table, where their left index finger was located. A phenomenon called 'proprioceptive drift' was observed, as the longer the period of synchronized brush strokes took place, the further towards the rubber hand participants indicated their real, hidden hand was (Botvinick & Cohen, 1998).

This seminal experiment has been replicated in a number of ways with different measures of ownership of the rubber hand including experimenters using threatening objects on the rubber hand (measuring participant's skin conductance) (Armel & Ramachandran, 2003), attaching the index finger of the rubber hand to that of the participant's real, hidden hand (a moving rubber hand illusion) (Kalckert & Ehrsson, 2012), and even blindfolding participants and using their own right hand to stroke a rubber hand while their left hand was simultaneously stroked by the experimenter (Ehrsson et al., 2005). The latter study shows that ownership does not rely on the dominance of vision, but rather a congruence of several multisensory signals from one's own body. Rubber hand illusions are not the only ones to have been discovered. While touching your nose, you can be made to feel like your nose is growing longer if your biceps muscle is vibrated at the appropriate frequency and intensity (appropriately dubbed the Pinocchio Illusion) (Lackner, 1988). A full out-of-body illusion can be induced when participants wear a head-mounted display with the video feed from a camera facing their back from behind them. Participants are seeing their own body as if it's in front of them. At this time, the experimenter touches their chest with a stick so the participant can both feel it, while simultaneously moving a second stick towards the camera, causing the participant to feel a drift of their body towards the location of the body they see through the camera feed (Ehrsson, 2007). This study represents how VR technology can be used to alter embodiment, an issue I return to in section 1.3.2. Finally, a range of associated physiologic changes have been documented to occur during ownership illusions. When a rubber hand illusion is induced, temperature in a participant's real hand has been shown to decrease (Moseley et al., 2008), and the processing of tactile information from that hand has also been shown to slow down (Hohwy & Paton, 2010). What's more, the intensity of the illusion rated by participants on questionnaires during ownership illusions have been shown to correlate with brain activity in the premotor cortex (Ehrsson et al., 2004), levels of proprioceptive drift (Longo et al., 2008), and real hand temperature (Moseley et al., 2008). Not only do changes in the feelings of ownership impact our perceptions of our body, but these studies show that those perception changes, in turn, affect the brain and body in objective measures.

It's been proposed that the feeling of ownership develops from a combination of bottom-up factors originating from our sensory receptors, and top-down, cognitive factors (Tsakiris, 2010). In short, the bottom-up sensory information like the feeling of touch on the skin must be combined with top-down cognitive information like the visual of a limb in a plausible anatomical orientation based on prior knowledge, for an ownership illusion to occur (Tsakiris, 2010). The global feeling of embodiment relies on ownership, but of course, in our everyday lives, we are rarely only passive receivers of sensory information. We are constantly moving and interacting with our environment, carrying out actions with our bodies that we perceive to be driven by ourselves.

1.2.2 Agency of action

"What is left over if I subtract the fact that my arm goes up from the fact that I raise my arm?" (Wittgenstein, 2009)

When I'm sitting out in the garden, and I decide to lift my arm to shake a bumble bee off of it, how is it that I know I am the author of that action? It seems an odd question, but we generally experience a sense of control over most of the movements we make throughout our lives. Does this sense of agency exist for all types of movements (eg. including reflexes and sneezing)? How is this feeling created, and does it stay at a constant intensity for all movements we make, or is it modifiable based on external, or internal, factors?

Broadly, it is argued that voluntary movements require both central and peripheral factors in the generation of a movement (Haggard, 2017). The experience of intending to make an action, choosing one action over another, and initiating an action are cognitive phenomena. These are putatively central mechanisms as they are driven by action preparation areas in the prefrontal cortex and delivery of signals to the body through the primary motor cortex (Passingham & Wise, 2012; Sherrington, 1952). But, the sense of agency also includes peripheral factors such as the relay of signals from sensory receptors providing information that a muscle contracted or that the body is moving. Importantly, agency is thought to require both these central and peripheral components. Haggard asserts that involuntary movements, like sneezing, reflexes, or even external brain stimulation, do not have a sense of agency as they are missing the same level of cognitive activation (2017). One continues to experience ownership during involuntary movements, and ownership is a necessary precondition for agency to occur. The experience of “my arm moved”, and “I made my arm move” is such that agency is an added component to the already present sense of ownership. “The core sense of agency, therefore, is the association between a voluntary action and an outcome” (Haggard, 2017).

Like many phenomena associated with embodiment, the simplest way to probe a person’s sense of agency is to ask them about it. That is, under whatever circumstances of an experiment, participants can be asked to indicate whether or not they were responsible for a certain outcome. Unfortunately, these types of studies using explicit agency judgments have been found to cause participants to overestimate their own agency, particularly when positive outcomes occur (Bandura, 1982; Tsakiris et al., 2005; Wegner & Wheatley, 1999). In light of this, more implicit measures of the sense of agency have been used, one of which involves measuring the change in time perception that one experiences when acting. So-called intentional binding is the phenomenon whereby participants will report perceived voluntary actions and their outcomes to occur closer together in time than movements they perceived as involuntary (Haggard et al., 2002). Figure 1.6 (borrowed from Haggard, 2017) illustrates this. From this, the sense of agency is said to be objectively measured by the compression of perceived time between action and outcome (Haggard & Clark, 2003). Another measure of the sense of agency uses the readiness potential, a slow electroencephalographic signature in premotor regions that precedes voluntary movement (Kornhuber & Deecke, 1965), the existence of which was later famously used to argue free will to be absent in humans (Libet et al., 1993). An increase in this readiness potential was found to correlate positively with intentional binding during voluntary action, but not during involuntary movements (Jo et al., 2014). One interesting study showed that causing an involuntary movement using external brain stimulation while a participant planned a different action did not create any intentional binding (Haggard & Clark, 2003). “The cognitive preparation of an action plan needs to match the muscular movement precisely to elicit an experience of agency” (Haggard, 2017).

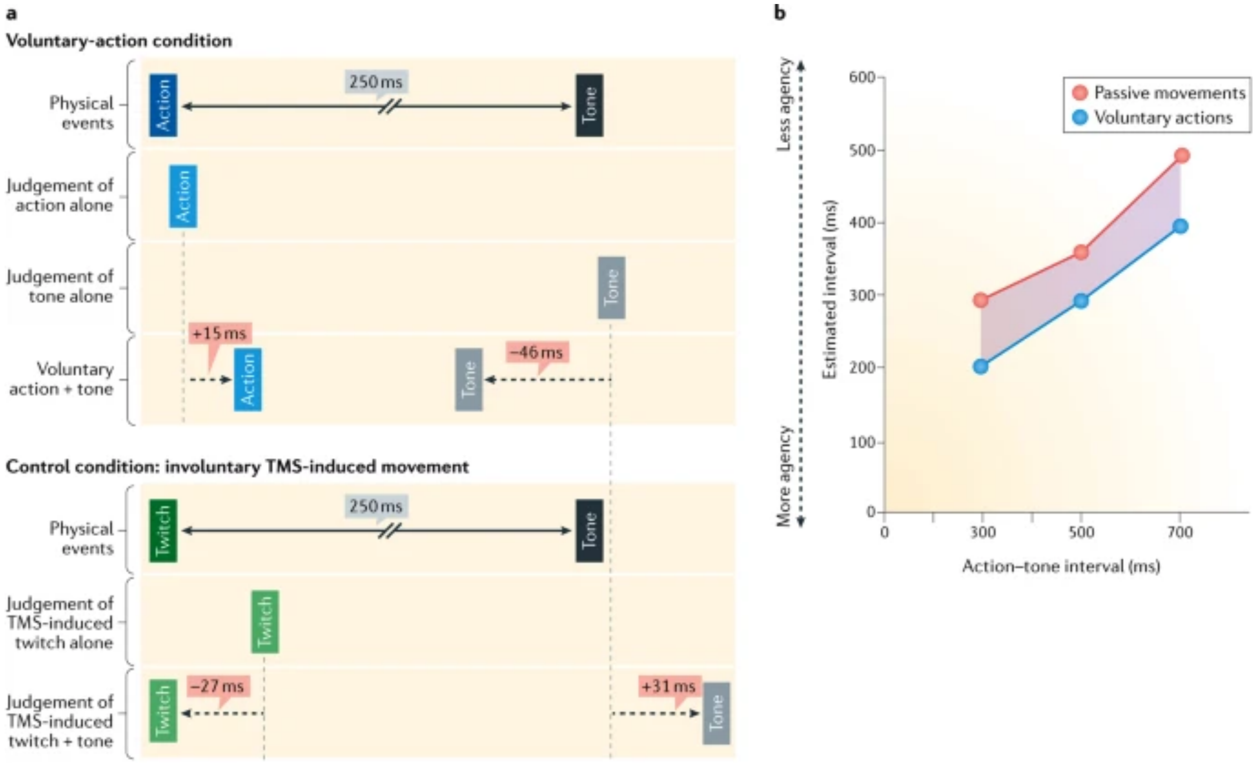

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Figure 1.6: A visual depiction of intentional binding a) where participants perceive their own action and an auditory tone to occur closer in time to one another when they make their own action (top), as opposed to when their movement is induced through TMS (bottom), with b) participants’ estimated interval between voluntary actions and auditory tone being much shorter compared to passively induced TMS movements and the auditory tone (borrowed from Haggard, 2017).

Now that we have some measures for the sense of agency, we can propose mechanisms for how this feeling is created. The most popular model is the comparator model of agency (Blakemore et al., 2000), which is under the umbrella of the optimal feedback model of motor control (previously discussed in section 1.1.4) (Todorov & Jordan, 2002; Wolpert et al., 1995). The optimal feedback model of motor control is based on the premise that motor commands are used to create predictions of sensory consequences of those motor commands in order to guide and correct goal-directed movements in real-time. Actual sensory information that is received by the body is compared to predicted sensory information of the motor command, yielding a prediction error. In the comparator model of agency, the prediction error is zero for actions that we feel we have agency over, as the predicted sensory information of our motor commands are exactly aligned with the actual sensory information that results. When a prediction error other than zero occurs, our sense of agency decreases (Blakemore et al., 2000). Of course, if this were the sole creative mechanism of the sense of agency, then we would be far less aware of the successful outcomes we make and we would only develop a sense of agency after an action had occurred (Wegner, 2002), which has pushed researchers to stress this model is best used for sensorimotor action and is only one component of the sense of agency (Bays et al., 2006; Haggard, 2017). One brilliant study using measures of intentional binding showed that the sense of agency is actually made up of both prospective, and the aforementioned retrospective components (Moore & Haggard, 2008). Participant actions were followed by an auditory tone on only 50% of trials, which resulted in greater intentional binding on these trials than on ones where no tone occurred (retrospective agency). But, when the probability that a tone would follow an action was increased to 75%, participants had greater intentional binding on the trials without a tone on this block, compared to the trials without a tone in the first block where the probability was 50% (Moore & Haggard, 2008). This shows that sensory prediction of one's actions creates a prospective component in the overall sense of agency.

The idea of agency is, of course, used in other contexts in our society, with other definitions being used in law and sociology. It's likely, also, that we can increase or decrease our sense of agency over events over time due to memory influences. The discussion above deals with the sense of agency during sensorimotor behaviour in the context of the construction of the feeling of embodiment. Having discussed how I know what my body is and that I am in control of it, next I ask how is it that I have any idea about where my body is located?

1.2.3 Bodily self-location

"Self-location is a determinate volume in space where one feels to be located." (Kilteni et al., 2012)

Once again considering the bumble bee example from above, as I both watch and feel the little creature walk along my arm, and then as I initiate and control the movement of my arm, I experience a sense of knowing where my body is in space. How is my experience of embodiment impacted by the spatial location of my body? Is the sense of self-location an independent component of embodiment, or does it depend on the previously discussed components, ownership and agency?

Self-location is the most difficult of the three subcomponents of embodiment to explain, as there are differing opinions of the role that it plays. Traditionally, self-location has been treated as an independent phenomenon in the study of embodiment (Longo et al., 2008), while more recently some argue that bodily self-location is a subcomponent of ownership (Braun et al., 2018). Some researchers even use the terms self-location and ownership interchangeably, making it that much more difficult to discuss it (Ehrsson, 2007), while others don't even consider self-location to be a factor in objective measures of embodiment (Bekrater-Bodmann, 2020; Zbinden et al., 2022). As with the senses of ownership and agency, bodily self-location only becomes apparent when the actual location that your body occupies differs from the perceived location that it occupies (Lenggenhager et al., 2009). In the full out-of-body experiment discussed earlier, participants wore a head-mounted display and visualized their own body from behind while an experimenter touched their chest with a stick while another stick was moved under the camera position to look as though it was touching their virtual body (Ehrsson, 2007). In questionnaires, participants reported feelings of being displaced so that they were behind their own body seeing their own back. Similar findings were found in another study where participants had their backs stroked while wearing a head-mounted display with a camera streaming a view looking at their own back (Lenggenhager et al., 2007). In a repeated series of experiments using a similar setup, researchers showed that participants not only felt an ownership of an illusory body near the location of the camera, but also "disownership of [their] real body" (Guterstam & Ehrsson, 2012). These results suggest that during this type of full out-of-body illusion, we don't just extend or increase our ability to feel self-located in more than one place, but rather that we must decrease feelings of self-location at one place in order to increase it at another. These studies focus specifically on self-location within an environment, but it seems as though self-location of individual body parts, like limbs, is more malleable, as participants can maintain ownership of their real right arm while also feeling ownership for a fake, rubber right arm (Guterstam et al., 2011).

As discussed previously (see section 1.1.4), our brains treat visualizations of our hands differently than other objects when we move in our environment (Reichenbach et al., 2014). The exceptional category that our brains hold for our hands during movement is likely connected to the feelings of self-location and ownership we have for them, created by simultaneous multisensory integration (Makin et al., 2008). In fact, using functional magnetic resonance imaging, neurons in the premotor cortex, among other brain areas, are believed to integrate visual, tactile, and proprioceptive sensory information to create a multisensory representation of the spatial location of limbs and body parts (Brozzoli et al., 2011; Petkova et al., 2011). In brief, our brains build a “hand-centred” spatial map from real-time visual, tactile, and proprioceptive information and use it to successfully interact with the environment. Any offset in the incoming sensory information can throw off the “hand-centred” map and may cause us to feel as though our hands are in a different location than they actually are (Botvinick & Cohen, 1998), or that we even have an extra limb (Guterstam et al., 2011).

One major problem with research studies aiming to define the role that self-location plays in embodiment is the fact that in real-world experiments on able-bodied participants, there is no illusion available to separate one’s body parts from their actual, real location. We truly have physical bodies in a physical world and cannot displace any body parts to a different spatial location. This has called for much experimentation with patient populations experiencing different forms of spatial neglect or extinction (Làdavas et al., 1998; Mattingley et al., 1997), as well as with upper-limb prosthesis-users (Hebert et al., 2019; Tsukamoto, 2000; Yamamoto & Kitazawa, 2001). Another major advancement in the study of self-location has been touched on briefly, but will be extensively explored in the third and final section of this introduction: Virtual reality. VR allows experimenters to solve the problem of being able to overlay objects of their choosing in the spatial location that a participant’s actual arm is located. It allows participants to move around relatively freely in their environment and interact with objects while maintaining experimental illusory conditions.

1.2.4 Conclusion

Embodiment is an elusive concept, but, as mentioned earlier, we all experience what it feels like to own, control, and be located within a body. Although each of the subcomponents described here can be manipulated independently in one form or another, it’s obvious that the whole is greater than the sum of its parts. One study even shows that ownership of a rubber limb increases with increased agency and movement of the rubber limb (Kalckert & Ehrsson, 2017), and another shows that increased agency towards a rubber limb leads to greater integration of body parts into one unified body (Tsakiris et al., 2006). The feeling of embodiment is not just a summation of ownership, agency, and self-location (if you subscribe to the view that this is an independent component), but an entirely new phenomenon that is created from these subcomponents, akin to the abilities of a human hand being so much more than just the sum of five fingers and a palm. One important population of people, prosthesis-users, have contributed substantially to knowledge of embodiment (Zbinden et al., 2022). Their experiences are unique compared to the general population in that no illusion is required to change their perception of reality. Importantly, a previously-discussed study (see section 1.1.7) integrated the connection between feelings of embodiment in prosthesis-users and improved visuomotor behaviours as a result of returning touch and kinesthetic feedback (Marasco et al., 2021). The authors beautifully summarized this connection stating: “The brain’s sensory-motor comparative mechanisms drive the processes of movement error correction and experiential learning, and those same mechanisms compare sensation, vision, and intent to construct a cognitive sense of wholeness. The naturalness of sensation, the sensory modalities themselves, and the cohesiveness of sensory-motor fusion have critical roles in establishing limb ownership” (Marasco et al., 2021). Outside of this population, VR is the only tool currently available to allow for a sustained embodiment illusion while participants carry out complex object interactions, and is discussed in this respect in the next section.

1.3 - Virtual Reality

“Illusory experiences are not only a consequence of using VR, but the very foundation of its operation. In VR, the participant is not merely an observer, but is the center of the system, both screen and viewer. In order to enable this self-centered experience, plausible sensory stimulation must persuade the brain that realism has not been lost when natural information derived from the physical environment is replaced by computer generated information. This process of successful substitution enables VR experiences to feel real.” (Gonzalez-Franco & Lanier, 2017)

One of the few benefits of the early stages of the Covid-19 pandemic was that I was able to bring home a VR system from the university. Although I did use the system to build experiments and analyze data, much time was spent in virtual games. I grew up playing traditional console video games on flat screens, but nothing could prepare me for the added experience that VR provides. In traditional video games, even those from a first-person perspective, climbing up a mountain or looking over a steep cliff does not instill in me any semblance of fear or discomfort. Even after hundreds of hours of VR experience, I still fear heights in VR as though I’m truly at risk of falling to my death. There is something about VR that creates a consistent illusion that you are supplanted into a different environment, and even a different body. There are both obvious benefits and detriments to this technology. VR can readily blur the lines between what’s part of our “real” experience and what’s “virtual”. Once you’ve experienced the advanced VR experiences of the modern day, it is easy to see why some believe our “real” world could actually be a virtual simulation that just appears real to us in our everyday lives. Many films and television shows use this major theme, including The Matrix, Ready Player One, Total Recall, Black Mirror, and Westworld to name a few. Obviously the VR we’ve developed isn’t at the level where we are cognitively unaware that we are in a simulated world, but it can’t help but force us to consider the fact that it’s possible to build technology so advanced that we may not know.

We’ve never been in a situation before, as a species, where we could readily manipulate the actual sensory inputs to our brains in a synchronized manner the way that VR can today, and we have to consider what this is going to do to us in the future. How is it impacting us, and how will it impact us? I’ve often wondered what even the most forward thinking people a century ago would think about the VR technology we have at our disposal. Would William James or H.G. Wells have believed that in a hundred years humans would have the technology to convince the average person’s mind that they were in a different world in a different body in a matter of seconds? If the human psyche is that malleable, what else will we be able to convince ourselves of in the next hundred years? VR has become so broad an area that writing a thesis section covering all its developments would be far too lengthy for even my writing style. Therefore I discuss VR here from the context of the previous two sections of this introduction and answer two questions. What do we know about human visuomotor behaviour during object interactions in VR, and what do we know about embodiment in VR?

1.3.1 Visuomotor behaviour in virtual reality

“Animals have evolved to survive in the natural world using brain mechanisms that perform actions guided by sophisticated perceptual and cognitive systems. Modern cognitive neuroscience relies heavily on reductionism, using impoverished stimuli and tasks that neglect the importance of actions as the outcomes upon which survival has depended for millions of years. Despite the importance of action outcomes for evolutionary selection, historically, psychology has neglected motor control, even though all cognitive processes, even those that are not explicitly motor (e.g., attention and memory), evolved in ultimate service of affecting motor behavior. Increasingly, researchers are realizing that theories developed in motor control, such as the importance of forward models and feedback loops, may explain many other cognitive functions from perception through social interactions. As such, one must question why so many cognitive studies use stimuli – particularly static images – that do not afford motor behavior or use tasks no more sophisticated than pressing a button or uttering a verbal response.” (Snow & Culham, 2021)

With the explosion of VR into every major scientific discipline that studies human behaviour, it’s immensely important to discuss the similarities and differences between how humans behave in VR compared to the real world. In this subsection, I first explain some of the possible reasons that our brains may treat VR differently than the real world and provide behavioural examples to highlight this. If there’s ever been doubt about the motivation to use VR as a tool to measure the human psyche, the quote above should dispel it, but the authors go on to describe the importance of remembering that every type of image (even a realistic, 3D, state-of-the-art, head-mounted, first-person view video), is still a proxy for the real world (Snow & Culham, 2021). Snow and Culham highlight the differences between real-world objects and proxies, and classify these proxy objects into categories of ecological validity from 2D and 3D images up to objects simulated through VR (Snow & Culham, 2021). The authors note many philosophical differences in how humans behave with proxies and real objects, and describe empirical findings. Humans recognize and remember real objects better than proxies, and pay greater attention towards real objects than proxies. The actability of real objects, compared to proxies, is thought to be the driver of these differences (Marini et al., 2019; Snow & Culham, 2021). Snow and Culham describe the ways in which simulated reality, like VR, can be used to better understand human behaviour and brain function, with regards to object interactions, especially with increased ecological validity (Snow & Culham, 2021). Figure 1.7, borrowed from Snow and Culham, eloquently shows how experimental control decreases as experimental techniques move from low to high ecological validity. I agree, and argue that the current set of studies fills an important gap, which will be discussed later (see section 1.4).

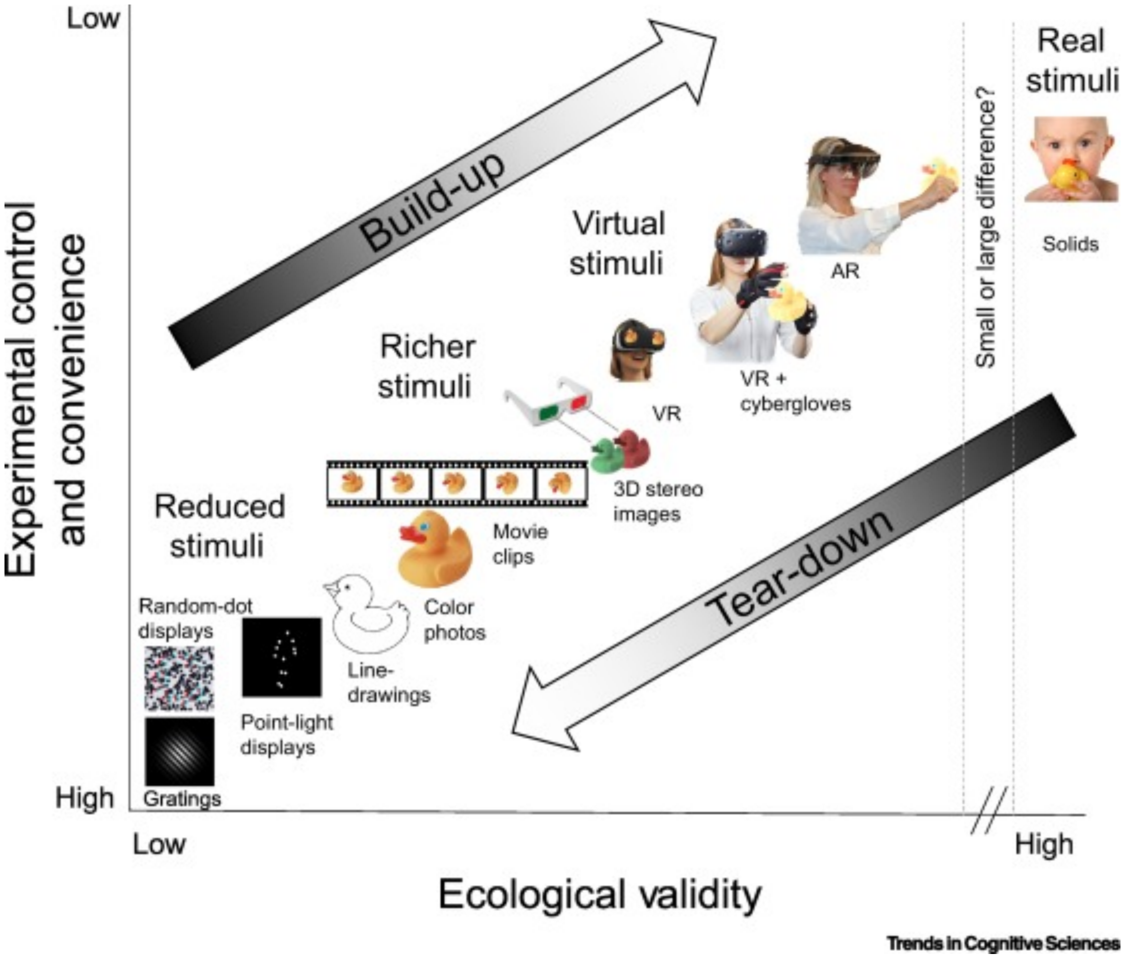

Figure 1.7: A visual explanation of the trade-offs that occur between ecological validity and experimental control in visuomotor research. As ecological validity increases using advanced technology, experimental control becomes more difficult to maintain (borrowed from Snow & Culham, 2021).

With a similar question in mind, other researchers have proposed that VR objects may evoke the ventral, vision-for-perception visual stream, instead of the dorsal, vision-for-action visual stream that is used in real-world object interactions (previously discussed in section 1.1.2) (Harris et al., 2019). The dorsal visual stream has been shown to be used for moment-to-moment real-time interactions with objects, occurring mostly without one's conscious perception, while the ventral stream is engaged more during perceptions, like identifying objects, and during delayed or pre-planned movements (Goodale, 2007, 2013; Goodale & Milner, 1992).

So, with respect to the visual system, the human brain does not appear to treat virtual objects the same way it treats real-world objects. One reason might be the major differences in the availability of haptic feedback. In the real world, when I pick up my bag of groceries, I visualize the bag and reach my arm out and down to approach it. I target the handles with my eyes and direct my hand towards them, forming the necessary grasp pattern to make successful contact. I experience proprioception of not just my arm, but my legs and torso as I bend down. I eventually receive haptic information at my fingertips at the exact moment I see my hand touch the handles. As I grasp the handles of the bag I feel its texture and the stretch of the fabric in my palm as it begins to take the weight of the groceries contained within it. I can feel the pressure on my fingers, straining my grip strength, and as the bag leaves the ground I can feel the swing of momentum as the poorly-packed items (nobody to blame but myself) shift inside. For the same action in VR, I receive a much less salient experience. The current state of the art uses computer-vision hand-tracking or tracking gloves, while the most widely used commercial interaction mechanism for VR is still handheld controllers. When reaching out to pick-up a grocery bag in VR, I feel proprioception in my body, but not in my fingers, as they are grasping a plastic controller. When I initiate a grasp using a button on the controller, at most I may receive a slight vibration from the plastic controller, and no contact on my fingertips, or any weight of the bag as it leaves the ground. The very limited haptic feedback in VR object interactions has been proposed to have even greater effects on visuomotor control, pushing participants to use the ventral stream even more (Harris et al., 2019). Above we discussed how the dorsal visual stream is the path for online, in-the-moment, object interactions, while the ventral stream is used for delayed or pre-planned, cognitively-supervised movements. This hypothesis rests in part on findings showing that pantomimed movements to remembered objects elicit greater ventral stream engagement than movements to objects in real time (Goodale et al., 1994). Harris and colleagues go on to conclude that, "the artificial presentation of visual depth cues, the peculiarities of haptic feedback, and the general uncertainty created by impoverished sensory information, seems likely to elicit a more ventral mode of control in VR than the real-world. If visually guided skills in VR do indeed rely on ventral mode control, even in part, skills learned or performed using these altered perceptual inputs may not be representative of their real-world counterparts" (Harris et al., 2019).

Therefore, if the lack of haptic feedback might drive differences in how visual information is used in the brain and in turn, how we move and look, what predictions might we make about eye-hand coordination in VR when haptic feedback is absent and when it is fully returned to the user? Here we can return to work with upper-limb prosthesis-users (discussed in section 1.1.7). Upper-limb prosthesis-users interact with objects with very limited haptic and proprioceptive feedback, similar to VR users. In these cases, we know that prosthesis-users move much slower, visually fixate for longer on objects before interacting with them, maintain fixation on them for much longer after interacting with them, and spend much more time fixating on their own limb than their able-bodied counterparts while doing the same object interaction tasks (Hebert et al., 2019). Recall when touch sensation is returned to prosthesis-users through a combination of reinnervation surgery, haptic and kinesthetic feedback, and intuitive motor control, their behavioural patterns shift closer to those of the able-bodied population (Marasco et al., 2021). Most importantly, returning haptic feedback frees the eye gaze to shift away from dedicated fixations to the end effector. This provides hope that development of reliable haptic feedback in VR will lead to user behaviour that is more similar to real-world behaviour.

The potential impact of VR on experimental design cannot be understated. VR allows an experimenter to create and control a completely novel, immersive environment for participants. Many have written about the immense possibilities (Parsons, 2015; Sanchez-Vives & Slater, 2005; Slater, 2009; Suzuki et al., 2017), but I here focus on studies conducted on visual behaviour and object manipulation in virtual environments. Visual behaviour in VR has been explored in many studies including the distribution of attention in one's environment. It's been shown that participants will adapt in real-time to modifications of a moving object with known physical properties in VR (Diaz et al., 2013). This study runs against the hypothesis that VR environments lead to a decrease in the dorsal visual stream, as participants were quite able to modify their actions based on both memories of how an object bounced previously, and real-time object movement information. In another study, researchers tested how participants distributed visual attention when searching for specific objects in a naturalistic virtual environment in three subsequent sessions (Kit et al., 2014). In the third session, researchers changed the color of certain objects and found that greater visual attention was directed to these objects than in a control group. There are VR eye tracking studies focused on decision-making (Meißner et al., 2019), and proposed assessment of cognitive skills and neurodegenerative disorders (Imaoka et al., 2020). There are even studies purporting to test and improve participants' eye-hand coordination, but these only measure the time to reach to a target, and not the interplay of eye and hand movements over the course of an interaction (Pratviel et al., 2021; Shin et al., 2015). We stress again that although understanding eye movements and hand reaction time in VR is important, this does not provide much in terms of how the eyes and hands behave together when interacting with objects in VR.

As has been stated time and again throughout this document, humans do not act on the world in isolation from their bodies, but rather with dynamic interplay between their brain, body, and the environment. Visuomotor behaviour during object interactions in VR is different from the real world, but technological advancement is making them more similar each year. If you've taken anything from this document so far, it's that our ability to act on and receive information from our environment through our bodies is a direct contributor to our feelings of embodiment, which is revisited in the next section, as I explore background literature about embodiment in virtual environments.

1.3.2 Embodiment in virtual reality

“Consciousness occurs when we can generate, automatically, the sense that a given stimulus is being perceived in a personal perspective; the sense that the stimulus is 'owned' by the organism involved in the perceiving; and, last but not least, the sense that the organism can act on the stimulus (or fail to do so), that is, the sense of ‘agency.’” (Damasio, 1998)

I step out onto the balcony of an old apartment building and look over a city in ruins. I walk towards the railing and look down at the street, catching a glimpse of my body in my peripheral vision. It’s a long way down. I hear a deep, rumbling sound over my left shoulder and turn around to see a towering machine ambulating over the apartment building. I feel small and vulnerable as I cower and slowly sneak back into the building. I reach down to pick up the machine gun and press a button on the plastic controller in my hand. I see my hand form around the tool as I prepare for battle…

VR technology has improved exponentially in the last decade, with the majority of progress occurring in visual input to the user. As has been stated earlier, human beings have historically been thought of as visually dominant, but more subtle assertions have described ways in which we “switch” between one sensory mode and another (Posner et al., 1976). It’s likely more correct to state that we may focus on one mode more than others at times, but that we integrate all sensory modes to construct a spatial representation of our body in space (Brozzoli et al., 2011; Petkova et al., 2011). In VR, some sensory modes may be telling us one thing, while others are telling us something else. In the example above, my vision is telling me I’m in a post-apocalyptic world on a balcony as a giant mechanical vehicle searches for humans to exterminate, while my haptic feedback reminds me that I’m really just in my basement. The more sensory information that can be artificially provided to me, the more convincing the VR experience. Increased congruence between sensory modes increases our feelings of presence (Sanchez-Vives & Slater, 2005). In the above example, although I do understand that I’m not in any real danger, I can’t help but cower away to regain my courage. “From a cognitive point of view, [I] know that there is nothing there, but, both consciously and unconsciously, [I] respond as if there is. This paradox is at the root of the concept of presence” (Sanchez-Vives & Slater, 2005). Presence, from a VR perspective, is the feeling of being located in a different environment than one is actually located, and can result from not only providing believable visuals, but also appropriate and synchronized auditory, haptic, and proprioceptive sensory information. Presence can be achieved when real-world sensory information is successfully replaced by artificial sensory information. In the above example, the visual and auditory information are convincing enough to make me think “I am in danger”, but of course the haptic input is less convincing. Presence is said to be made up of several different components, including visual realism, haptics, virtual body representation, and body engagement (Sanchez-Vives & Slater, 2005), seemingly encompassing embodiment which was discussed previously (see section 1.2). Embodiment is the sense of one’s own body while presence is the feeling of being situated in a virtual space (Nostadt et al., 2020). Although embodiment and presence in VR are not the same thing, I assert that embodiment is the major impediment to maximizing presence in virtual worlds.

I reiterate that I use the term “embodiment” to mean the sense we all have of owning and having control over a body that is located where we believe it is located (Longo et al., 2008). Although VR experiments didn’t begin studying this concept until the mid 2000’s, visionaries have been thinking about it outside academics for much longer. The first use of VR to manipulate body ownership was termed “homuncular flexibility” and took place in the late 1980s (Lanier, 2006). VR experiments inducing embodiment illusions in participants began with a virtual version of the rubber hand illusion (Slater et al., 2008) and previously discussed third-person out-of-body illusions (Ehrsson, 2007; Lenggenhager et al., 2007). The first first-person body-swapping illusion had participants wear a head-mounted display with a camera feeding in visuals from the first-person perspective of a nearby plastic mannequin (Petkova & Ehrsson, 2008). This study used a combination of head movement and tactile stimulation synchrony to induce an illusion strong enough for participants to respond physiologically to the threat of a knife towards the mannequin. Another study provided the first evidence for transfer of ownership to a virtual body (Slater et al., 2010). Researchers found that the synchronization of touch and head movement of the virtual body with the participant’s real body played important roles in creating this illusion, but that the most important factor was giving participants a first-person view of their virtual body (Slater et al., 2010).

Previous examples of the malleability of body ownership and agency have been discussed (see section 1.2), but VR provides researchers new ways to manipulate these concepts. One major addition that VR provides, previously mentioned, is that it allows seamless overlay of any visual onto a participant’s real body, with the ability to move that visual representation. An important study combined several aspects of previous real-world and virtual embodiment illusions to show that visuomotor synchrony of a virtual arm induces proprioceptive drift that correlates with embodiment survey results (Sanchez-Vives et al., 2010). That is, when participants see a virtual arm that moves with their real-world arm in a location extending from their virtual body, higher self-reported feelings of embodiment correlate with greater proprioceptive drift towards the virtual arm. The illusory abilities of VR are even powerful enough to induce feelings of embodiment in limbs that are spatially distorted. Researchers used a combination of synchronized visual, haptic, and motor information to induce an embodiment illusion in participants with limbs up to four times their normal length (Kilteni et al., 2012). See Figure 1.8 for a visual re-creation of what participants saw. Going further, another experiment showed that humans will quite readily accommodate changes to intended outcomes of their motor inputs (Won et al., 2015). In this study, real-world participant movements were altered such that leg movements in the real-world translated to arm movements in the virtual world. Within ten minutes, participants were able to pop balloons with their virtual arms by moving their real-world legs (Won et al., 2015). These studies show the power of VR to manipulate feelings of embodiment in users. As stated earlier, previous embodiment experiments in the real world typically require participants to stay still either seated or standing with a passive manipulation of ownership through synchronized visual and haptic feedback (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005), or agency of movement via a connection from the participant's real finger to the finger of a rubber hand (Kalckert & Ehrsson, 2012; Kalckert & Ehrsson, 2014). Although these studies achieved much, including knowledge of the fact that ownership and agency can be dissociated, VR allows much greater flexibility in the types of illusions to be induced, and far greater freedom of movement for participants. It therefore opens the door for researchers to test feelings of embodiment as participants carry out more naturalistic movements (including object interactions), and allows researchers the opportunity to test the limits of embodiment.

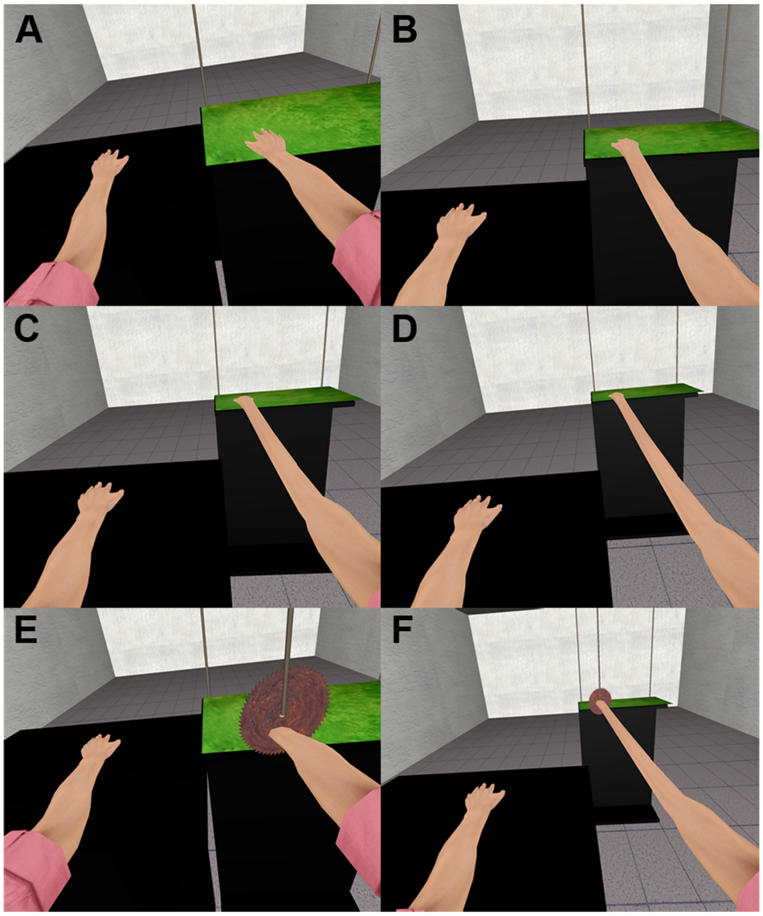

Figure 1.8: A visual timeline of the induction of a virtual embodiment illusion in which participants feel as though their own limb is extending four times its normal length before a virtual saw induces a physical threat to assess feelings of embodiment (borrowed from Kilteni et al., 2012).

In addition to studies mentioned previously, further research has shown the importance of the continuity of a virtual limb, with virtual limbs missing visual connections to one's body yielding reports of lower subjective ownership than those fully connected (Seinfeld & Müller, 2020; Tieri et al., 2015, 2017), and the importance of a realistic hand-like visual appearance (Pyasik et al., 2020; Tieri et al., 2017). Interestingly, it's been found that simply observing a virtual limb, in the absence of one's own limb or any sort of tactile stimulation results in illusory ownership over the virtual limb (Maselli & Slater, 2013; Tieri et al., 2015, 2017). This can't be overstated. VR has shown that vision alone can induce the rubber hand illusion. Moreover, it has been shown that providing users with altered visual feedback of an embodied limb influences their movement amplitude and muscle activity (Bourdin et al., 2019). Using a combination of elastic bands to allow participants to flex muscles without moving their real-world arm but having their virtual limb move, researchers not only showed participants will develop illusory ownership of a virtual limb in spite of the fact that their real-world limb and virtual limb are unaligned kinematically, but also that changes in motor performance are possible due to visual feedback of a virtual limb. Many interesting studies are probing the extent of the malleability of the embodiment of virtual bodies, including increasing embodiment of virtual limbs solely by synchronizing the participant's heart rate (Suzuki et al., 2013) and breathing rate (Monti et al., 2020) with the color intensity of the virtual limbs. In these studies, experimenters measured participants' live heart rate (Suzuki et al., 2013) and breathing rates (Monti et al., 2020) and showed participants virtual limbs that either fluctuated their color intensity in synchrony or out of synchrony with these physiological recordings. Participants reported stronger feelings of embodiment towards limbs that had color intensity fluctuate in synchrony with their physiological recordings. As with real-world embodiment illusions, it's been shown that the visual appearance of a virtual limb decreases temperature of a participant's real world hand in correlation with participants' feelings of embodiment (Tieri et al., 2017). This aligns closely with Chapter 2 of this thesis which details how body movements and feelings of embodiment changed in a correlative manner with changes to participants' body visualization. It seems as though, when available, vision is the dominant mode of understanding what is our limb and what is not, and when other streams of sensory information (eg. heart rate and breathing rate) align with what our visual information is telling us, these feelings are strengthened, in turn affecting our physiology.

As stated earlier, a major impediment to maximizing feelings of embodiment in VR is consistent, reliable, and realistic haptic feedback that synchronizes with visual feedback (Berger et al., 2018; D'Alonzo et al., 2019). In fact, some evidence suggests that haptic information about object size is more valuable at predicting object weight than visual information (Buckingham, 2019). An important additional finding is that the combination of haptic and visual information made greater impacts on expected object weight than either sensory stream on their own. Akin to the findings from prosthesis-using populations discussed earlier (see sections 1.1.7 and the conclusion of 1.2), embodiment in VR relies on synchronized sensory input and intended motor output, along with reliable feelings of cause and effect in the environment. This strongly connects the three main themes of this document: visuomotor behaviour, embodiment, and virtual reality. In fact, the sensorimotor contingencies model of VR embodiment (Gonzalez-Franco & Lanier, 2017), visualized in Figure 1.9, is based upon the optimal feedback model of motor control (Todorov & Jordan, 2002; Wolpert et al., 1995) previously discussed in section 1.1.4. It describes how bottom-up and top-down sensory and cognitive information come together to allow VR illusions to be experienced as real (Tsakiris, 2010). When a motor command is generated, a copy of it is translated into a predicted sensory outcome. At the same time, the motor command leads to actual movement which creates actual sensory feedback to the body. The predicted sensory feedback and actual sensory feedback are then compared, with smaller differences between the two leading to greater acceptance of the VR illusion (Gonzalez-Franco & Lanier, 2017). This description also aligns closely with the comparator model of agency, in reference to embodiment, discussed in section 1.2.2 (Blakemore et al., 2000). Interestingly, the sensorimotor contingencies model, like the comparator model of agency, admits that external factors are at play and allows for reinforcement of predicted sensory information through successful interaction, such that deficiencies in actual sensory information may be accepted over time due to cognitive, top-down alterations (Gonzalez-Franco & Lanier, 2017; Haggard et al., 2002).

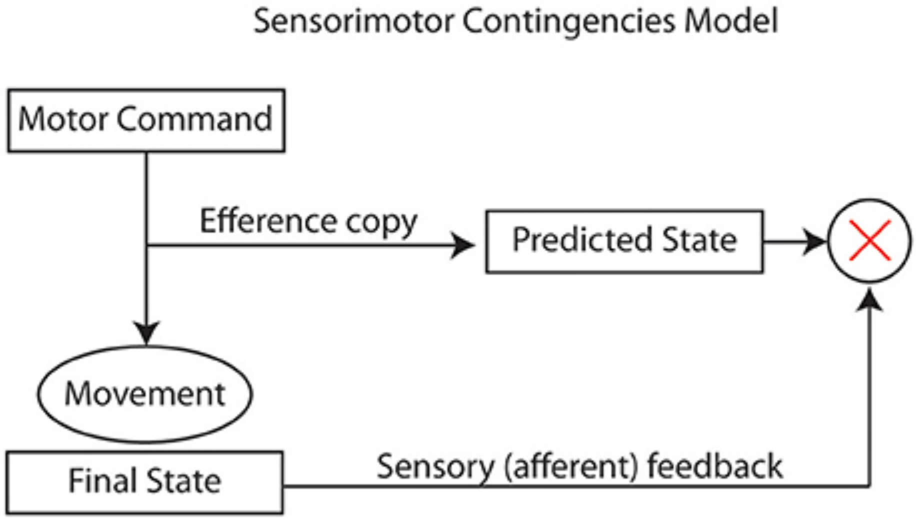

Figure 1.9: A depiction of the sensorimotor contingencies model of virtual embodiment. As participants create a motor command, an efference copy is used to predict the state of what sensory information should be returned to the body. At the same time actual movements induce actual sensory feedback to the body, which is then compared to the predicted sensory feedback. Embodiment is maximized when the difference between predicted and actual sensory feedback is minimized (borrowed from Gonzalez-Franco & Lanier, 2017).

1.3.3 Conclusion

VR has the potential to improve outcomes for firefighters and surgeons, increase range of motion for those rehabilitating from stroke, help students learn and understand complex information faster, and better the quality of life of those suffering from mental health conditions. Imagine what the future holds. A patient could walk into a doctor’s office, throw on a VR headset, carry out a simple 5 minute object interaction task, and know, objectively, just how well, from a daily-living, functional perspective, medications are benefiting their newly-diagnosed Parkinson’s disease. Or, a surgical resident could practice each surgical procedure the evening before they are to carry them out on patients, with fine haptic feedback, and even a virtual reconstruction of each individual patient's anatomy. Consider an elderly person who's unable to walk or travel independently. VR headsets will soon be able to transport them to virtual environments that they'd otherwise be unable to experience. They'll be able to relive musical performances from their favourite artists or visit a vacation destination they never had the chance to see in the real world. To continue to push the envelope of VR's potential, we need to continue to discover how we behave in virtual worlds and in virtual bodies, and what technological areas need to be targeted to improve efficacy. In the next section, I outline the motivations and predictions for the current set of studies presented in this document.

1.4 - Thesis in Context

Having previously discussed the foundational importance of visuomotor behaviour and embodiment to the human condition, I reiterate that both phenomena typically run under the radar of our consciousness. That is, our ability to quickly and reliably interact with the world in bodies that we know to be our own necessarily evolved to function unconsciously so that we could focus on other goals in the world, like obtaining food in our environment, forging social bonds, and even attending to our own thoughts. How useful would our bodies be to us if we had to constantly remind ourselves that we were in them and that we can use them to sense and act in our world? My position in this thesis aligns most closely with theories of embodied cognition (Shapiro, 2019), in which human consciousness is said to have evolved *because* we are inside bodies, and that the consciousness we experience is directly impacted by our beyond-the-brain body. There's no denying that the affordances provided to us by current VR technologies alter our embodied experience, and future advancements may completely reshape our ideas of what being embodied even means. The goal of this thesis is to describe how behaviour and embodiment change when people interact with objects in virtual worlds, and to quantify the roles that each of visual and haptic feedback play. More specifically, I describe how eye-hand coordination and feelings of embodiment in VR changes under different visual and haptic feedback conditions during object interactions. Three projects were carried out in VR, using a previously-validated real-world task as a comparator, to test how participants' visual representations of their bodies, and haptic feedback from virtual objects, impacted their feelings of embodiment towards a virtual body and their eye-hand coordination during object interactions.

All three projects in this thesis use the same object interaction task, but with different variations. The task, called the Pasta Box Task, was developed in 2015 as part of the DARPA HAPTIX Project (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018, 2019). Originally, able-bodied participants carried out the task while having their eye movements tracked with a head-mounted eye tracker and their body movements tracked using an infrared motion capture system to assess coordination of gaze and movement during everyday object interactions. First, participants move the pasta box from the Start/End Target on a table on their right side onto the Mid Shelf Target in front of them (Figure 1.10(a)). Then, participants move the pasta box from the Mid Shelf Target to the High Shelf Target by crossing the body's midline (Figure 1.10(b)). Finally, the pasta box is picked up from the High Shelf Target and placed back on the Start/End Target (Figure 1.10(c)). At the start and end of each trial and after each pasta box placement, participants touch the Home position (pink rectangle in Figure 1.10(a,b,c)). Participants are instructed to move at a comfortable pace and interact with the pasta box on its side. There are colored targets indicating where the pasta box should be placed for each movement. Additionally, participants are to avoid dropping the pasta box, contacting the apparatus, hesitating, or making undesired or unnecessary movements.

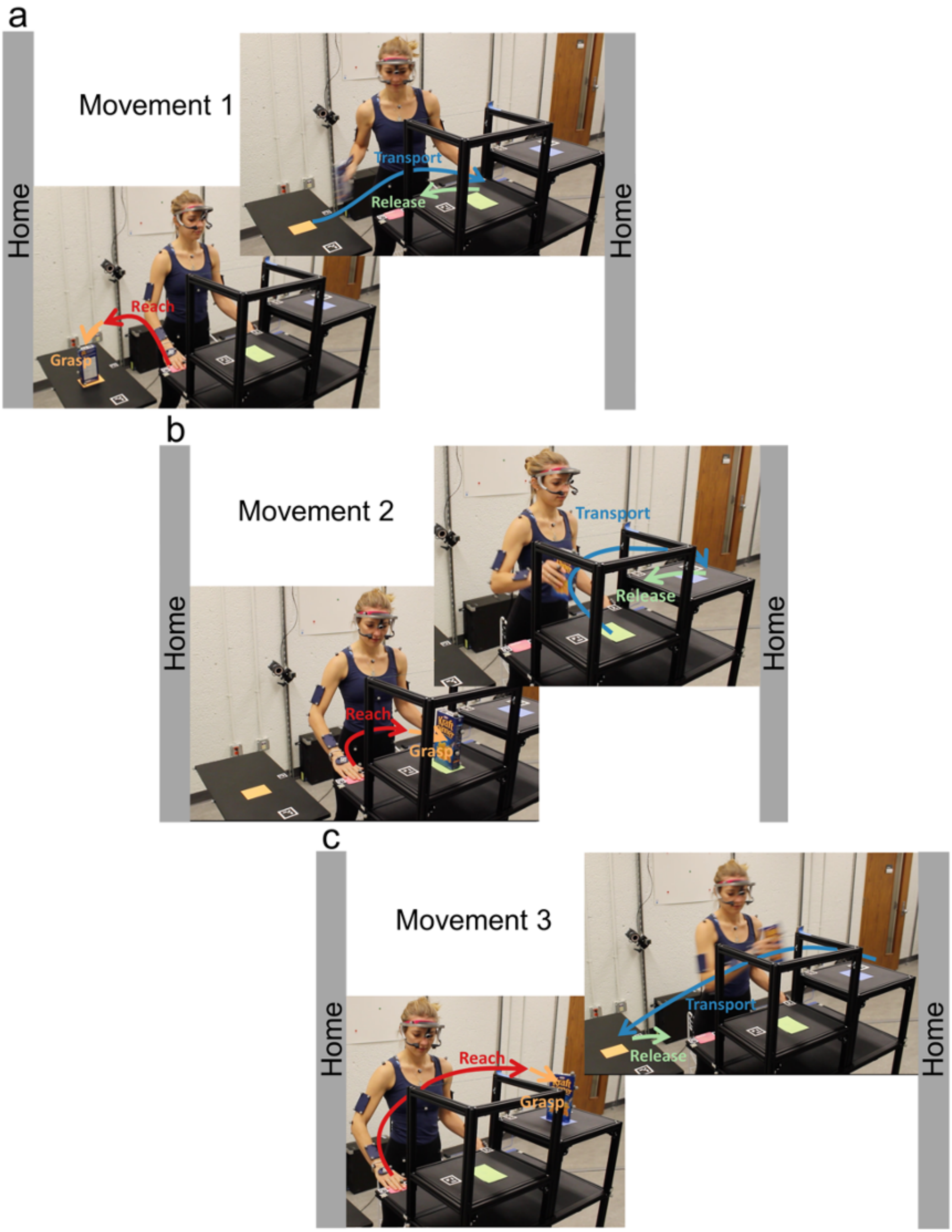

Figure 1.10: The Pasta Box Task includes Reach, Grasp, Transport, and Release of a Pasta box at 3 target locations. a) Movement 1: Grasp from side cart (Start/End Target) and Release on Mid Shelf Target. b) Movement 2: Grasp from Mid Shelf Target and Release on High Shelf Target. c) Movement 3: Grasp on High Shelf Target and Release on Start/End Target (borrowed from Lavoie et al., 2018).

Below I briefly describe the motivations for each of the three projects in this series. Recall again that the goal of this thesis is to measure aspects of visuomotor behaviour during object interactions in VR after embodiment (measured via questionnaire) has been manipulated through visual and haptic feedback changes. Project 1 tests the impact that visualization of one's own body has on one's movement and feelings of embodiment during object interactions in traditional, controller-mediated VR. Project 2 limits haptic feedback through traditional, controller-mediated VR and measures eye-hand coordination compared to the exact same task carried out in the real world. And, Project 3 returns haptic feedback to the same task in VR with full, authentic haptic feedback, and measures eye-hand coordination and embodiment once again.

1.4.1 Project 1: Interaction orientation in VR while visualizing limbs or controllers

Although some studies have explored the effects that ownership over a virtual body may have on movement, none have shown the extent of this during object interactions. As mentioned earlier, it's been shown that being in control of one's actions increases the strength of embodiment during the rubber hand illusion (Kalckert & Ehrsson, 2014), but perhaps there is something additionally important about moving one's hand, receiving visual confirmation that one's hand is moving towards an object, predicting that that object will provide haptic feedback in the immediate future, and then receiving that haptic feedback. As interacting with our environment, specifically manipulating objects, is a key defining characteristic of human evolution (Heldstab et al., 2020), the extent to which interacting with objects and movement is impacted by our feelings of embodiment need to be charted. Specifically, how does the visual information about our bodies impact how we move and how we experience embodiment when interacting with objects? Project 1 compares the real-world movements of participants completing object interactions in VR under conditions where the visual representation of their body is either an inanimate plastic controller, or a dynamic, human-like limb (ie. all that is changed is the visual information one receives of their own body). We aim to show how real-world movement behaviours during object interactions change (by way of motion tracking) based solely upon the visual information presented to a person about their own body. And, in turn, we aim to show how a person's experience of embodiment changes (through a self-reported embodiment survey), and how it relates to their movement patterns.

We predict that participants will self-report greater feelings of embodiment towards the virtual, human-like limbs compared to the virtual controllers, and that they will move these virtual limbs, by way of altered real-world movements, to orient the virtual hand into a plausible grasping pattern around the virtual object.

1.4.2 Project 2: Comparing eye-hand coordination in VR and the real world

Traditional, controller-mediated VR is the most popular control style for commercial VR today. It also provides a readily-accessible medium to limit haptic feedback for Project 2. Briefly, the goal of Project 2 is to describe the eye-hand coordination differences that arise when haptic feedback is limited during object interactions. Here we compare eye and hand movements of an everyday object interaction task from the real-world to the same task in traditional, controller-mediated VR. Using the eye movements recorded from the dataset used in Project 1, we compare eye-hand coordination between the two Project 1 conditions and the previously recorded, original, real-world dataset for this task (Lavoie et al., 2018). This is the first in-depth study of eye-hand coordination between traditional, controller-mediated VR object interactions and the exact same task in the real world. Using our in-house data analysis tool, GaMA, these data are combined to create measures that describe important aspects of participants' behaviour, with the real-world dataset being analyzed in the exact same way as the VR one.

We predict that participants in the controller-mediated VR dataset will take much longer to complete each trial, and will necessarily have to visually fixate on the object and their own hand much more than participants in the real-world dataset. VR is novel to most people, and with novelty comes trepidation. The interaction pattern in the VR conditions is not natural. Having to physically move a piece of plastic around and press a trigger button to interact with objects, although an easy pattern to learn, is not how we interact in the real-world. As well, the VR conditions lack detailed haptic feedback, which we expect will lead to greater time spent ensuring the pasta box is picked up and dropped off successfully. We also expect participants' eyes will fixate on objects to be picked up, and the target for drop-off, earlier in VR than in the real world because they will be moving slower, and they will stay fixated on the object being picked up and the target for drop-off longer after pick-up/drop-off in VR because their visual attention will be needed to check for successful interaction.

1.4.3 Project 3: VR eye-hand coordination and embodiment with full and no haptic feedback

One of the most elusive feedback modalities in VR is haptics. As mentioned earlier, as our hands reach and move towards an object, we are simultaneously predicting what the haptic feedback on our hands will be from that object in the future. When I (agency) move my hand (ownership), and it arrives (location) at an object, the haptic feedback I receive at the exact time and location that I expect is what creates my unified experience of embodiment. Every stream of motor and sensory information lines up and confirms that my hand has touched the object I intended to touch. Currently, the standard mode of interaction in VR is through the use of hand-held controllers that lack the full, naturalistic control of the virtual world that our real hands provide for us in the real world. The fact that prosthesis-users have to dedicate greater visual attention to their device when interacting with objects compared to the able-bodied population shows just how important returning reliable haptic information is (Marasco et al., 2021), and provides the motivation for Project 3. To understand the full effect that haptic feedback from object interactions has on human behaviour, we compare object interactions without any haptic feedback, to those with full, authentic haptic feedback from the real-world equivalents of the virtual objects they see. In this way, we aim to understand the full effect of haptic feedback on eye-hand coordination during object interactions.

Project 3 in this series will elucidate the role that haptic information plays in the feeling of limb embodiment and eye-hand coordination during object interactions. By integrating top-of-the-line VR tracking gloves, built by ManusVR, participants are able to use their real-world hands to control the position and grasp action of the virtual limbs they see in VR. In both conditions, participants complete the Pasta Box Task using a VR headset like in the previous projects, but here participants use their real-world arms and hands to control the spatial location and grasping pattern of their virtual arms and hands. In this study, participants see objects and their virtual limbs using a VR headset, and are either able to feel an actual, real-world pasta box when they grasp the virtual box with their hands, or not. This is achieved by tying the spatial location and rotation of a real-world version of a pasta box to a virtual version of the same pasta box (Haptic condition), or by having a stand-alone virtual pasta box that is not tied to a real-world one (No Haptic condition). In addition, after each set of trials, participants complete an Embodiment Survey similar to that from Project 1, to uncover the differences in feelings of embodiment that full haptic feedback delivers compared to no haptic feedback.

We expect greater visual attention will be dedicated to the pasta box when it does not provide haptic feedback, specifically around the time participants are transporting the box. As well, we expect participants will maintain visual fixation on the pasta box longer as they pick it up and drop it off during the No Haptic condition, accounting for the lack of haptic feedback with greater visual attention. Finally, we expect higher feelings of ownership and agency will be reported towards virtual limbs when the pasta box provides haptic feedback, compared to when haptic feedback is lacking.

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2 - What's limbs got to do with it? Real-world movement correlates with feelings of ownership over virtual arms during object interactions in virtual reality[1]

2.1 - Abstract

Humans will initially move awkwardly so that the end-state of their movement is comfortable. But, what is comfortable? We might assume it refers to a particular physical body posture, however, humans have been shown to move a computer cursor on a screen with an out-of-sight hand less efficiently (curved) such that the visual representation *appears* more efficient (straight). This suggests that movement plans are made in large part to satisfy the demands of their visual appearance, rather than their physical movement properties. So, what determines if a body movement is comfortable – how it feels or how it looks? We translated an object interaction task from the real-world into Virtual Reality (VR) to dissociate a movement from its visual appearance. Participants completed at least 20 trials in two conditions: Controllers – where participants saw a visual representation of the hand-held controllers, and Arms – where they saw a set of virtual limbs. We found participants seeing virtual limbs moved in a less biomechanically efficient manner to make the limbs *look* similar to if they were interacting with a real-world object. These movement changes correlated with an increase in self-reported feelings of ownership over the limbs as compared to the controllers. Overall this suggests we plan our movements to provide optimal visual feedback, even at the cost of being less efficient. Moreover, we speculate that detailed measurement of how people move in VR may provide a new tool for assessing their degree of embodiment. There is something about seeing a set of limbs in front of you, doing your actions, that affects your moving, and in essence, your thinking.

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2.2 - Introduction

People may adopt an initially awkward posture to increase the “end-state comfort” of a movement (Rosenbaum et al., 1990; Rosenbaum et al., 2012). But what is comfortable? We might assume it refers to a physical body posture, however, people have been shown to move less efficiently (curved) such that the visual representation of the movement *appears* more efficient (straight, Flanagan & Rao, 1995). Additionally, when people are shown a visual representation of their fast-reaching hand being perturbed along its reach path, they make smooth unconscious corrections to stay on course (Saunders & Knill, 2003). This suggests that movement plans are made and updated in part to satisfy the demands of their appearance, rather than their physical movement properties (Wolpert et al., 1995). Here we test whether movement planning priority for particular visual feedback extends to end-state comfort.

When interacting with a real-world object, how you move and how your movements look to you are inseparable. But, using Virtual Reality (VR, Slater, 2009), we can dissociate these two properties. Here, we test how the visual representation of participants’ own limbs during object interactions affects their movements, and if any changes in movements correlated with changes in their subjective experience of the task. Recreating in VR a task we previously conducted in the real-world measuring eye and body movements of normative and prosthetic-using populations (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018; Valevicius et al., 2019; Williams et al., 2019), participants used a VR controller to move a virtual pasta box to three shelf locations. Participants completed this task in two body-visualization conditions: 1) Controllers: the positions and orientations of the real controllers were reproduced in VR; 2) Arms: virtual hands and arms accurately reflected the positions and orientations of the real controllers.

Despite identical control mechanisms, we noted profound differences in movement driven entirely by body-visualization. When seeing arms, participants extended their real-world wrist in a biomechanically less efficient position such that the virtual thumb and forefinger *appeared* to grasp the side of the pasta box. This does not align with recent evidence from a rapid reach decision-making experiment showing that even in light of changes in task demands, humans tend to minimize biomechanical effort and refrain from altering their movement strategy (Hesse et al., 2020). Overall this suggests, like movement-path efficiency (Flanagan & Rao, 1995), end-state comfort is largely dictated by the way things look, not how they physically feel. In addition, in this study, participants reported equally high judgments of agency after completing the task in both conditions, but reported much higher feelings of ownership when they saw a representation of virtual limbs, supporting claims that agency and ownership are separable components of embodiment (Kalckert & Ehrsson, 2012; Synofzik et al., 2008). More importantly we find a significant relationship between changes in movement and feelings of ownership – people who felt more ownership over virtual limbs also showed larger differences in their movements of those limbs. Taken as a whole, these findings suggest that a detailed analysis of movements may be a useful tool in measuring levels of embodiment in VR.

2.3 - Materials and Methods

2.3.1 - Participants

21 self-reported right-handed undergraduate students provided informed consent to participate in our study. 20 (1 dataset dropped due to software issue) participants (17 male; average height of 174.45 ± 2.19 cm) were analyzed. 10 participants removed their glasses and 1 participant was color blind and was told the colors of the placement targets. Procedures were approved by the University of Alberta Health Research Ethics Board (Pro00085257).

2.3.2 - Apparatus and stimuli

Participants donned an HTC Vive head mounted display (HMD, Vive; HTC and Valve, New Taipei City, Taiwan, and Bellevue, WA, USA, respectively) with a Deluxe Audio Strap. They were immersed in a model of our lab space (built in Unity (Unity Technologies, San Francisco, CA) and using NewtonVR (Today Tomorrow Labs, Seattle, WA)). The virtual task apparatus consisted of a set of shelves with 3 placement targets and a pasta box (see Fig. 1(a) and Videos 1 and 2). Participants held an HTC Vive controller (real controllers) in each hand.

2.3.3 - Procedure

Before entering the VR environment, participants carried out a brief (~15s) eye-tracking calibration (PupilLabs GmbH, Berlin, Germany), as eye movements were tracked but are not the focus of the current study. The experiment consisted of two sessions (one per condition) of at least 20 error-free repetitions of an object interaction task. After each condition, participants removed the HMD and completed a self-reported subjective experience of embodiment survey (based on Longo et al., 2008) rating statements on a scale from 1 (Strongly Disagree) to 7 (Strongly Agree).

We replicated a real-world task designed to assess the coordination of gaze and movement during everyday object interactions (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018; Valevicius et al., 2019; Williams et al., 2019). Each trial was initiated with an auditory cue and consisted of three object interactions. First, participants moved the pasta box from the Start/End Target on a table on their right side onto the Mid Shelf Target in front of them. Then, participants moved the pasta box from the Mid Shelf Target to the High Shelf Target by crossing the body's midline. Finally, the pasta box was picked up from the High Shelf Target and placed back on the Start/End Target (Figure 2.11(a)). At the start and end of each trial and after each pasta box placement, participants touched the Home position (pink rectangle in Figure 2.1(a, b)).

We manipulated the visual representation of a participant's end effector. In the Controllers condition (Figure 2.1(c), and Video 1), participants saw a virtual model of the real controller. In the Arms condition (Figure 2.1(d), and Video 2), participants saw a virtual representation of arms which extended from their torso, with hands that moved naturally with the real controllers (Full Arms VR (Bad Plan Games)). Condition order was counterbalanced across participants.

The mechanism of control was identical across both conditions - participants used the real controller in their right hand to interact with the pasta box. This interaction was governed by a 5 cm diameter invisible sphere (see Figure 2.1(b)) with its centre located approximately 10 cm distal to the participant's real-world hand. The real controller would vibrate when this sphere intersected the pasta box or Home position. Vibration indicated the participant could initiate an interaction with the pasta box by pulling the trigger button. When the trigger was depressed >50%, an interaction began and the pasta box would then move with the real controller until the trigger was released (<50%).

Participants were instructed to move at a comfortable pace and interact with the pasta box on its side. There were colored targets indicating where the pasta box should be placed for each movement. Additionally, participants were to avoid dropping the pasta box, contacting the apparatus, hesitating, or making undesired movements (like scratching one's leg).

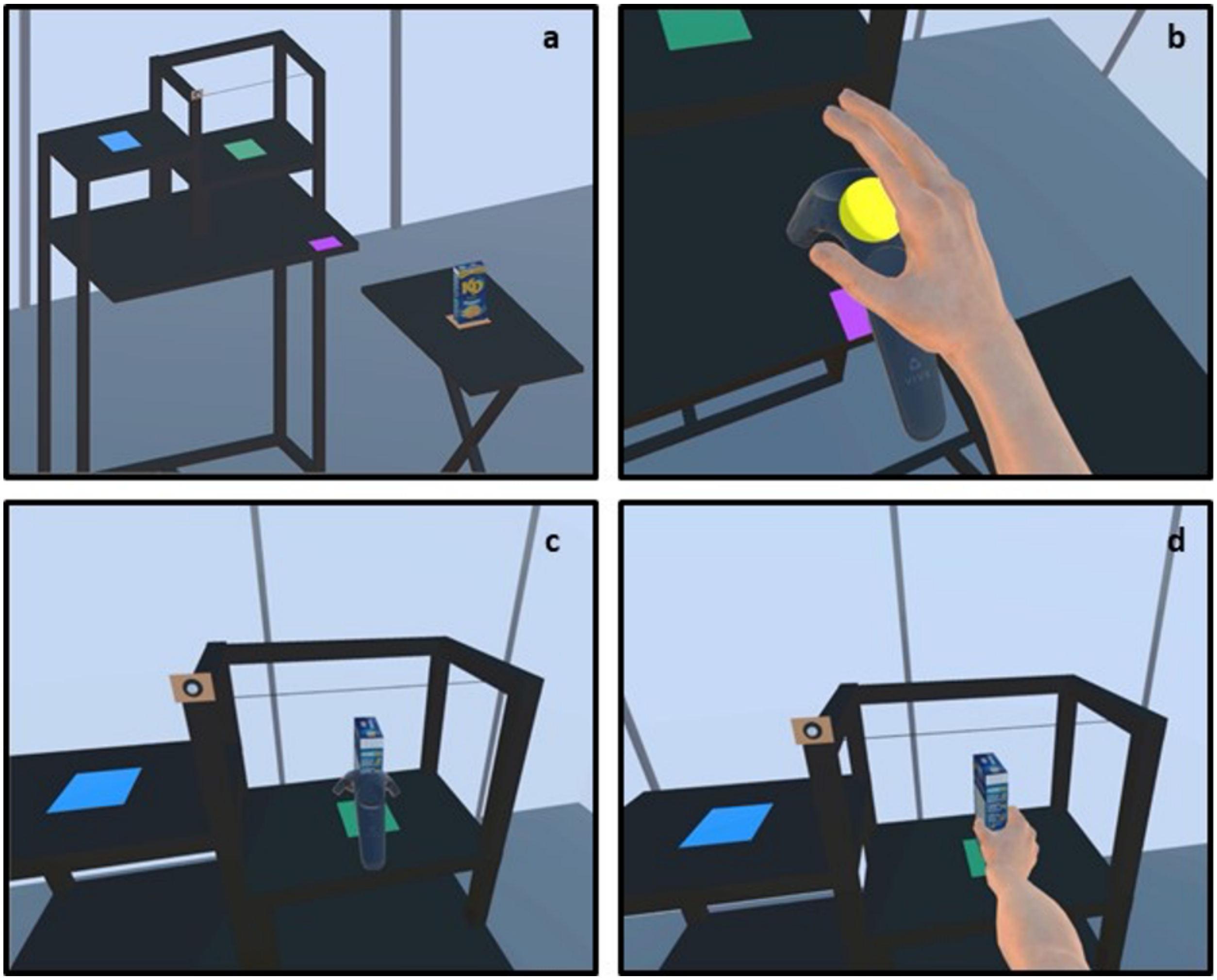

Figure 2.1: The task consists of a) a pasta box beginning on the Start/End Target (orange rectangle) on a side table, the Mid Shelf Target (green rectangle) and High Shelf Target (blue rectangle) where the pasta box is moved to, and the Home position (pink rectangle where participants started, ended and touched in between each movement). In both the Controllers and Arms conditions, participants could interact with the pasta box when b) an invisible sphere, visualized in yellow, contacted the pasta box which vibrated the real controller signalling an interaction could occur. In the Controllers condition, c) participants saw a visual representation of the real controller they were holding, while in the Arms condition, d) participants saw a limb that extended from their virtual torso with a hand that increased grip aperture as it moved towards the pasta box and closed in a clamping fashion upon a trigger-press interaction.

2.3.4 - Data Processing

Using custom C# scripts, 3D position and rotation of each real controller, the HMD, pasta box, placement targets, and other relevant objects were recorded (90 Hz) on each trial. We used our Gaze and Movement Assessment (GaMA) software (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018; Valevicius et al., 2019; Williams et al., 2019) to extract the position and orientation of the real controllers and pasta box at the beginning of the three object interactions. This generated a 3D position (In/Out, Left/Right, Up/Down) and orientation (Yaw, Pitch, Roll) for the pasta box (Pasta box Measures - centre of pasta box relative to centre of placement target) and controller (Hand Measures - centre of interaction sphere relative to centre of pasta box) for each of the three movements.

2.3.5 - Statistical Analyses

Pasta box and Hand Measures were analyzed with a 2 (Condition) x 3 (Target) repeated measures analysis of variance (RMANOVA) using JASP (Love et al., 2019). Measures with a significant main effect of Condition or a Condition x Target interaction effect are reported if the Greenhouse-Geisser corrected p-value was less than 0.05. Any significant interactions were followed by paired t-tests comparing Condition at each Target.

Self-reported subjective experience of embodiment survey responses (judged on a 7-point scale) were compiled into components of Embodiment (Ownership, Location, Agency) and Control statements and were analyzed with a 2 (Condition) x 4 (Component) RMANOVA, with paired t-tests comparing Condition across Component.

2.4 - Results

2.4.1 - Pasta box Measures: When seeing Arms, the pasta box was placed further from the body and rotated

Participants placing the pasta box on the shelf targets released it further from their body and rotated it more when they saw Arms compared to Controllers. This was confirmed statistically for the Pasta box In/Out measure with an interaction of Condition x Target, $F(1.523, 28.941) = 4.90$, $p = 0.022$, $\eta^2 = 0.042$, with paired t-tests showing a significant difference, $t(19) = 3.20$, $p = 0.005$, Cohen's $d = 0.716$, between Pasta box In/Out at the Mid Shelf Target such that the pasta box placement during Controllers (-1.87mm, $SD = 3.20$mm) was closer to the participant than during Arms (0.27mm, $SD = 3.72$mm). Pasta box Yaw showed a main effect of Condition, $F(1, 19) = 9.78$, $p = 0.006$, $\eta^2 = 0.078$, and interaction effect of Condition x Target, $F(1.278, 24.288) = 7.89$, $p = 0.006$, $\eta^2 = 0.034$, with paired t-tests showing significant differences between Arms and Controllers at all three targets: Start/End Target (Controllers = -1.73°, $SD = 0.35°$ and Arms = -1.17°, $SD = 0.97°$), $t(19) = 2.81$, $p = 0.011$, Cohen's $d = 0.629$ (Figure 2.2); Mid Shelf Target (Controllers = -3.23°, $SD = 5.45°$ and Arms = 7.91°, $SD = 17.83°$), $t(19) = 2.66$, $p = 0.015$, Cohen's $d = 0.598$; High Shelf Target (Controllers = 12.80°, $SD = 10.34°$ and Arms = 25.09°, $SD = 23.98°$), $t(19) = 3.43$, $p = 0.003$, Cohen's $d = 0.767$. In all cases, the pasta box was more rotated at the start of an interaction when participants viewed Arms (amplified at the shelf locations). The small differences at the first interaction are likely caused by movements occurring before initiation detection.

2.4.2 - Hand Measures: When seeing Arms, the real-world controller was positioned so that the virtual hand formed a grasping pattern

Despite no limitations on how they could move, when seeing Arms participants oriented their real-world wrist in a biomechanically inefficient position to visually orient the virtual limb in a plausible grasping pattern. This meant they held the real controller further into and lower on the pasta box and rotated it so that the virtual hand appeared to have the thumb and forefinger in opposition (see Figure 2.2).

The following statistics support this. For position measures, Hand In/Out yielded a main effect of Condition, $F(1, 19) = 53.43$, $p < 0.001$, $\eta^2 = 0.510$, and interaction effect of Condition x Target, $F(1.506, 28.622) = 38.614$, $p < 0.001$, $\eta^2 = 0.080$, with paired t-tests showing significant differences between Arms and Controllers at each target: Start/End Target (Controllers = -48.00mm, *SD* = 14.70mm and Arms = -37.49mm *SD* = 13.67mm), $t(19) = 4.11$, $p < 0.001$, Cohen's $d = 0.919$ (Figure 2.2); Mid Shelf Target (Controllers = -47.83mm, *SD* = 15.75mm and Arms = -26.35mm, *SD* = 15.65mm), $t(19) = 6.39$, $p < 0.001$, Cohen's $d = 1.430$; High Shelf Target (Controllers = -45.11mm, *SD* = 15.70mm and Arms = -14.25mm, *SD* = 17.53mm), $t(19) = 8.84$, $p < 0.001$, Cohen's $d = 1.976$. In the Arms condition, participants extended the real controller further into the pasta box, yielding values closer to the pasta box-centre. Hand Left/Right yielded a Condition x Target interaction effect, $F(1.821, 34.604) = 6.59$, $p = 0.005$, $\eta^2 = 0.035$, although no significant pairwise differences were found at any location. Finally, Hand Up/Down yielded a main effect of Condition, $F(1, 19) = 195.31$, $p < 0.001$, $\eta^2 = 0.882$ with participants in the Arms condition (-27.54mm, *SD* = 12.46mm) ending their movements much lower on the pasta box than during the Controllers condition (31.31mm, *SD* = 18.45mm).

For rotation measures, Hand Roll yielded a main effect of Condition, $F(1, 19) = 66.478$, $p < 0.001$, $\eta^2 = 0.722$. Participants seeing Controllers kept the real controller nearly level (0.45°, *SD* = 2.38°), while during Arms, it was significantly rotated (-25.16°, *SD* = 15.05°). Hand Yaw yielded a main effect of Condition, $F(1, 19) = 130.496$, $p < 0.001$, $\eta^2 = 0.774$, and interaction effect of Condition x Target, $F(1.196, 22.721) = 4.812$, $p = 0.033$, $\eta^2 = 0.005$, with subsequent analysis showing significant differences between Arms and Controllers at each target: Start/End Target (Controllers = 4.66°, *SD* = 7.35° and Arms = -24.82° *SD* = 13.58°), $t(19) = 10.93$, $p < 0.001$, Cohen's $d = 2.444$; Mid Shelf Target (Controllers = -0.74°, *SD* = 7.72° and Arms =

-35.16°, *SD* = 16.27°), $t(19) = 10.55$, $p < 0.001$, Cohen's $d = 2.360$; High Shelf Target (Controllers = 1.58°, *SD* = 8.11° and Arms = -34.16°, *SD* = 19.15°), $t(19) = 10.33$, $p < 0.001$, Cohen's $d = 2.309$. When seeing Arms, participants rotated their real hand such that the virtual hand positioned the finger and thumb opposed (amplified at the shelf locations). By comparison, during Controllers, participants moved straight into the pasta box and did not rotate their hand. Finally, Hand Pitch yielded a main effect of Condition, $F(1, 19) = 39.947$, $p < 0.001$, $\eta^2 = 0.515$. During Controllers, participants angled the real controller upwards (18.66°, *SD* = 16.43°), while during Arms, participants angled it downwards (-4.89°, *SD* = 5.88°).

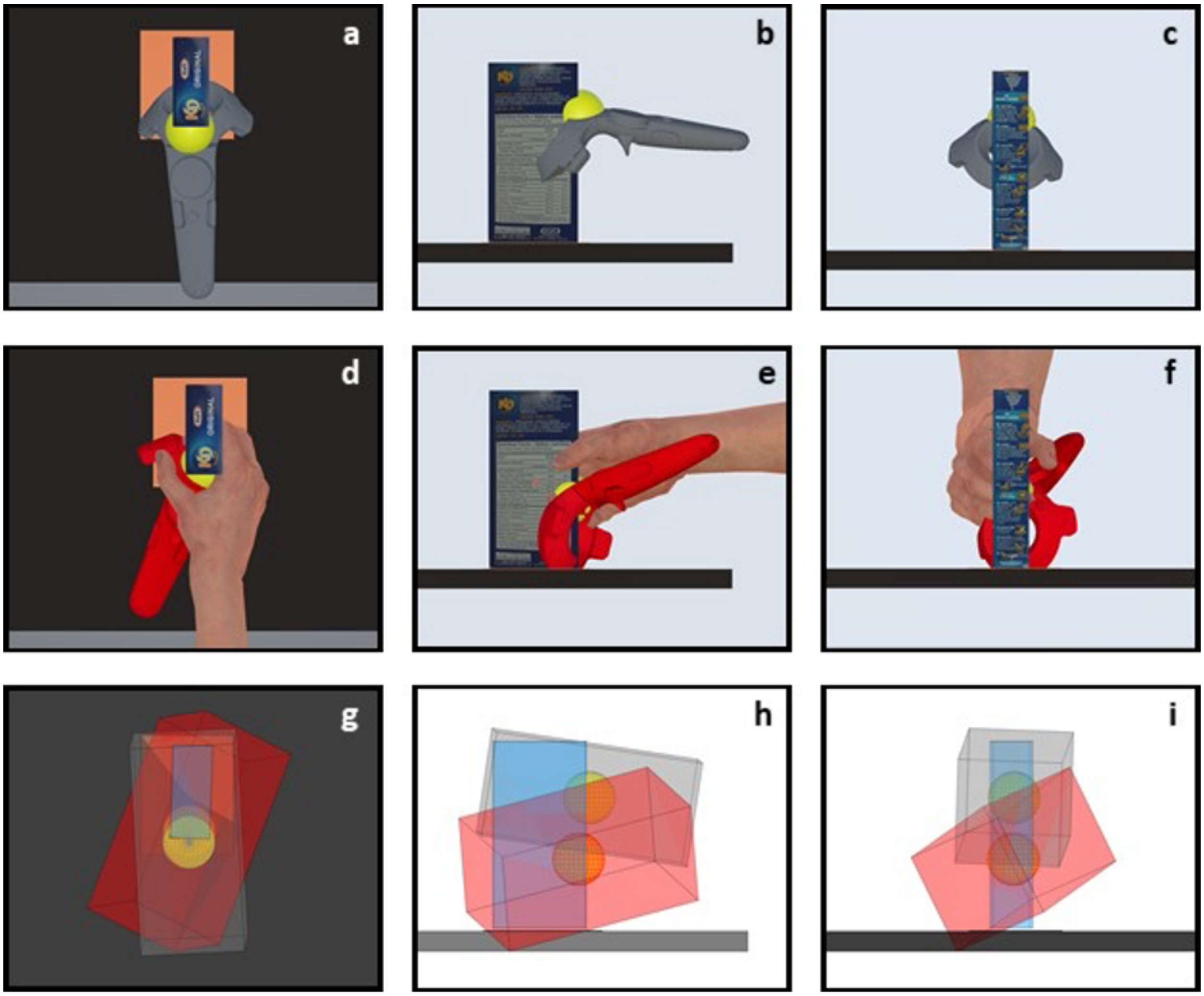

Figure 2.2: The average position of the real controller during an interaction at the Start/End Target from all participants during the Controllers condition (in gray), from a) a top-view, b) a side-view, and c) a front-view, and during the Arms condition (in red), from d) a top-view, e) a side-view, f) and a front-view. Software developed to analyze gaze and movement data (GaMA) show the differences in the average position of the real controller rectangle collected from Unity during the Controllers (gray) and Arms (red) conditions from g) a top-view, h) a side-view, and i) a front-view. The interaction sphere, which stayed in the same place relative to the real controllers (and was never visible) is shown in yellow in all frames.

2.4.3 - Embodiment: When seeing Arms, participants reported greater feelings of ownership

We compiled participant responses to the statements into the 3 components of Embodiment (Ownership, Location, and Agency) from Longo and colleagues (2008), and also a Control statement component. Here, control statements were those that were not expected to differ between the Arms and Controllers conditions, but were meaningfully related to the task (e.g. ease of using the trigger on the hand-held controller, difficulty of the task, real and virtual world synchronization). The RMANOVA yielded a main effect of Condition, $F(1, 19) = 4.679$, $p = 0.043$, $\eta^2 = 0.072$, and Component, $F(2.258, 42.910) = 5.842$, $p = 0.004$, $\eta^2 = 0.113$, and an interaction effect of Condition x Component, $F(2.378, 45.183) = 5.637$, $p = 0.004$, $\eta^2 = 0.036$. To examine the interaction, we ran four follow-up paired t-tests comparing Arms and Controllers at each of the four Components and adjusted the alpha to accept t-tests with p-values less than 0.0125. Here, the Ownership component was found to be significantly higher in the Arms condition (Arms = 5.20, *SD* = 1.23 and Controllers = 3.98, *SD* = 1.74, $t(19) = 3.05$, $p = 0.007$, Cohen's $d = 0.682$), while all other components did not differ (Figure 2.3(a)).

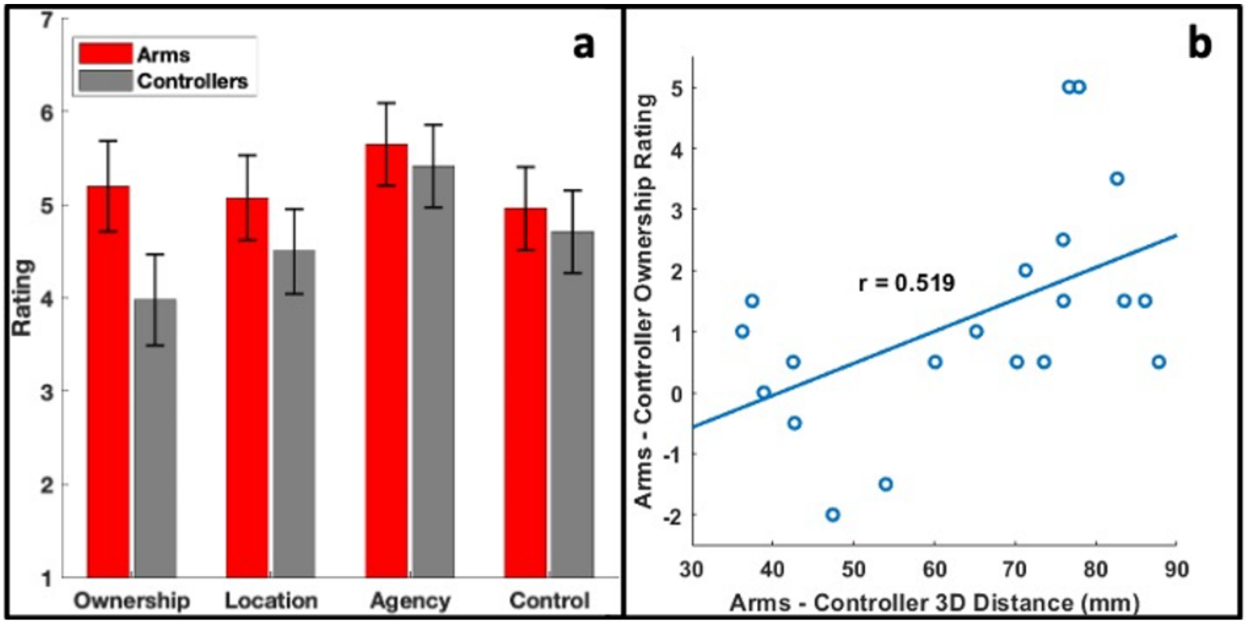

Figure 2.3: a) The average ratings to the statements of the self-reported subjective experience of embodiment survey compiled into the components of Embodiment (Ownership, Location, and Agency) and a Control statement component across both conditions. The error bars are the 95% CI of the difference between conditions for that component. b) The correlation between the difference in real controller 3-dimensional (3D) position and Ownership rating between the Arms and Controllers conditions.

2.4.4 - Changes in Feelings of Ownership Correlates with Changes in Movement

Next, we aimed to see if changes in self-reported feelings of ownership correlated with changes in the movement measures. Specifically, we correlated 1) The average 3-dimensional (3D) distance in real controller placement on the pasta box between the two conditions at each interaction with 2) the difference in Ownership rating between the two conditions. We found a strong correlation between the difference in real controller placement and Ownership rating between the two conditions ($r = 0.519$, $p = 0.019$), compared to weak and insignificant findings for Location ($r = 0.295$, $p = 0.207$), Agency ($r = 0.369$, $p = 0.110$), and Control ($r = 0.298$, $p = 0.201$). As well, we tested the strength of the evidence in support of the hypothesis that a positive correlation exists between the difference in 3D controller placement and Ownership using Bayes factors (BF). This analysis revealed that the hypothesis that there is a positive correlation predicts the data just over 7 times better than a null hypothesis of no correlation ($BF_{+0} = 7.118$) at a moderately robust level. In other words, strong evidence supports the relationship wherein the further apart a participant positioned the real controller when grasping the pasta box during the Arms versus Controllers condition, the higher their self-reported feelings of Ownership for the virtual Arms was (Figure 2.3(b)).

2.5 - Discussion

This experiment used VR to test whether participants would alter their real movements to create more “comfortable” visual feedback. Indeed, when seeing virtual arms as compared to virtual controllers interacting with a virtual pasta box, participants moved their real hand such that the virtual limb was lower, extended further from their body, and rotated in three dimensions to make the virtual thumb and forefinger appear opposed, as a real-world limb would if it were interacting with this object (Lukos et al., 2007).

Stark movement differences were accompanied by survey responses indicating that virtual arms induced a greater sense of ownership than virtual controllers, while reported sense of agency was high in both conditions. This increase in ownership for a realistic arm-like object has been well documented in other domains (e.g. Botvinick & Cohen, 1998) including in VR (Argelaguet et al., 2016; Lin & Jörg, 2016; Pyasik et al., 2020; Slater et al., 2008) and can be enhanced via visual feedback that synchronizes with a person’s physical respiration (Monti et al., 2019) or heart rate (Suzuki et al., 2013). As well, visual discontinuity of a virtual limb being passively observed by a participant has been shown to decrease the feeling of ownership and sense of agency of that limb (Tieri et al., 2015), which is likely a contributor to our findings of decreased ownership over the virtual controllers compared to the virtual arms. As mentioned earlier, it has been shown that agency and ownership are dissociable aspects of the feeling of embodiment in the real world (Kalckert & Ehrsson, 2012; Longo, et al., 2008; Synofzik et al., 2008), and in VR (Lin & Jörg, 2016). Our results support this, as participants' reported sense of agency was high in both conditions, while sense of ownership was much greater for the virtual arms than the virtual controllers. Although it has been widely shown that ownership over a body will impact the sense of agency of that body, our results support the notion that there are other factors at play in creating a sense of agency (Pyasik et al., 2019). In our study, virtual controllers may be more like using a tool like a hammer in the real world. We understand that we have agency over the hammer, but that it is not part of our body. When seeing a pair of virtual arms moving like real limbs, these arms may go one step further and begin to replace our own limbs in our body schema, creating increased ownership. It has been shown previously that ownership over a limb influences sensorimotor behaviour (Burin et al., 2019). Our findings support this, and show that humans will move their own real-world limb into biomechanically inefficient positions to elicit a plausible grasping position in a virtual limb that they experience ownership over.

Importantly, we found a relationship between these two measurement types (physical movement and subjective report) which rarely get reported together. That is, not only did a change in visual feedback of a person's body change how they moved *and* how they felt about ownership over those bodies, but these two properties were significantly correlated (see Figure 2.3(b)). Participants who felt more ownership over the Arms versus Controllers tended to be the same participants who were more willing to change their physical movements to accommodate the difference in visual feedback. Previous work has shown that during the rubber hand illusion, participants will not only feel as though their real hand is drifting towards the rubber hand, but that when possible through use of a horizontally sliding board, participants' real hands will actually drift towards the rubber hand (Asai, 2015). Not only that, but when participants' hands are not able to slide, they generate force that would move their real hand in line with the rubber hand (Asai, 2015). In a domain where features of subjective experience are notoriously difficult to quantify, we submit that capturing measures of physical movement behaviour can serve as important objective correlates to changes in the experience of embodiment. The beauty of VR platforms is that this movement data is a necessary component of the VR experience and is natively available. We must note that a major limitation of this study is that an appropriate control condition is missing. To more fully compare the effects of visual representation of virtual arms, a comparison to non-arm-like objects with similar dimensions extending from the torso should be tested (Pyasik et al., 2020).

More broadly, these findings contribute to models in which body memory influences behaviour (Riva, 2018), bodily self-consciousness relies on the integration of multiple sensory modes (Blanke, 2012), and motor commands are generated together with predictions of their sensory outcomes (Adams et al., 2013). In brief, these models rely on the integration of bottom-up sensory components, with continuous tuning by top-down cognitive predictions. As a person is acting, top-down motor outputs are created, as are predictions of what the incoming bottom-up sensory information should be for that action. Real bottom-up sensory information is acquired, and modulation of the top-down motor outputs occur based on the error between the real sensory information and the sensory prediction. The impact that action intentions have been found to have on perceptions of incoming sensory information is well-documented, with the perceived results of an action pulled closer in time to the action itself as participants perceive they are the cause of the result (Haggard et al., 2002). Reinforcing or violating certain sensory predictions can induce various misperceptions, in VR (see Gonzalez-Franco & Lanier, 2017 for review) and the real world (e.g. Haggard et al., 2002). Presenting participants with the visual representation of virtual arms created a set of motor-induced sensory predictions (e.g. that thumbs should oppose forefingers) which they sought to confirm by altering their movements. Although, a recent study questions the validity of the results of rubber hand illusion experiments, finding significant correlations between embodiment measures and hypnotisability (Lush et al., 2020). Further studies involving the manipulation of embodiment should account for participant perceptual suggestibility.

The results of our study also align with models of how the sense of agency develops (Synofzik et al., 2008). Here, prediction error of external percepts may be enough for ownership to develop, but is not enough for the sense of agency to occur, which requires that motor intentions and resulting motor-related sensory feedback are integrated into a unified bodily awareness (Tsakiris et al., 2006). In our study, participants would have the motor intention of moving either the virtual controller or virtual arm to interact with the pasta box. When they successfully manipulated the box, they would receive visual sensory feedback of this, and would thus develop agency over their actions in both conditions. Our results are consistent with this hypothesis since the judgment of agency is similar for both the limb (Arms) and non-limb-like (Controllers) effectors. These results highlight the distinctions between agency and ownership, with the sense of agency perhaps relying more on motor intentions and sensory outcomes, while the sense of ownership being largely influenced by the visual appearance of the effector (e.g. Pyasik et al., 2020).

2.6 - Conclusions

Previous work shows that participants will adopt an initially awkward posture to increase the end-state comfort of the movement (Rosenbaum et al., 1990; Rosenbaum et al., 2012), implying that physical body posture dictates movement planning. But, other work demonstrates that participants controlling a cursor with an out-of-sight hand move in a way so that the cursor looks like it moves straight, even though their hand moves in a curved path (Flanagan & Rao, 1995). This aligns with movement planning theories suggesting that predicted visual feedback may be the primary driver of motor control, rather than posture (Wolpert et al., 1995). Here, using the power and flexibility of VR, we precisely measured real-world movements to test whether participants would change their behaviour to create more “comfortable” visual feedback when seeing a virtual hand versus a virtual controller. Profoundly, in no way required by the task and inconsistent with recent research putting an emphasis on biomechanical efficiency (Hesse et al., 2020), participants adopted biomechanically inefficient physical postures such that the virtual limb *appeared* like a real-world limb would if it were interacting with an object (Lukos et al., 2007). These altered movements correlated with stronger participant-reported feelings of ownership towards the set of virtual arms compared to virtual controllers along with comparably high agency ratings in both, offering a tantalizing clue that embodiment is more tightly bound to the visual representation of our body than our actual body posture. Further, this study offers strong support that visual feedback plays a dominant role in movement planning (Flanagan & Rao, 1995; Wolpert et al., 1995), contributing to motor control theories that down-weight considerations of posture and proprioceptive information and place a premium on generating visual feedback that matches visual sensory predictions of movements. Finally, most excitingly, our results suggest we may be able to harness the readily available movement data from VR experiences as a means of providing objective quantification of questionnaire-reported changes in subjective experience.

2.7 - Acknowledgements

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3 - Comparing eye-hand coordination between controller-mediated virtual reality, and a real-world object interaction task[2]

3.1 - Abstract

Virtual Reality (VR) technology has advanced significantly in recent years, with countless potential applications. However, it is unclear how well VR simulations mimic real-world experiences, particularly in terms of eye-hand coordination. This study compares eye-hand coordination from a previously validated real-world object interaction task (Lavoie et al., 2018) to the same task recreated in controller-mediated VR. We recorded eye and body movements and segmented participants' gaze data using the movement data. In the real-world condition, participants wore a head-mounted eye tracker and motion capture markers, and moved a pasta box into and out of a set of shelves. In the VR condition, participants wore a VR headset and moved a virtual box using hand-held controllers. Unsurprisingly, VR participants took longer to complete the task. Before picking up or dropping off the box, participants in the real world visually fixated the box about half a second before their hand arrived at the area of action. This 500 ms minimum fixation time before the hand arrived was preserved in VR. Real-world participants disengaged their eyes from the box almost immediately after their hand initiated or terminated the interaction, but, VR participants stayed fixated on the box for much longer after it was picked up or dropped off. We speculate that the limited haptic feedback during object interactions in VR forces users to maintain visual fixation on objects longer than in the real world, altering eye-hand coordination. These findings suggest that current VR technology does not replicate real-world experience in terms of eye-hand coordination.

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[2] *Chapter 3 of this thesis has not yet been published, but is in the revision stage as: Lavoie, E.B., Hebert, J.S., & Chapman, C.S. (2023). Comparing eye-hand coordination between controller-mediated virtual reality, and a real-world object interaction task. Journal of Vision. As well, many versions of this content have been presented at international, peer-reviewed conferences. This work is presented here with minor changes to acronyms for consistency.*

3.2 - Introduction

If you don't own a Virtual Reality (VR) headset, there's a good chance you know someone who does, showing just how ubiquitous this technology is becoming. In most cases, people use VR for gaming and entertainment as it allows creators to immerse users in fantastical virtual environments. However, the exact same tools can simulate the real world and experiences can be designed with the desired goal of changing real-world behaviour. It is this more practical use of VR that we are interested in studying. Here we focus on the possible utility of VR for improving movements in the real world as with skill training (Lerner et al., 2020), medical simulations (Pottle, 2019), sport performance (Oagaz et al., 2022), and rehabilitation (Levac et al., 2019). In these use-cases, a user can practice a skill in VR that may be high risk in the real world. For example, firefighter trainees can learn to assess the inside of a burning building in VR hundreds of times before ever having to step anywhere near a dangerous real fire. Moreover, VR allows users to practice skills in situations that have a low probability of occurring in the real world, but may have severe negative consequences if performed inappropriately. For example, a surgeon can practice a difficult, emergency surgery in VR that has a low probability of occurring in the real world, reducing the risk of making a mistake when it does occur. Of course, many differences still exist between the real world and simulations using VR headsets, and because of those differences, it's important to explore how closely our behaviour in virtual environments translates to the real world. If doing a task in VR leads to real-world behaviours that are suboptimal, are these simulations actually helping? Using the surgical example, what if doing hundreds of hours of simulated VR surgery (Mao et al., 2021) actually leads to worse real-world outcomes because surgeons learned a set of motor plans that don't transfer to a real operating theater?

If we want to compare performance in the real world to performance in a VR environment, especially from a lens of motor skill learning, it's important that we test the right kind of task with the right kind of measures. From this perspective, two important features of people's behaviour are how they move in and look at the world. The dance that our eyes and hands engage in when we are manipulating our environment provides a useful tool for uncovering just how immersive and embodying a VR world is (Lavoie & Chapman, 2021). If our eye-hand interactions are the same in VR as in the real world, a strong case can be made that we are behaving as naturally as we do in the real world. Of course, even though technologies like hand-tracking and haptic feedback devices are emerging, in the vast majority of VR deployments, interactions are mediated through a hand-held controller. At some level, it might therefore seem obvious that there will be a departure between eye-hand and eye-controller coordination. However, it is important to recognize that, as described above, controller-mediated VR is already being deployed as a proxy for real motor skill learning. So, even though we might scientifically expect differences, commercially this technology is being used in a way that assumes a fundamental - and importantly, untested - assumption of similarity.

Thus, in the current study we compare a detailed analysis of eye-hand coordination during an object interaction task performed in the real world and the identical task performed in VR with hand-held controllers. We acknowledge that our results might therefore be specific to the task we selected and the VR device we used. But, we hope to make the case that measuring eye-hand coordination during object interactions provides - as a class of tasks - diagnostic power in multiple domains, including the testing of new VR devices. We also acknowledge that object interactions in controller-mediated VR lack the salient haptic feedback that people receive from objects in the real world. As we explain later in this Introduction, without reliable haptic feedback it is expected that vision will be relied on to ensure successful interactions. But, what we do not know is exactly how the distribution of gaze will change across conditions. For example, one might predict that controller-mediated VR will demand additional gaze resources throughout all phases of a movement, or that they are only required when targeting an object, picking it up, or releasing it. Our hope is to show the value of adopting eye and body movement measures as tools to measure behavioural proficiency in virtual environments. This is imperative not only to provide guidance on how VR is being used for real-world skill learning right now, but also to set a benchmark against which to compare future human performance in altered realities. As we embrace new technologies that augment or replace our experiences (e.g. mixed reality headsets, haptic feedback devices, advanced prosthetic limbs) it is important that we have a tool to sensitively document the impact of their adoption.

3.2.1 Eye-hand coordination in the real world

Of course there are many measures of behavior we could collect in VR and compare to the real world. We use eye-hand coordination during an object interaction task because it is highly stereotypical among humans, and it is traceable back along the primate evolutionary path (Cisek, 2022; Heldstab et al., 2016). It is also fundamental for so many of our daily activities that it is likely tightly linked to the way visual information flows through the brain to control actions. Specifically, it's been shown that the unconscious, dorsal visual stream plays an important role in creating movement plans of hands and arms during object interactions (Desmurget, 1998;

Milner & Goodale, 2006), and that the eyes fixate on upcoming targets of pointing movements, and obstacles during object manipulation tasks (Johansson et al., 2001; Neggers & Bekkering, 2000). A recent review article explores functional eye and hand movements, highlighting behavioural, neurophysiological, and clinical studies (de Brouwer et al., 2021).

With the ultimate goal of the current study being an in-depth comparison of naturalistic eye-hand coordination between VR and the real world, we discuss eye and hand movements from object interaction studies that allow participants to move their bodies mostly unimpeded. In a previous study, we confirmed that eye movements precede and predict hand reaches for nearly all object interactions, and provided evidence that a minimum of approximately half a second of visual fixation on an object before arrival of the hand at that object is necessary for successful computation of grasp dynamics (Lavoie et al., 2018). This 'just-in-time' phenomenon is described as the eyes fixating on an object or area immediately prior to its use (Ballard et al., 1995; Hayhoe & Ballard, 2005) and, with some contextual flexibility, is incredibly consistent, having been found in many environments and populations, including on screens with cursor interactions (Bertrand & Chapman, 2023), prosthetic limb using populations (Hebert et al., 2019), and even in non-human primates (Ngo et al., 2022).

After starting to interact with an object, gaze patterns in the real-world retain a consistent pattern with participants disengaging their eyes from an object almost immediately after their hand began or completed interacting with it, making a saccade to the next location of hand action (Land & Hayhoe, 2001; Lavoie et al., 2018). Taken together, this allows us to generate the following summary of real-world eye-hand coordination during naturalistic, sequential object interactions:

1. When the goal is to pick up and move an object, people need to visually fixate approximately 500 ms before the hand arrives at the object. This duration can be altered by the distance of the object. For example, this time could be extended if it's going to take the hand a long time to get to the object (e.g. object is across the room), or truncated if the objects are closer together (Lavoie et al., 2018).
2. People will maintain visual fixation on the object they are picking up until they are confident that they will be successful in initiating a movement. This can be nearly instantaneous after the hand has arrived at the object, as with mouse clicks (Bertrand & Chapman 2023), or can take an extended period of time, as in the case of object movements carried out by prosthesis-users (Hebert et al., 2019; Lavoie et al., 2018).
3. Once that specified level of confidence has been achieved, visual fixation will immediately shift from the object to its future drop-off location. The duration of this

advanced fixation is tied to the length of the distance the object needs to travel. If the transport distance is short, as with mouse clicks, then the advanced look will be short. But if transport distance is long, as with walking across a kitchen when making tea, then the advanced look will be long.

4. The eyes will remain fixated on a drop-off target for a minimum of half a second, and as long as it takes for the object to confidently be released. Even for short, confident transports like mouse movements, the visual fixation lingers at the drop off location until about 500 ms has been reached (Bertrand & Chapman 2023). For slow (>500ms), confident transports, like transporting a pasta box in the real world, the eyes instantaneously shift away upon releasing the box (Lavoie et al., 2018).

This generalized understanding of eye-hand coordination during naturalistic object interactions in the real world, gives us a measuring stick against which we can compare eye-hand coordination during similar tasks in VR.

3.2.2 Predictions for eye-hand coordination in VR

There are theoretical reasons why the brain may fundamentally perceive VR differently. Snow and Culham (2021) break down the key differences between real, tangible objects, and several levels of proxy objects, including 2-dimensional images, 3-dimensional images, and objects simulated as real through VR. This work shows that humans recognize real objects better than proxies, remember real objects better than proxies, and have greater attention towards real objects than proxies. Ultimately, and pertinent to the current study which uses an object interaction task, this is thought to be driven by the actability of real objects, compared to proxies (Marini et al., 2019; Snow & Culham, 2021).

Another reason the human brain may treat virtual objects differently than real-world objects is the availability of haptic feedback. In the real world, when we reach out with our limb to interact with an object, we experience proprioception, and eventually haptic information at our fingertips, like the pressure of our fingers on the object as we secure it and the weight of the object as we lift it. For the same action in controller-mediated VR, we have a much less salient experience. Here, we may feel similar proprioception in our limb, but not in our hand as it is grasping a plastic controller. When we are able to initiate a grasp at most we may receive a slight vibration from the plastic controller - with no information about pressure or object weight. Indeed, this impoverished haptic feedback is cited as one of the reasons why the brain may shift from using the more dorsally driven, online visual information stream, thought to underlie real eye-hand coordination, to using the more offline ventral visual stream (Harris et al., 2019). This hypothesis rests heavily on findings showing that pantomimed movements to remembered objects elicit greater ventral stream engagement than movements to objects in real time (Goodale et al., 1994). The consequences of a ventral stream shift to eye-hand coordination are largely unknown.

If the lack of haptic feedback is predicted to drive differences in movement and gaze, what specific alterations in eye-hand coordination might we observe? Here we can turn to work with upper-limb prosthesis-users as a possible model. Upper-limb prosthesis-users also interact with objects while receiving limited haptic feedback, similar to VR users. We know that prosthesis-users move much slower, visually fixate for longer on objects before interacting with them, maintain fixation on objects for much longer after interacting with them, and spend much more time fixating on their own limb while performing object interaction tasks (Hebert et al., 2019). Even more interesting, when touch sensation is returned to prosthesis-users through a combination of reinnervation surgery, grip kinesthesia, and intuitive motor control, their behavioural patterns shift closer to those of the able-bodied population (Marasco et al., 2021). Most notably the return of some haptic feedback liberates the eye gaze to move away from dedicated fixations to the end effector and make more advance fixations toward upcoming movement targets (Hebert & Shehata, 2022).

Taken together, there is good reason to predict differences in gaze distribution between real and virtual object interactions. In this study we provide a test of this prediction and in doing so, bring a specificity to the visuomotor processes engaged - not just *that* eye-hand coordination is different but *how.* To the crux of the problem we wish to investigate - if VR elicits visuomotor behaviours that are not well matched to the real world, we argue they may lack utility as a skill learning tool. Motor skill learning is highly contextual, so learning to perform a task in VR that elicits a known difference in visuomotor strategy might actually be counter productive. Moreover, we hope that by comparing detailed eye-hand coordination patterns in VR to a previously validated object interaction task from the real world (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018, 2019; Williams et al., 2019) we expose its utility as a benchmark for future advancements in the assessment of human motor performance.

3.3 - Methods

The data used here is a re-analysis and comparison of data from two previous studies. The first dataset has been used to publish an exploration of eye-movement patterns during object interactions in the real-world (Lavoie et al., 2018), while the second for a comparison of embodiment and movement differences between two virtual reality limb visualizations (Lavoie & Chapman, 2021). Here we describe the details necessary for our comparison of parts of each of these datasets, and for full details, encourage readers to seek out those previous publications.

3.3.1 Participants

3.3.1.1 Real world

This previously published study contained 24 able-bodied adults, with no-upper body pathology or history of neurological or musculoskeletal injuries within the past 2 years (Boser et al., 2018; Lavoie et al., 2018; Valevicius et al., 2018, 2019). Participants provided written informed consent to participate in the study. 7 participants were dropped due to software and hardware issues, including insufficient ability to track eye movements, freezing of collection computer, and missing motion capture markers. The remaining 17 participants (9 male, 8 female) had an average height of 173 ± 10.9 cm, and were made up of 16 self-reported preferred right-hand users and 1 self-reported preferred left-hand user. All participants had normal or corrected-to-normal vision, while 2 participants were tested without corrected vision, as they removed their glasses to don the eye tracker. These participants assured the experimenters they could complete the task normally. All participants were unaware of the purposes of the experiments. All procedures were approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program, and the SSC-Pacific Human Research Protection Office.

3.3.1.2 Virtual reality

21 self-reported right-handed undergraduate students received course credit, and provided informed consent to participate in this study. 14 participants (11 male, 3 female) with an average height of 171.1 ± 8.87 cm from this VR condition were used for this study, with 7 participants being dropped (6 due to poor eye tracking data, and 1 due to a software issue during data collection). 8 of the remaining 14 participants removed their glasses, and 1 participant was colour blind and was told the colours of the placement targets by the experimenter. Procedures were approved by the University of Alberta Health Research Ethics Board (Pro00085257).

3.3.2 Apparatus

3.3.2.1 Real world

Participants were fitted with a head-mounted, binocular eye tracker (Dikablis Professional 2.0, Ergoneers GmbH, Manching, Germany). They were asked to position the headset comfortably before experimenters tightened the built-in elastic strap on the back to hold it steadily in place. In addition to the head-mounted eye tracker, 57 upper-body motion-capture markers were placed on the participant and were tracked with 12 infrared cameras (Bonita, Vicon Motion Systems, Oxford, UK), including markers on the index finger and thumb and a plate with three markers on the back of the hand. Additional markers were placed on the pasta box, and other task-relevant parts of the apparatus. The Pasta Box Task was developed as part of the DARPA HAPTIX project, as an assessment tool for upper-limb prosthetic users (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Valevicius et al., 2018, 2019). The apparatus consists of a shelving unit, with an accompanying side table (Figure 3.1a). A first-person view of a participant performing part of the task can be seen in Figure 3.1c.

3.3.2.2 Virtual reality

Participants donned an HTC Vive head-mounted display (HMD, Vive; HTC and Valve, New Taipei City, Taiwan, and Bellevue, WA, USA, respectively) with a Deluxe Audio Strap, and inserted binocular eye trackers collecting pupil position at 200Hz (PupilLabs GmbH, Berlin, Germany). They were immersed in a model of our lab space [built in Unity (Unity Technologies, San Francisco, CA) and using NewtonVR (Today Tomorrow Labs, Seattle, WA, USA)]. The virtual task apparatus was built to the same measurements and appearance as the real-world task described above, consisting of a set of shelves with three placement targets and a pasta box (Figure 3.1b). Participants held an HTC Vive controller in each hand for the duration they wore the HMD, while what they saw was a set of dynamic limbs (Figure 3.1d).

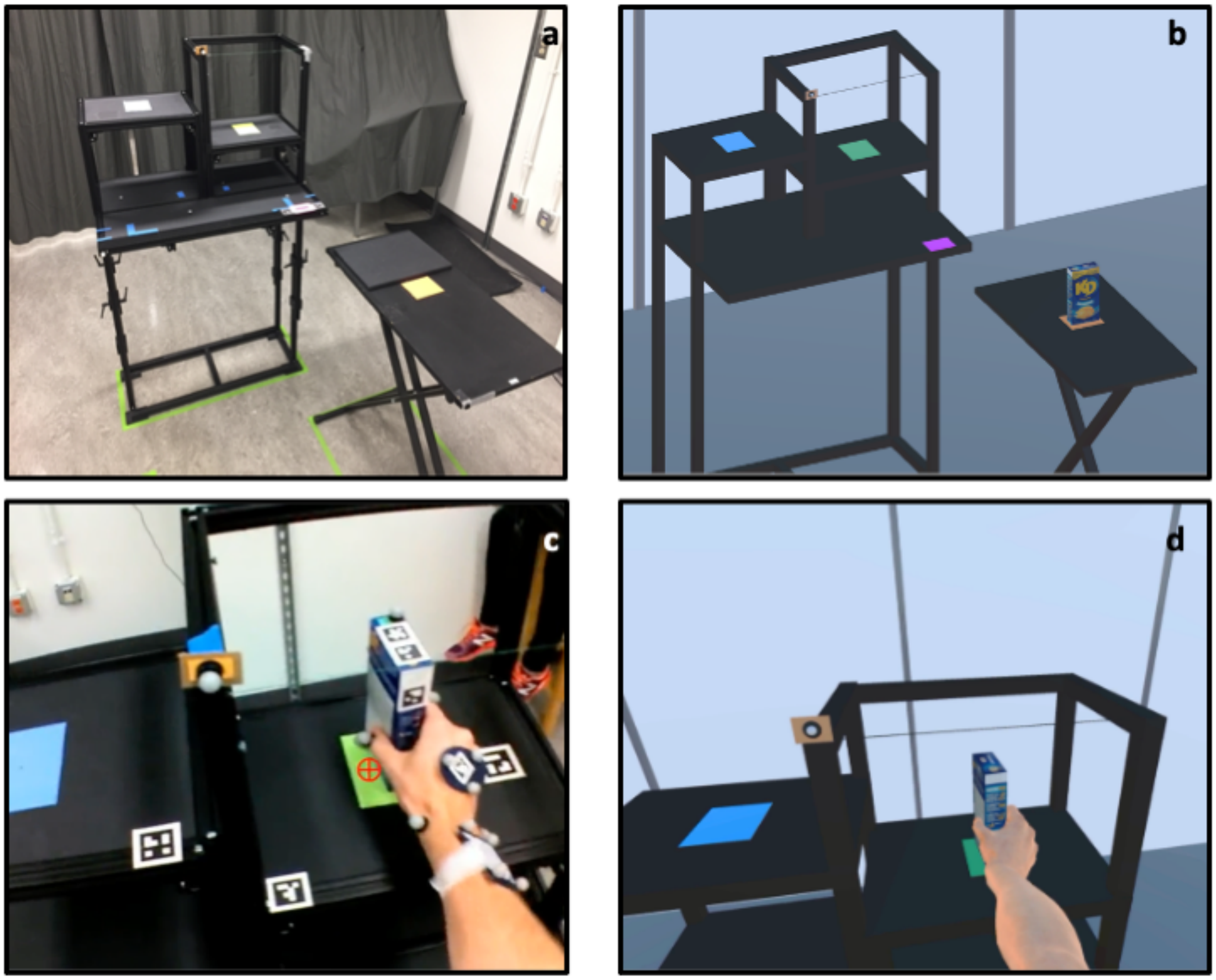

Figure 3.1: The apparatus of the Pasta Box Task a) in the real world, and b) in VR. The first-person view of a participant carrying out the task c) in the real world, and d) in VR.

3.3.3 Procedure

3.3.3.1 Real world

The data used here was collected as part of a larger experiment. Each participant underwent 6 data collection blocks, 3 of the pasta task which we use here and 3 of another object movement task which we did not use in this study. Only 1 of these 3 pasta task blocks is used here as it is the only block where both eye and body movements were collected. The sets of collection blocks were randomized in order for each participant. Before each collection block, participants underwent a series of calibration exercises, fully described in (Lavoie et al., 2018). Each collection block consisted of as many trials as necessary to obtain at least 20 trials without errors.

Participants performed the object-movement task with their right hand. The task was designed to assess the coordination of gaze and movement during everyday object interactions. Each trial was initiated with an auditory cue and consisted of three object interactions. First, participants moved the pasta box from the Start/End Target on a table on their right side onto the Mid Shelf Target in front of them (Figure 3.2(a)). Then, participants move the pasta box from the Mid Shelf Target to the High Shelf Target by crossing the body's midline (Figure 3.2(b)). Finally, the pasta box is picked up from the High Shelf Target and placed back on the Start/End Target (Figure 3.2(c)). At the start and end of each trial and after each pasta box placement, participants touched the Home position (pink rectangle in Figure 3.2(a,b,c)), and were instructed to visually fixate on a small grey sphere (Neutral position) before each trial began and after each trial was completed.

Participants were instructed to move at a comfortable pace and interact with the pasta box on its side. There were colored targets indicating where the pasta box should be placed for each movement, and participants were instructed to place the box on the short edge within the boundaries of each placement target. Additionally, participants were to avoid dropping the pasta box, contacting the apparatus, hesitating, or making undesired movements (like scratching one's leg). If a rule was violated, participants were told to complete the trial to the best of their ability and an extra trial was added at the end of that group of trials.

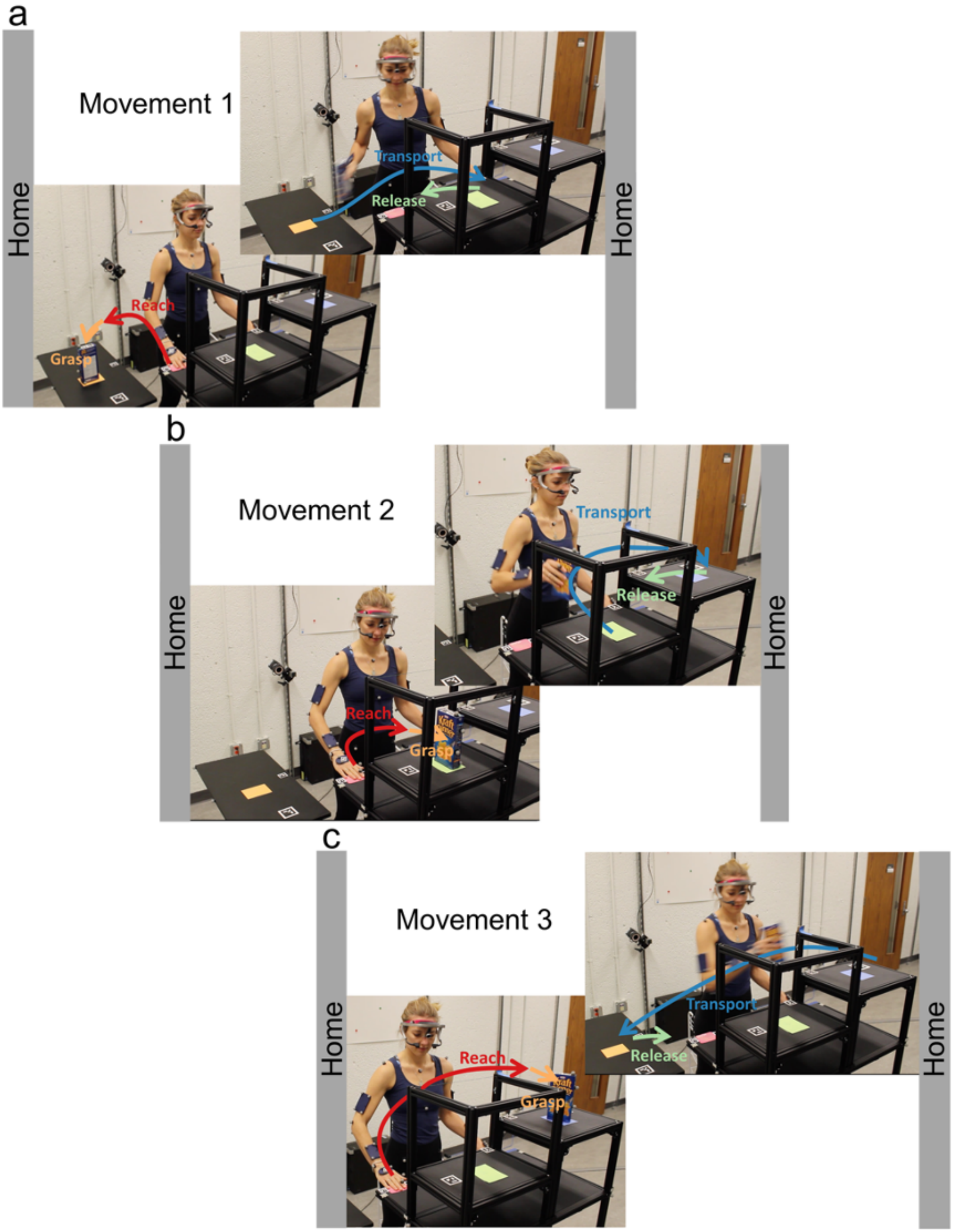

Figure 3.2: The Pasta Box Task includes Reach, Grasp, Transport, and Release of a Pasta box at 3 target locations. a) Movement 1: Grasp from side cart (Start/End Target) and Release on Mid Shelf Target. b) Movement 2: Grasp from Mid Shelf Target and Release on High Shelf Target. c) Movement 3: Grasp on High Shelf Target and Release on Start/End Target (first published in Lavoie et al., 2018).

3.3.3.2 Virtual reality

After donning the VR headset (HTC Vive), but before entering the VR lab environment, participants carried out a brief (~15s) eye-tracking calibration (PupilLabs GmbH, Berlin, Germany), prompting them to fixate one-by-one on a set of small grey circles presented virtually in a larger circle in front of them. The experiment consisted of two counterbalanced sessions of at least 20 error-free repetitions of the object interaction task. One session showed participants virtual models of the plastic controllers they were holding, while in the other session, participants saw a virtual representation of arms that extended from their torso, with hands that moved spatially with the plastic controllers they held (Full Arms VR (Bad Plan Games)). For this study, only the VR Condition with a virtual representation of arms was used.

Participants used the plastic controller in their right hand to interact with the virtual pasta box. This interaction was governed by a 5 cm diameter invisible sphere with its centre located approximately 10 cm distal to the participant’s real-world hand. The plastic controller vibrated when this sphere intersected the pasta box or Home position. Vibration indicated the participant could initiate an interaction with the pasta box by pulling the trigger button. When the trigger was depressed >50%, an interaction began and the pasta box moved with the plastic controller until the trigger was released (<50%).

3.3.4 Data processing

3.3.4.1 Real world

Custom software was used to trigger the collection of the eye and motion tracking software simultaneously and synchronize these datastreams for segmentation and analysis. With our custom GaMA software, we used the *x* and *y* coordinates of each eye from the video frame of the eye tracker, and, combined it with the calibration data including the movement of the head and objects in a regression function, generating a virtual location of the participant’s gaze (as represented by a gaze vector) in the coordinate frame of the motion-tracked objects and body.

Using a combination of hand and object velocities and positions each trial was segmented into its three object movements, with each object movement subsequently segmented into Reach (hand moving toward object), Grasp (hand starting the object interaction), Transport (hand moving object between locations), and Release (hand completing the object interaction and moving away) phases (see Lavoie et al., 2018 for full segmentation details and Figure 3.3 for sample segmentation). A fifth Home phase (when the hand was returning home after completing each movement) was also segmented from the data but not included in the analysis.

Because we are interested in overt fixations to areas relevant to object interactions, and since previous research has shown that participants rarely fixate on objects or areas irrelevant to the goal of a task (Lavoie et al., 2018; Land & Hayhoe, 2001; Hayhoe et al., 2003; Land, 2009; Tatler et al., 2011), we selected specific regions during each phase of movement for analysis. For this study, the areas of interest (AOIs) within each phase were defined as the current location being acted on by the hand (*Current*), and the hand itself or an object being moved by the hand when no other AOI is being fixated (*Hand in Flight*). A fixation to an AOI was said to occur when the distance between gaze vector and AOI was sufficiently small and the velocity from gaze vector to AOI was also sufficiently low. To account for blinks, any brief periods of missing data in each AOI fixation were filled in. Then, to avoid erroneous fixation detection (e.g., fly-throughs), any brief fixations were removed. Full details can be found in a previous publication (Lavoie et al., 2018).

3.3.4.2 Virtual reality

Using custom C# scripts, the 3D position and rotation of each plastic controller, the HMD (HTC Vive), pasta box, placement targets and other relevant objects were recorded (90 Hz) on each trial. We then used the exact same segmentation procedure from the real world to generate equivalent events and measures for each trial of our VR data. To further emphasize this point, the real-world and VR raw data were treated identically, with only the following two minor adjustments: in VR, eye and motion data was synchronized during collection through Unity, and in VR the gaze vector was automatically generated by the PupilLabs software.

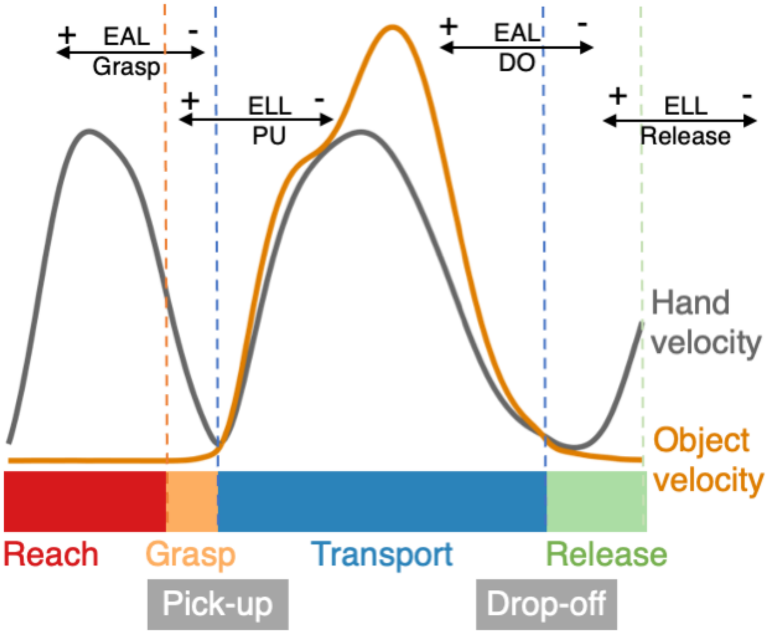

Figure 3.3: The segmentation of an object Movement into its Reach, Grasp, Transport, and Release phases is determined by the velocity of the object (orange trace), the velocity of the hand (grey trace), and distances to task relevant locations. Also shown are the approximate temporal locations defined by the terms Pick-up and Drop-off, and the Eye Arrival Latency (EAL) and Eye Leaving Latency (ELL) measures associated with each (adapted from Lavoie et al., 2018).

3.3.5 Dependent measures and predictions

The real-world measures here are based on those from our previously published study (Lavoie et al., 2018), but values may differ slightly as the segmentation and measure generation procedures are continually being improved. We grouped our measures into three families answering three broad questions. Family 1 includes the *Absolute Duration* and *Relative Duration* of each phase (Reach, Grasp, Transport, Release), and answers the question: “How long do people take?”. Family 2 includes the *Number of Fixations* and the *% Fixation Time* to the Current AOI in each phase and to the Hand in Flight AOI during the Reach and Transport phases, and answers the question: “Where do people look?”. For Family 3, we calculated the *Eye Arrival Latency* which measures when the gaze lands on a location around the time a Grasp begins and Transport ends (Drop-off), and also the *Eye Leaving Latency* which measures when the gaze leaves a location around the time when Transport starts (Pick-up) and when Release ends. These four latency measures were calculated for each object movement and answer the question: “When do people look?”. The definition and our predictions for each measure are as follows:

3.3.5.1 Family 1: How long do people take?

- *Absolute Duration*
    - The time in seconds spent in each phase as determined by our segmentation.
    - The sum of the Absolute Durations of each phase equals the Total Movement Time for each of the three Movements
- *Relative Duration*
    - The percentage of time each phase contributes to the Total Movement Time determined by our segmentation.

We predict that participants will move slower in VR because, for most, VR is a novel medium, and with novelty comes hesitation (Joyner et al., 2021). We expect to find greater *Absolute Duration* values in VR for each of the movement phases compared to the real world, but with disproportionately large values in the Grasp and Release phases, the moments when participants are initiating and terminating an object interaction with limited haptic feedback. We predict this will show up in the *Relative Duration* values as well. Although the general proportions of each phase of movement will be more similar than different between VR and the real world, we expect VR to have larger *Relative Duration* values for Grasp and Release phases, and, as a result, smaller *Relative Duration* values for Reach and Transport phases. Thus, we expect the lack of haptic feedback in VR will cause participants to move with absolute and relative durations more similar to prosthetic-using populations (Hebert et al., 2019).

3.3.5.2 Family 2: Where do people look?

- *Number of Fixations*
    - The number of distinct (separated by at least 100 ms) continuous (> 100 ms) fixations to an AOI in a given phase.
- *% Fixation Time*
    - The amount of time fixated on an AOI in a phase divided by the Absolute Duration of that phase, multiplied by 100.

We expect fairly similar patterns of visual fixation between the real world and VR versions of the task. That is, we predict participants will fixate objects and areas that they are interacting with or will be interacting with in the future, with little visual attention to objects and areas irrelevant to the task (Hayhoe & Ballard, 2005; Land & Hayhoe, 2001; Lavoie et al., 2018). However, we anticipate that fixations to a participant's own hand, and the object in their hand, will increase while transporting the object in VR, akin to prosthetic users who also lack haptic feedback (Hebert et al., 2019).

In general, we expect that the *Number of Fixations to Current* and to the *Hand in Flight* will be similar between VR and the real world except during Transport. Here we predict participants may increase their *Number of Fixations to Current* and to the *Hand in Flight* in VR as a result of the need to fixate back and forth on the object in their hand, to be sure that the object is being successfully transported, and back again to the drop-off target.

Keeping the 'just-in-time' phenomenon in mind, participants will likely fixate about half a second before their hand arrives at a location to pick up or drop off the box. When coupled with the increase we expect to see for the *Absolute Duration* values, we predict that the *% Fixation Time to Current* during Reach and Transport will be lower in VR than in the real world. Similarly, considering our predicted need for participants in VR to look more toward their hand while it Transports an object, we expect to see a disproportionately low *% Fixation Time to Current*, and high *% Fixation Time to the Hand in Flight* during Transport while in VR.

Finally, owing to degraded haptic feedback we think participants will have reduced confidence in the success of the start and end of an object interaction, resulting in *% Fixation Time to Current* during Grasp and Release that will be higher in VR than in the real world. Even though these phases will likely be longer in VR, we believe participants will have to fixate for the majority of each of them to ensure a successful interaction occurs.

3.3.5.3 Family 3: When do people look?

See Figure 3 for a visual description.

- *Eye Arrival Latency at Grasp (EAL Grasp)*
    - EAL Grasp is defined as Grasp start time minus the time of eye arrival at the Grasp location.
- *Eye Leaving Latency at Pick-up (ELL PU)*
    - ELL PU is defined as Transport start time minus the time of the eye leaving the Pick-up location or object.
- *Eye Arrival Latency at Drop-off (EAL DO)*
    - EAL DO is defined as Transport end time minus the time of the eye arriving at the Drop-off location.
- *Eye Leaving Latency at Release (ELL Release)*
    - Eye Leaving Latency at Release is defined as Release end time minus the time of the eye leaving the Release location or object.

Finally, here we predict the differences between VR and real-world behaviour will extend to the temporal dynamics of eye hand coordination. Importantly, we predict that the 'just-in-time' phenomenon will be preserved, as it has been across numerous studies and contexts (Ballard et al., 1995; Hayhoe & Ballard, 2005; Hebert et al., 2019; Land & Hayhoe, 2001; Lavoie et al., 2018; Ngo et al., 2022); Bertrand & Chapman, 2023). That is, in VR we expect that participants will begin fixating on an object at least half a second before their hand arrives to pick it up, leading to an *EAL Grasp* that will be similar in VR and the real world. In the same vein, we predict participants will fixate the drop-off target of the box for about the same amount of time prior to the box arriving in VR and the real world, giving similar *EAL DO* measures.

However, due to the lack of haptic feedback, we expect VR participants to continue fixating for much longer than real-world participants on the object they are picking up or releasing, as a way to ensure that the start and end of an interaction is successful. Therefore, we predict the *ELL PU* and *ELL Release* values will be much larger in VR compared to the real world. Because participants in VR lack haptic feedback, they will need to use visual attention to take its place to ensure a successful object interaction has occurred. Again, these predictions in VR are based on prosthetic users, who lack detailed touch information while interacting with objects, and so adapt their visual fixation patterns to be able to complete the task successfully (Hebert et al., 2019; Marasco et al., 2021).

3.3.6 Overview of statistical analysis

With the large number of tests and the fact that we were aiming to find ways in which the VR condition differed from the real-world condition, we used a modified procedure developed by Cramer and colleagues to correct for our large number of tests (Cramer et al., 2016). We divided measures into three families of results: Family 1 (How long do people take?), Family 2 (Where do people look?), and Family 3 (When do people look?), and listed the *p*-value (Greenhouse-Geisser corrected if available) of every mixed analysis of variance (RMANOVA) comparing the VR condition to the real-world condition in descending order (most to least significant) within each Family. Using the formula: Adjusted α = [0.05] / [(# of tests) - (rank order - 1)], and selecting the tests whose calculated *p*-value were less than their Adjusted α, we had a conservative list of tests we would move forward with. Any Omnibus Mixed ANOVA that showed significant interaction effects of Condition were followed up with a similar process in which each *p*-value from the post-hoc tests for this measure were listed in descending order. Using the same formula as above and the number of tests for this follow-up set, any significant main and interaction effects were found. From this, all possible pairwise comparisons of the relevant factors were conducted using a Bonferroni correction with a corrected $p < 0.05$ marking a significant effect.

It should be repeated that only significant interactions or main effects of Condition were pursued as this study is focused on the differences between eye-hand behaviour in VR and the real world. Details about the effects of specific Movement and Phase effects of the task can be found in previous studies (Lavoie et al., 2018).

For each participant in both conditions, each of the dependent measures was calculated for every trial, then averaged across trials. Below is a breakdown of the statistical analyses run within each Family of tests.

3.3.6.1 Family 1: How long do people take?

For both *Absolute Duration* and *Relative Duration*, we ran Condition (RW vs VR) x Movement x Phase Mixed ANOVAs, where there were 2 Conditions and 3 Movements. *Absolute Duration* and Relative Duration were split into 4 phases (Reach, Grasp, Transport, Release).

- Condition (RW vs VR) x Movement x Phase Mixed ANOVA
    - *Absolute Duration*: 2 Conditions, 3 Movements, 4 Phases
    - *Relative Duration*: 2 Conditions, 3 Movements, 4 Phases

In addition, because of its novelty, we tested whether participants would show a different learning effect in VR and therefore show a steeper decrease in duration in VR compared to the RW. To test this we compared the change from the first 5 trials to the last 5 trials between the two conditions. We calculated the average *Total Movement Time* (sum of the *Absolute Duration* of all 5 phases, including Home) for the first 5 and last 5 trials for each participant in VR and the real world. Each participant had a value for the First 5 trials and for the Last 5 trials. This was titled the Trial Position. We ran a 2 x 2 Mixed ANOVA of Trial Position x Condition specifically searching for an Interaction Effect between Trial Position and Condition.

3.3.6.2 Family 2: Where do people look?

For both *Number of Fixations to Current*, *% Fixation Time to Current, Number of Fixations to Hand in Flight* and *% Fixation Time to Hand in Flight* we ran Condition (RW vs VR) x Movement x Phase Mixed ANOVAs. There were 2 Conditions, 3 Movements, and 4 Phases (Reach, Grasp, Transport, Release) for the measures to Current, while there were 2 Conditions, 3 Movements, and only 2 Phases (Reach, Transport) for the measures to the Hand in Flight.

This reduction in phases during Grasp and Release is because the participant's hand is at the pick-up or drop-off location and is indistinguishable from the target

- Condition (RW vs VR) x Movement x Phase Mixed ANOVA
    - *Number of Fixations to Current*: 2 Conditions, 3 Movements, 4 Phases
    - *% Fixation Time to Current*: 2 Conditions, 3 Movements, 4 Phases
    - *Number of Fixations to Hand in Flight*: 2 Conditions, 3 Movements, 2 Phases
    - *% Fixation Time to Hand in Flight*: 2 Conditions, 3 Movements, 2 Phases

3.3.6.3 Family 3: When do people look?

To compare the eye latency measures (*EAL Grasp*, *ELL PU*, *EAL DO*, *ELL Release*), we carried out a 2 x 3 Mixed ANOVA of Condition (RW vs VR) x Movement for each.

- Condition (RW vs VR) x Movement Mixed ANOVA
    - *EAL Grasp*: 2 Conditions, 3 Movements
    - *ELL PU*: 2 Conditions, 3 Movements
    - *EAL DO*: 2 Conditions, 3 Movements
    - *ELL Release*: 2 Conditions, 3 Movements

3.4 - Results

As the amount of data and possible comparisons are rather large, here we focus on the main similarities and differences found in our behavioural measures between the real world and in VR. In the Methods section, we describe our correction procedure for the large number of statistical tests we did. Here we provide the results after this correction, and only state which tests yield significant differences. Full results and statistical analyses with significance levels will be provided upon request.

3.4.1 Family 1: How long does it take people to move?

3.4.1.1 Absolute duration in VR twice as long as RW

First, we compared the *Absolute Duration* of each phase of movement between VR and the real world, with VR being much longer in each. The most pronounced increase in *Absolute Duration* between the two conditions was found in the Release phase (RW = 0.30s, SD = 0.07s; VR = 0.88s, SD = 0.34s; $p = 4.76 \times 10^{-8}$), and the least pronounced increase was found in the

Grasp phase (RW = 0.22s, SD = 0.06s; VR = 0.35s, SD = 0.16s; *p* = 4.00 x 10^{-3}). See Figure 3.4(a).

As predicted, participants in VR took much longer to complete the task than participants in the real world. In fact, the *Total Movement Time* of each trial in VR was approximately twice that of the RW (RW = 8.73 s, SD = 1.19 s; VR = 16.51 s, SD = 3.70 s; *p* = 4.88 x 10^{-9}). We compared the change from the first 5 trials to the last 5 trials in the two conditions to test for a variance in the learning effect. *Total Movement Time* in both VR (VR: First 5 = 17.77 s, SD = 4.71 s; Last 5 = 15.75 s, SD = 3.62 s; *p* = 3.90 x 10^{-2}) and the real world (RW: First 5 = 9.01 s, SD = 1.26s; Last 5 = 8.57 s SD = 1.17 s; *p* = 2.67 x 10^{-4}) did indeed show the predicted speeding up with practice, but surprisingly, there was no significant effect of condition found, providing no evidence for different learning rates across environments. See Figure 3.4(b).

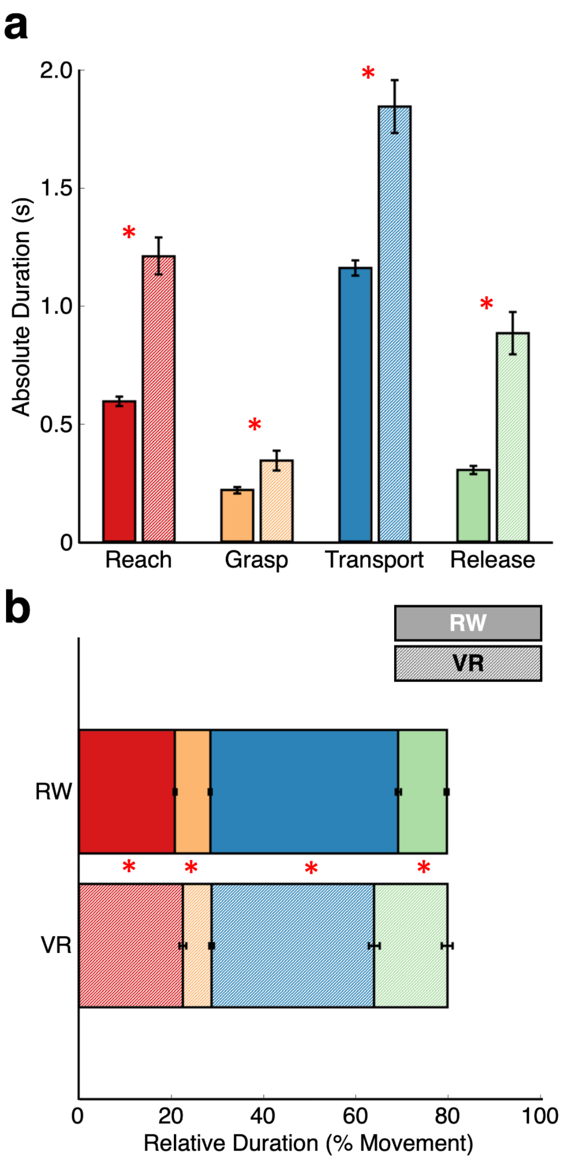

Figure 3.4: The average of all participants' a) *Absolute Duration* (s), and b) *Relative Duration* (%), of each phase of movement of the Pasta Box Task in controller-mediated virtual reality (VR) and the real world (RW). Error bars represent standard error of the mean (SEM). In both a) and b) the Home phase is omitted as it is irrelevant to the object interaction.

3.4.1.2 Predictable durations of each phase of movement

Overall, people move slower in VR but our results from *Relative Durations* suggest that the relative distribution of time over the course of an object interaction is mostly the same between conditions. That is, the most time is spent Transporting and Reaching for an object in both VR and the real world, with less time spent Releasing and even less Grasping. However, despite this general similarity the fact that the *Absolute Durations* during Grasp were more similar while the *Absolute Durations* during Release were less similar between conditions leads to commensurate differences in the *Relative Duration* measures, with subsequent effects to all phases of movement.

First, participants spend slightly more ($p = 8.00 \times 10^{-3}$) relative time in the Reach phase in VR (22.52%, SD = 2.84%) than in the RW (20.82%, SD = 4.05%) and slightly less relative time in the Grasp phase in VR (RW = 7.64%, SD = 1.39%; VR = 6.25%, SD = 1.92%; $p = 1.90 \times 10^{-2}$). *Relative Duration* is much lower ($p = 5.79 \times 10^{-5}$) in the Transport phase in VR (35.20%, SD = 4.47%) compared to the real world (40.71%, SD = 2.33%) and much higher ($p = 4.20 \times 10^{-5}$) in the Release phase in VR (15.87%, SD = 4.46%) compared to the real world (10.54%, SD = 1.84%). The difference in Release *Relative Duration* is the most pronounced. It should be noted that because this measure is designed to be proportional, when one measure accounts for “more of the pie”, another measure takes up “less of the pie”. Here, in VR, we see the *Relative Duration* during Grasp take up “less of the pie” resulting in the *Relative Duration* during Reach taking up more. While, again in VR, we see the *Relative Duration* during Release take up much “more of the pie”, leaving less for the *Relative Duration* of Transport.

The two major takeaways from this measure are that the distribution of time to phase is similar across VR and the RW except that in VR, there is a significant extension of the time spent releasing.

3.4.2 Family 2: Where do people look?

3.4.2.1 Participants fixate temporally relevant objects and areas

Participants’ visual fixation behaviour in VR followed the same characteristic pattern as we found in the real world (Lavoie et al., 2018). When planning to move an object from one location to another, participants almost always fixate on the object for approximately half a second before their hand arrives to interact with it. They then stay fixated on the object as they initiate an interaction before breaking this fixation once they’re confident the interaction is a success. At this moment, the eyes shift to the drop-off location and fixate there until the hand, along with the object, arrives to release the object. Almost no fixations are made to objects and areas that are irrelevant to the object movement being made. In fact, we found no significant differences in the *Number of Fixations to Current* between the real world and VR (see Figure 3.5(a)). Despite these broad similarities, there are notable differences in the distribution of gaze between the real world and VR, especially when factoring in the total duration differences across the two environments.

During the Reach and Transport phases, participants in the real world consistently spent a larger proportion of time fixating on the location they were about to interact with (*% Fixation Time to Current*) compared to VR participants (Reach to Box at pickup: RW = 71.56%, SD = 11.88%; VR = 48.41%, SD = 20.54%; $p = 1.15 \times 10^{-4}$; Transport to drop-off location: RW: 73.86%, SD = 7.27%; VR 52.00%, SD = 11.46%; $p = 1.26 \times 10^{-9}$). See Figure 3.5(b). Conversely, no significant differences between the RW and VR for *% Fixation Time to Current* were found during either the Grasp (RW = 90.63%, SD = 14.38%; VR = 84.81%, SD = 23.15%) or Release (RW = 84.34%, SD = 12.57%; VR = 92.12%, SD = 15.43%) phases.

It is important to consider this pattern of *% Fixation Time to Current* with respect to the *Absolute Duration* differences between the two environments. From this lens, two important findings emerge. First, recall the 'just-in-time' effect refers to around half a second of visual fixation on an object/area being required before an individual’s end effector arrives to interact there. This 'just-in-time' phenomenon can account for a decrease in *% Fixation Time to Current* during Reach and Transport in VR. VR participants move slower, creating more time in each phase of movement. Since the eyes arrive at the same fixed time of about half a second before the hand does, this leads to the reduced % time. Second, the lack of a significant difference in *% Fixation Time to Current* during Release between RW and VR needs to be considered in light of the extremely extended *Absolute Duration* of the Release phase in VR. Participants in both conditions dedicate nearly all their visual attention to the box as it’s being released, but this takes much longer in VR.

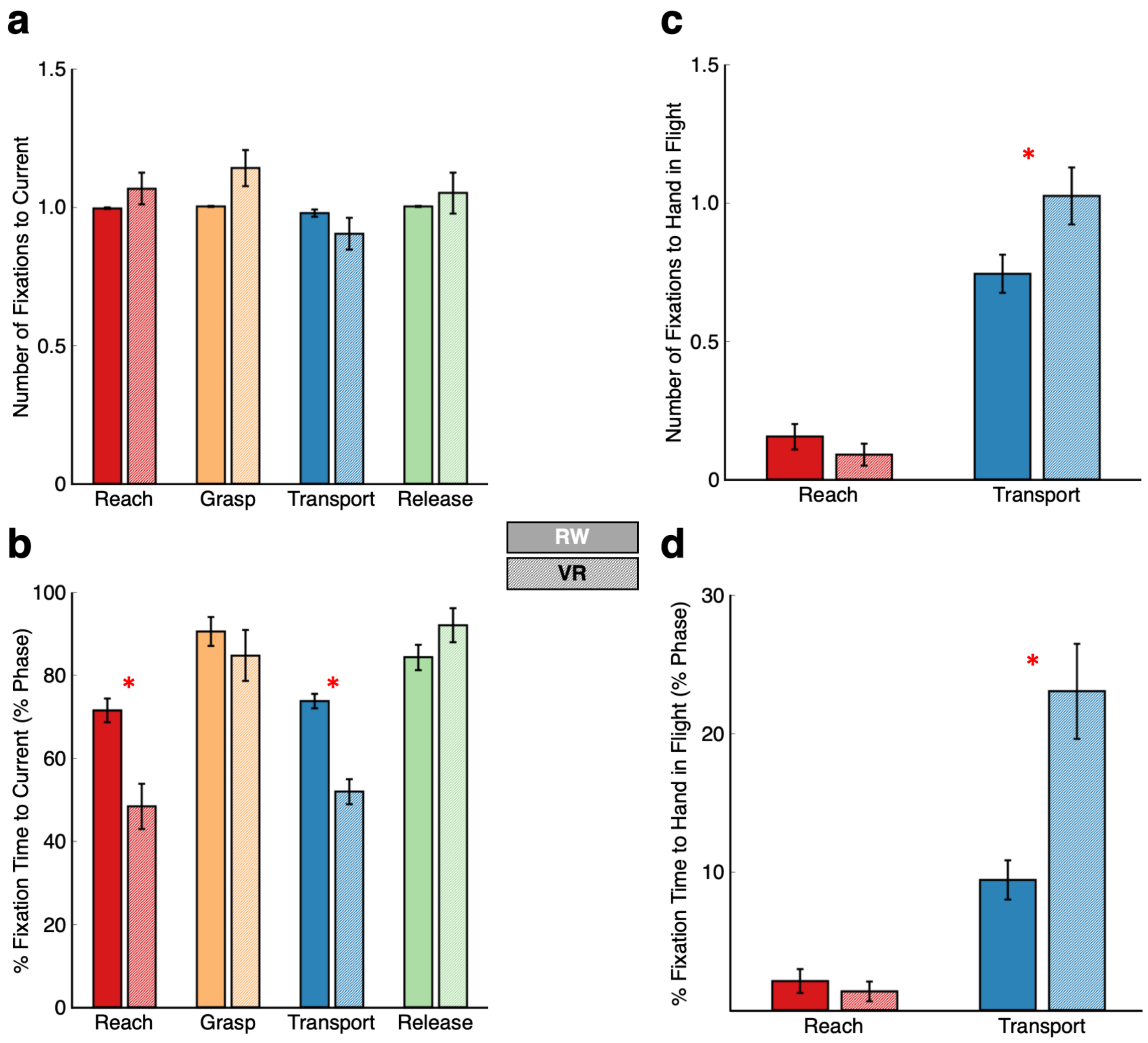

Figure 3.5: The average of all participants' a) *Number of Fixations to Current* (#), b) *% Fixation Time to Current* (%), c) *Number of Fixations to Hand in Flight* (#), and d) *% Fixation Time to Hand in Flight* (%) of each phase of movement of the Pasta Box Task in controller-mediated virtual reality (VR) and the real world (RW). Error bars represent standard error of the mean (SEM).

3.4.2.2 Eyes fixate significantly more on hand in flight during Transport in VR

One of our key predictions was supported in our results - participants in VR looked more toward their own hand and the object in their hand while they were transporting an object compared to participants in the real world. This occurred at the start of each Transport, which we interpret as participants using eye gaze in VR to ensure they'd initiated an object interaction successfully. The first evidence for this is an increase in the *Number of Fixations to the Hand in Flight* during the Transport phase (RW = 0.74, SD = 0.29; VR = 1.03, SD = 0.38; *p* = 5.00 x

10^{-3}). See Figure 3.5(c). Since this pattern was not seen in other movement phases (e.g. Reach) this is strong evidence that this difference is not due to differences in eye tracking calibration or some other hardware or software difference between the real world and VR datasets. The *% Fixation Time to the Hand in Flight* results follow a similar pattern (Figure 3.5(d)). Participants spent much more (p = 7.56 x 10^{-5}) time fixating the Hand in Flight during the Transport phase in VR (23.04%, SD = 12.81%) than in the RW (9.43%, SD = 5.86%) while there were no statistical differences between condition for the other movement phase (Reach). These percent fixation time results are even larger when considering that the *Absolute Duration* values of the Transport phases in VR were much longer than in the real world. Recall that participants in VR fixate significantly less relative time during Transport on the location they're transporting the object to compared to the RW. This finding gains more clarity knowing that the reason for this is in part that participants are spending more relative time fixating on their own hand, or the object in their hand, during VR, and therefore less fixation time is dedicated to the drop-off location.

3.4.3 Family 3: When do people look?

3.4.3.1 Visual fixation lingers on objects after pick-up and release in VR

Below we describe the similarities and differences seen between the 4 eye latency measures in the real world and VR in chronological order. That is, we describe these measures in the order that they would occur as a participant fixates on an object before picking it up (*EAL Grasp*), moving their hand towards the object, picking the object up, shifting their fixation away from the pick-up location (*ELL PU*) and on to the drop-off location (*EAL DO*), then moving the object towards the drop-off location, dropping off the object, and shifting their fixation away from the object (*ELL Release*). For a visual depiction of these results, see Figure 3.6.

First, *EAL Grasp* measures the time the eye arrives at the object location prior to the start of an interaction. Here we see the consistent pattern of about 500 ms of advance looking time in both the real world (RW = 0.42s, SD = 0.10s) and in VR (VR = 0.48s, SD = 0.32s), with no significant differences. This is more evidence for the 'just-in-time' phenomenon found previously across a number of studies and testing environments (Ballard et al., 1995; Hayhoe & Ballard, 2005; Hebert et al., 2019; Land & Hayhoe, 2001; Lavoie et al., 2018; Ngo et al., 2022); Bertrand & Chapman, 2023). Moving chronologically, *ELL Pick-up* was significantly longer in VR than the real world (RW = -0.11s, SD = 0.12s; VR = -0.78s, SD = 0.49s; p = 3.71 x 10^{-7}), meaning participants stayed fixating on the object after they'd picked it up more than half a second longer in VR than in the real world. This reinforces and refines our main point from the previous section. Not only does lack of haptic information cause participants to visually fixate more on the object during an interaction, but it also concentrates that increased visual fixation at the start of the object interaction.

EAL Drop-off was not significantly different between VR than the real world (RW = 0.85s, SD = 0.15s; VR = 1.00s, SD = 0.23s). That is, participants visually fixated for a similar period of time in the real world and VR on the drop-off target before their hand arrived with the object to initiate the drop-off. Finally, and also perhaps most importantly, *ELL Release* in VR was much longer than in the real world (RW = -0.03s, SD = 0.12s; VR = -0.42s, SD = 0.36s; $p = 1.24 \times 10^{-5}$), meaning that while participants in the real world shifted their fixation away from the object almost immediately after their hand finished releasing it, in VR, they stayed fixating on the object for nearly half a second after they had completed the release.

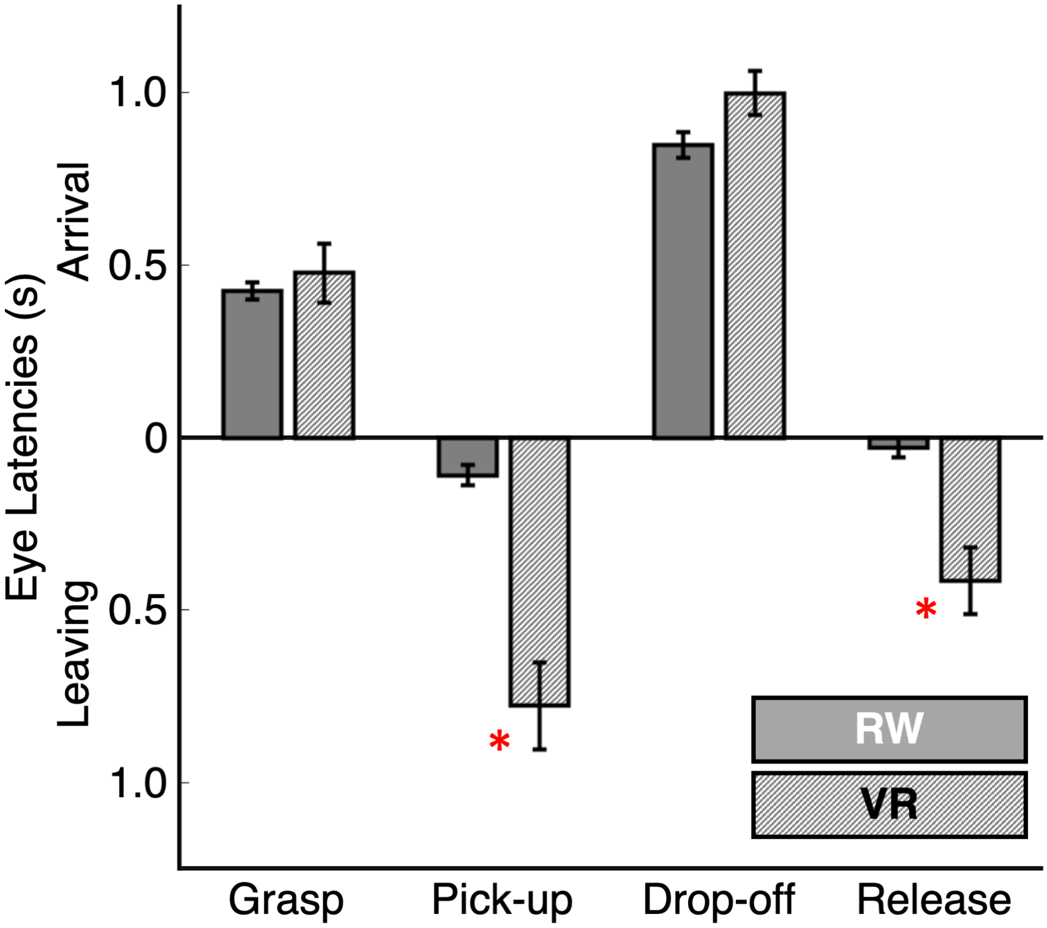

Figure 3.6: The average of all participants' *EAL Grasp* (s), *ELL PU* (s), *EAL DO* (s), and *ELL Release* (s) of the Pasta Box Task in controller-mediated virtual reality (VR) and the real world (RW). Error bars represent standard error of the mean (SEM).

3.5 - Discussion

This study compares eye-hand coordination during object interactions in real and virtual worlds by re-creating a previously published object interaction task from the real world (Boser et al., 2018; Lavoie et al., 2018; Valevicius et al., 2018, 2019) in controller-mediated VR. Given the lack of haptic feedback the general assumption is that there would be stark visuomotor differences between controller-mediated VR and the real world. While this is in some ways true (see below), it is also, in important ways, false. To summarize the similarities, we found that participants in VR spent close to the same relative time as their real-world counterparts on the first three phases (Reach, Grasp, Transport) of each object movement. VR participants also fixated objects and targets that were relevant to the immediate task they were doing, or the task they would be doing next, just like real-world participants. Finally, perhaps the most striking similarity was that, like many studies across many different contexts, we found evidence for the 'just-in-time' phenomenon of gaze leading the hand. Just like in the previous work including this task in the real world, VR participants using hand-held controllers fixated an object / location they were about to interact with a minimum of half a second before their hand arrived.

The consistency of the 'just-in-time' hypothesis of eye hand coordination is remarkable, and importantly, not strictly predicted by the hypothesis that eye-hand coordination in VR would be categorically different that that observed in the RW. Whether it is moving a mouse cursor to drag an object on a screen (Bertrand & Chapman, 2023), a monkey catching prey in the wild (Ngo et al., 2022), a person making tea (Land & Hayhoe, 2001), moving a real pasta box (Lavoie et al., 2018) or even a virtual one (current study), successful object interactions seem to require about half a second of visual fixation prior to the initiation of an interaction. Advanced visual fixation helps hand accuracy for several reasons. First, foveating the object allows the combination of multiple signals to locate the object, such as high-resolution visual information, efference copy information from the motor command to the eye muscles, and proprioceptive information from the eye muscles (Bridgeman & Stark, 1991; Poletti et al., 2013). Then, visual information of the hand reaching towards an object leads to greater accuracy since humans use vision as a feedback mechanism for the movement system (de Brouwer et al., 2021). An involuntary correction of hand trajectory has been shown in several studies, detailing the tightly-coupled nature of vision as the feedback mechanism for reaching movements (de Brouwer et al., 2021; Franklin & Wolpert, 2008; Franklin et al., 2017; Saunders & Knill, 2003; Wolpert & Flanagan, 2001). Together, this research shows there is an intimate connection between the eyes and hands that can be affected by tiny variations in hand trajectory and gaze location. It seems as though this minimum half a second is necessary to compute grasp dynamics and other required information in advance to the initiation of a successful interaction. Of course, in most movements, there is a tradeoff present between speed and accuracy. The faster we move, the less accurate our movements are and the greater our risk of making a mistake. Perhaps this half second minimum advanced fixation provides the necessary confidence that the task will be completed successfully within a certain reasonable period of time. In the context of the current study what this highlights is that the mechanisms of visual feedback control to guide a hand toward an object do not appear to be impacted by its "virtuality", suggesting, as others have through neuroimaging (Cavina-Pratesi et al., 2018; Culham et al., 2003), that reach and grasp planning are somewhat dissociable.

As expected, there were differences between the VR and real-world conditions. First, participants in controller-mediated VR took nearly twice as long to complete each trial than their real-world counterparts with a disproportionate amount of time in the Release phase of each object movement. VR participants spent more relative time visually fixating their hand and the pasta box in their hand during the Transport phase and less relative time fixating on the upcoming drop-off target compared to real-world participants. As well, VR participants spent less relative time fixating on the box during the Reach phase than real-world participants, which can be accounted for by the 'just-in-time' phenomenon described above. Finally, we found that in VR, participants held longer fixations on the box while initiating its pick-up before shifting their gaze to the drop-off target compared to real-world participants. And, while dropping off the box in VR, participants fixated on their virtual hand for nearly half a second after the box had been successfully placed on the target, while in the real world, participants ended that fixation almost immediately after the object was successfully placed.

The way VR participants differ from real-world participants in some ways follows the pattern we have previously observed for prosthesis-users (Hebert et al., 2019; Marasco et al., 2021). In short, commercial prosthetic limbs do not provide detailed haptic information to the user, except for slight vibrations that may make their way through the end effector to the residual limb, or high-end devices that provide tactile stimulation to the skin of the residual limb or nerve stimulation, neither of which are widespread (Hebert et al., 2019; Marasco et al., 2021). VR participants move slower than their real-world counterparts, just like prosthesis-users. They spend more time fixating on their own limb while transporting an object, like prosthesis-users. And, when they are starting to move an object (e.g. the end of the "pick-up" interaction) or moving their hand away from an object (e.g. the end of the "drop-off" interaction), VR participants fixate on their hand to ensure the box is doing what they want it to. A lack of haptic feedback means participants don't feel the box as they interact with it. They don't experience the weight of the box as it is lifted up, whether it's gripped tightly or slipping, if it's rotating in their grasp, and if the load is lightened as they go to put it down. As a result, we speculate that both VR and prosthesis-users compensate at these key moments by extending visual fixation.

In contrast to what we predicted, participants in VR do not behave like prosthesis-users when initiating a grasping movement. Specifically, in our study, we see limited evidence for a prolonged Grasp phase in VR while in prosthesis-users the Grasp phase is significantly lengthened. Again, this highlights an important way that a more simplistic expectation of difference between the real and virtual worlds fails to account for the observed results. Upon reflection, in the VR condition the vibration of the controller provided an additional haptic feedback cue indicating it was in a position to initiate a grasp and no extra visual attention was required. The feedback vibration likely increased VR participants' confidence in initiating a successful grasp and the simplicity of pulling the controller trigger meant that the time spent grasping was quite similar to participants in the real world. This stands in stark contrast to the complex grasp mechanisms that many prosthesis-users must control (Hebert et al., 2019; Marasco et al., 2021). Unlike in VR, where the vibrating controller guarantees a successful interaction will be initiated, prosthesis-users have no such shortcut to confidence and instead must rely on visual feedback through an elongated grasp fixation.

Taken together these results weave an intricate pattern of how gaze is distributed during object interactions that depends crucially on a participant's confidence that each phase of an interaction will be completed successfully. When one grabs an object a simple buzz on the hand which perfectly cues interaction success is enough for eye-hand coordination to proceed close to normally, even in the absence of more detailed haptic feedback. But, as one starts to move the object, or moves one's hand away from an object after putting it down, participants without haptic feedback appear to rely on extra time spent looking at the site of interaction to attain confidence of its successful completion. This supports the astute observation from Land and Hayhoe (2001) that, "Vision is a scarce and valuable resource, and it is disengaged from a particular aspect of an action as soon as another sense is available to take over". In a typical real-world interaction, that other sense is haptic and proprioceptive sensory information from the hand. In situations with reduced haptic feedback like controller-mediated VR or using a prosthesis, with no other sense "available to take over" vision is required to linger longer at the site of an interaction.

Theoretically, this also aligns with the Attentional Landscapes Theory of Visual Attention (Baldauf & Deubel, 2010) which explains the deployment of overt and covert attention across time and space. Previously, we explained eye-hand coordination in the real world using the Attentional Landscapes Theory (Lavoie et al., 2018). The shift of visual fixation from the current, overtly attended action site to the future covertly attended action site occurs fluidly and quite close to the onset and termination of object movement, as observed by *ELL Pick-up* and *ELL Release* being quite close to zero. Here, we propose that in controller-mediated VR, confidence is compromised at the current site of action and necessitates maintaining overt attention. This delay stalls the increase of covert attention at the next site of action, leading to an attentional landscape that is unable to shift fluidly resulting in the reported *ELL Pick-up* being nearly a full second longer, and *ELL Release* being nearly half a second longer than in the real world. The halting of the fluid flow of the attentional landscape likely contributes to the slow down in VR compared to the real world during object interactions. It's not in the participant's best interests to get the box to the drop-off target too quickly, as the eyes won't have visually fixated the drop-off target for long enough to compute the appropriate drop-off motor dynamics. Participants, therefore, slow down their movement, leaving enough time for successful drop-off computation.

While a lack of haptic feedback is likely the dominant explanation for the differences we observed, there are a number of other possible factors that could be contributing to the reported effects. First, VR participants have to wear a headset, while the real-world participants only had to wear a head-mounted eye tracker. Wearing a heavier headpiece may have caused VR users to move slower. The knock on effects of a head that cannot orient as quickly could also explain some of our results. Second, as mentioned earlier in this paper, it's been shown that VR objects are treated differently than real-world objects, which could have caused some of the differences we've found here. While we feel the consistency of the 500 ms advance look time when reaching runs counter to this idea, the overall slowness of movements in VR may in part be due to acting on virtual object proxies. Finally, in this experiment, VR users actually received a small vibration on their hand when they were able to initiate a grasp, meaning there was some haptic feedback. This highlights the need to truly explore a situation with full and fully-deprived haptic feedback to more conclusively isolate our results to that modality. For the above reasons and more, we plan to pursue further investigation that tests the precise changes that occur in visuomotor behaviour in VR when full haptic feedback is provided to users' hands during object interactions, compared to when no or minimal haptic feedback is provided.

3.6 - Conclusions

In some ways, these results show that participants in controller-mediated VR doing the same task behave quite similarly to those in the real world - they look at the same objects and locations in the same order and for about the same amount of relative time. Most strikingly, their eye gaze seems to follow the 'just-in-time' phenomenon seen in myriad contexts - the eyes arrive at the site of an interaction at least 500 ms before the interaction begins. But, despite these similarities, there are also important differences. Participants take nearly twice as long to complete the set of movements in controller-mediated VR than in the real world, especially when releasing an object after moving it. We speculate that this difference is mainly driven by a lack of haptic feedback. Deprived of haptics, VR participants become more reliant on vision to confirm that an interaction has been completed successfully. Thus, their eyes look more toward their hand as it moves an object and lingers at the site of interaction longer, putatively necessitating slower movements.

Taken together, this study shows that, although VR is a useful tool, its use for skill training is unlikely to be effective for visuomotor behaviours. Until accurate haptic feedback in VR is accomplished, we expect to see compensatory strategies, particularly invocation of greater visual attention during specific portions of object interactions, to make up for the lack of the rich, touch information that our hands so importantly provide. If the intention is to increase the performance of users' dexterous eye-hand behaviour in the real world, the lack of haptic feedback from most VR technology could do more harm than good as users learn a non-optimal compensatory strategy. This last point highlights the acute need to develop better and more standardized assessments of skilled motor performance in virtual and augmented realities. As new VR technologies are developed, including hand-tracking and haptic feedback devices, we suggest that eye-hand coordination metrics during object interactions - like those reported in this study - should be used as an important benchmark to see how close users of new devices are with respect to real world visuomotor behaviour.

3.7 - Acknowledgements

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4 - Virtually a little more real: Comparing eye-hand coordination in virtual reality with true haptic feedback and no haptic feedback[3]

4.1 - Abstract

Virtual reality (VR) technology has improved markedly in the last few years, with VR gloves capable of tracking, and even delivering haptic feedback to users' hands and fingers. But, it's not known how behaviour, specifically eye-hand coordination, differs in VR when haptic feedback is received from objects compared to when it's not. Going further, with many different haptic gloves on the market, each one differing in their delivery system, it's important to know just how different humans behave in VR when receiving full haptic feedback compared to no haptic feedback. Having previously compared eye-hand coordination in traditional, controller-mediated VR to the exact same task in the real world (Chapter 3), we fitted participants with VR tracking gloves and had them perform the same task. In two conditions, participants saw the same visualization of virtual limbs, and received either no haptic feedback from an object (No Haptic), or full haptic feedback with the same weight, balance, texture, and tactile sensation as a real-world object (Haptic). We recorded eye and body movements and segmented participants' gaze data using the movement data. As well, after each condition, participants filled out an embodiment survey indicating their agreement with feelings of embodiment to the virtual limbs they saw. Interestingly, we found that in the Haptic condition, participants did the task faster, and spent less time visually fixating on their own hand while transporting the object. Moreover, in the Haptic condition, participants were able to disengage their eyes from the object immediately after their hand began a grasp and ended a release, while in the No Haptic condition, participants maintained visual fixation on the object for much longer after it was picked up or dropped off. The introduction of full haptic feedback pulls eye-hand coordination measures towards the real-world values for this task that have previously been published (Lavoie et al., 2018, Chapter 3). In addition, participants in the Haptic condition

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[3] *Chapter 4 of this thesis has not yet been published. A version of this chapter has been presented at the 2023 Canadian Association for Neuroscience Annual Meeting as Lavoie, E.B., Hebert, J.S., & Chapman, C.S. (2023). How real is virtual reality? Comparing eye-hand coordination between VR and real world object interactions.*

reported greater feelings of embodiment towards their virtual limbs compared to the No Haptic condition, with an exploratory linear correlation analysis showing a possible connection between eye-hand behaviour and feelings of embodiment. This dataset provides a behavioural gold standard for researchers and developers as VR haptic technology continues its development and answers the question, “How does full haptic feedback change behaviour in VR?”

4.2 - Introduction

Most people take for granted the miracle that is moving through and interacting with our dynamic world. The fact that one can, with very little thought, control fingers on a keyboard to type a sentence like this or move their eyes on a screen or paper to read it, is representative of one of the marvels of human behaviour. This capacity demands an intricate interplay of sensory feedback and motor control that we are typically aware of only when it fails. For example, if one reaches out to pick up a cup of coffee they expect to see their hand as it approaches the mug and feel its smooth warmth as they grasp it. But, what happens in situations where this predicted feedback *is not* received? We argue that the mug-grasping agent would likely feel disembodied from their movement *and* that there would be changes in their gaze and movement behaviour. This argument is based on the fact that there are at least two domains where this exact situation occurs - virtual reality (VR) and upper-limb prosthetic users, and in both, embodiment and haptic feedback are identified as key impediments to widespread adoption.

Virtual reality (VR) is on the precipice of taking the world by storm. Astronauts and fighter pilots have used VR training for many years now (Homan & Gott, 1996; McCarty et al., 1994), but more recently we’ve seen VR applications for surgical (Syamlan et al., 2022), firefighter (Clifford et al., 2019; Narciso et al., 2020; Wheeler et al., 2021), and crane-operator training (Pooladvand et al., 2021), as well as rehabilitation platforms for those experiencing movement differences (Laver et al., 2017; Rodríguez-Mansilla et al., 2023). VR has come a long way since its inception in the 1980s, but as alluded to, realistic haptic feedback (Harris et al., 2019) and embodiment (Kilteni et al., 2012) are two major bottlenecks that plague widespread adoption. Interestingly, a lack of haptic feedback and a decreased sense of embodiment are also thought to stand in the way of increases in the quality of life of prosthesis-users (Bates et al., 2020; Cheng et al., 2023; Zbinden et al., 2022; Zopf et al., 2018). This problem, although well-documented, is a difficult one to solve because it’s multi-faceted. One major component being that it is not trivial to know *what* to measure when looking for the impacts of changes to embodiment nor is it obvious how one would manipulate haptic feedback reliably - after all, while you can manipulate visual feedback by turning off the lights or shutting your eyes, there is no simple equivalent for the sense of touch. Here we show a path forward. In the current study, we measure participants' feelings of embodiment and key components of eye-hand coordination during a well-established object interaction task (Boser et al., 2018; Hebert et al., 2019; Lavoie et al., 2018; Lavoie & Chapman, 2021; Valevicius et al., 2018, 2019). Moreover, we leverage the cutting-edge in virtual reality technology to deliver and deprive users of full haptic feedback. The result is a new benchmark to assess the confluence of feedback and embodiment.

We can turn to our two exemplary domains for evidence of what will happen to visuomotor behaviours when haptic feedback is deprived during object interactions. Previous work in a population of prosthesis users with limited haptic feedback has shown that they take much longer to complete each object movement, spend much more time visually fixating their prosthesis while grasping, transporting, and releasing objects, and in turn, less time fixating on future areas of interaction, compared to normative populations (Hebert et al., 2019). In addition, prosthesis-users necessarily have to maintain visual fixation on an object much longer after they've picked it up and dropped it off, as vision must account for the lack of detailed haptic information (Hebert et al., 2019). This parallels what we've shown in virtual reality. Replicating the same task that we've used previously in the real-world (Lavoie et al., 2018) and that was used in the prosthetic work just described (Hebert et al., 2019) we found that, during controller-mediated VR object interactions, participants took much longer to complete each trial, visually fixated their own virtual hand or the object in their hand much more than their real-world counterparts, and were greatly delayed in disengaging their visual fixation from the object when picking it up or dropping it off (Chapter 3). Taken together, these results confirm that an object interaction task is the right tool for examining the effects of haptic feedback and highlight that the specific dynamics of how the eye can, *or cannot*, lead the hand during the start and end of the interaction is the most sensitive benchmark for assessing natural visuomotor skills.

But, this leaves two outstanding questions: first, how do these changes in haptic feedback and eye-hand coordination impact a person's experience of embodiment and second, what evidence do we have for what will happen to eye-hand coordination if we return haptic feedback? For both these questions, we can turn to a recent study where, through a combination of reinnervation surgeries and technological ingenuity, researchers were able to provide intuitive motor control to prosthesis-users along with tactile and proprioceptive feedback from the prosthesis to signal touch and movement (Marasco et al., 2021). That is, when participants initiated an action to grasp a box, for example, their prosthesis moved in the intended manner, and provided proprioception that their hand was moving along with tactile information when the fingertips of the prosthesis touched an object (Marasco et al., 2021). When participants carried out a cup transfer task, previously validated with able-bodied and prosthesis-using populations (Hebert et al., 2019; Lavoie et al., 2018), their eye-hand coordination patterns shifted such that, during those crucial moments around the start and end of an object-interaction, they spent less time visually fixating on their own prosthesis, and more time fixating on future areas of interaction (like the location the cup would be dropped off, (Marasco et al., 2021). Moreover, prosthesis-users who experienced these added sensory feedback streams reported an increased sense of ownership to their prosthesis (Marasco et al., 2021). That is, the combination of visual, haptic, and proprioceptive sensory streams, along with quick-response motor intentional control, provided congruent information to the user leading to an increase in their feelings of embodiment towards their prosthesis. This is consistent with our own previous work showing that more authentic visual feedback in VR also elicits higher self-reported experiences of embodiment (Lavoie & Chapman, 2021).

These findings allow us to make a strong prediction for the current study and a provocative speculation about the relationship between feedback and embodiment. We predict that when we deprive participants in VR of haptic feedback their eyes will linger longer at the site of an object interaction in the key moment when they would typically receive a sense of touch. Conversely, when we return haptic feedback, the eyes will be liberated in these key moments to proactively scan the environment for the next movement target. Furthermore, we predict that the liberation of the eyes with haptic feedback will be commensurate with an increase in a participant's experience of embodiment. This intriguingly allows us to present the idea that haptics and embodiment - the two elephants in the room standing in the way of spectacularly immersive VR experiences and prosthetics that lead to better quality of life - are actually just one elephant. We experience embodiment because all the sensory information we receive is synchronized to create one unified experience of being. Without this continuous, expected, synchronization of datastreams, it would be impossible to know that the object moving in front of me is, in fact, my own hand, and not just another object in the world. Over a hundred years ago, William James profoundly wrote that, "Where the body is is 'here'; when the body acts is 'now'; what the body touches is 'this'; all other things are 'theres' and 'thens' and 'thats'" (James, 1905). Our minds experience certainty of what is part of our body because of the consistent timing and organization to incoming sensory information. When the incoming sensory streams don't line up or one completely ceases to exist, we lose the unified experience of embodiment, and have to change our behaviour in order to function. In a dynamic world where we move, see, and touch objects, it's the only way we can know, for certain, what is part of us, and not part of us. It’s how I know my body is ‘here’ and ‘now’ and ‘this’, and everything else is ‘there’ and ‘then’ and ‘that’.

The current study employs the latest in VR hand and eye tracking technology to manipulate haptic feedback and measure its visuomotor impact in a way that, to our knowledge, has not been done before. In both the “Haptic” and “No Haptic” conditions, participants wore a VR headset and used their own arms, hands, and fingers to control the spatial location and grasping position of a set of dynamic virtual arms by way of a pair of VR tracking gloves. In both conditions, participants were tasked with moving a virtual pasta box into and out of a set of shelves which exactly replicated the real-world lab environment they were in. To provide haptic feedback, we painstakingly paired a real-world pasta box to the same spatial location as the virtual pasta box, so that participants saw a virtual pasta box, but felt a real one when grasping it. To deprive participants of haptic feedback we simply removed the real-world pasta box. So, participants saw the identical virtual pasta box, but felt absolutely nothing when their hand arrived at the box’s location. That is, in one condition, participants fully experienced the shape, texture, weight, and load on their hands of the virtual pasta box they interacted with, while in the other condition, they saw the same pasta box, and interacted with it in the same way with their hands, but experienced none of the haptic inputs.

As described above, we make the theoretically motivated prediction that depriving a participant of haptic feedback will cause their eyes to linger at the site of interaction longer and decrease their experience of embodiment. Conversely, returning haptic feedback will liberate their eyes and increase their experience of embodiment. To test our hypothesis that these two seemingly disparate obstacles - embodiment and feedback - are really two aspects of the same problem, we will also conduct a correlation analysis, comparing the changes in feelings of embodiment with the changes in visuomotor behaviors with and without haptic feedback. While exploratory and non-causal, showing that these two phenomena move together is a step toward tackling a single, albeit large, elephant.

4.3 - Methods

The object interaction task used in this dataset was originally used to study eye-hand coordination in the real world (Lavoie et al., 2018), and has previously been translated into VR using hand-held controllers (Lavoie et al., 2021, Chapter 3). The version of the task used here had participants visualize a completely virtual environment through a VR headset, while they interacted with objects with their hands. In other words, this was a virtual task performed with participants' own hands around a real, physical apparatus allowing the real world to provide appropriate haptic feedback to the participant. The task performed here is known as the Pasta Box Task, where a box of pasta is moved with the participant’s right hand onto three different targets on a set of shelves at three different locations a total of twenty times. The experiment consisted of two counterbalanced sessions of at least 20 error-free repetitions of the object interaction task. Both sessions showed participants a virtual set of limbs with hands and fingers that moved with their real-world hands and fingers (see Figure 4.1). In the “Haptic” session, participants were able to feel a real-world pasta box with the appropriate weight, balance, and texture, while in the “No Haptic” session they received no haptic feedback from the virtual box. For full details of the task and apparatus we encourage readers to seek out these previous publications.

4.3.1 Participants

40 self-reported right-handed undergraduate students received course credit, and provided informed consent to participate in this study. 34 participants (16 male, 18 female) with an average age of 20.9 years, average self-reported height of 171.1 ± 9.31 cm, and average measured wrist-to-wrist wingspan of 135.8 ± 9.37 cm were included in this study, with 6 participants being dropped due to poor eye tracking data. 16 participants removed their glasses to don the VR headset, and the remaining 18 participants had normal or corrected to normal vision (contact lenses). Procedures were approved by the University of Alberta Health Research Ethics Board (Pro00085257).

4.3.2 Apparatus

Participants donned an HTC Vive Pro Eye head-mounted display (HMD, Vive; HTC and Valve, New Taipei City, Taiwan, and Bellevue, WA, USA, respectively). The HMD has two 3.5” OLED screens (1 per eye), each refreshing at 90Hz with a resolution of 1440 x 1600 pixels giving the user a field of view of 110°. Built-in eye tracking hardware collects gaze data at 120Hz with an accuracy of 0.5° - 1.1° (https://www.vive.com/ca/product/vive-pro-eye/specs/). We collected eye-tracking data at 90Hz, in synch with the refresh rate of the visual display in the HMD. Participants were immersed in a model of our lab space [built in Unity (Unity Technologies, San Francisco, CA) . The virtual task apparatus was built to the same measurements and appearance as the real-world task (Figure 4.1a) described above, consisting of a set of shelves with three placement targets and a pasta box (Figure 4.1b). This virtual task apparatus was aligned spatially with the real-world set of shelves used in the original real-world version of this task. Participants wore a pair of Manus Quantum Metagloves (Manus Meta, Eindhoven, The Netherlands) (https://www.manus-meta.com/products/quantum-metagloves) while what they saw was a set of dynamic limbs with accurate hand and finger tracking (Figure 4.1(a,c)). Each glove includes 5 finger trackers that were taped to participants' fingernails (visible on the thumb in Figure 4.1b and 4.1d), weighs 138 grams, and refreshes at 120 Hz. In addition, to track the location of participants' hands, each Manus glove had an attached Vive Tracker 3.0. As well, during the Haptic session, the pasta box was fitted with a Vive Tracker 3.0 (see Figure 4.1d). This box was matched for weight and balance by removing pasta, inserting a cardboard divider, and refilling with enough pasta to match the weight of an unmodified box with no tracker on it. The combination of tracked real-world hands, fingers, and objects aligned to their virtual counterparts allowed the real world to provide haptic feedback to participants who experienced the visual world virtually.

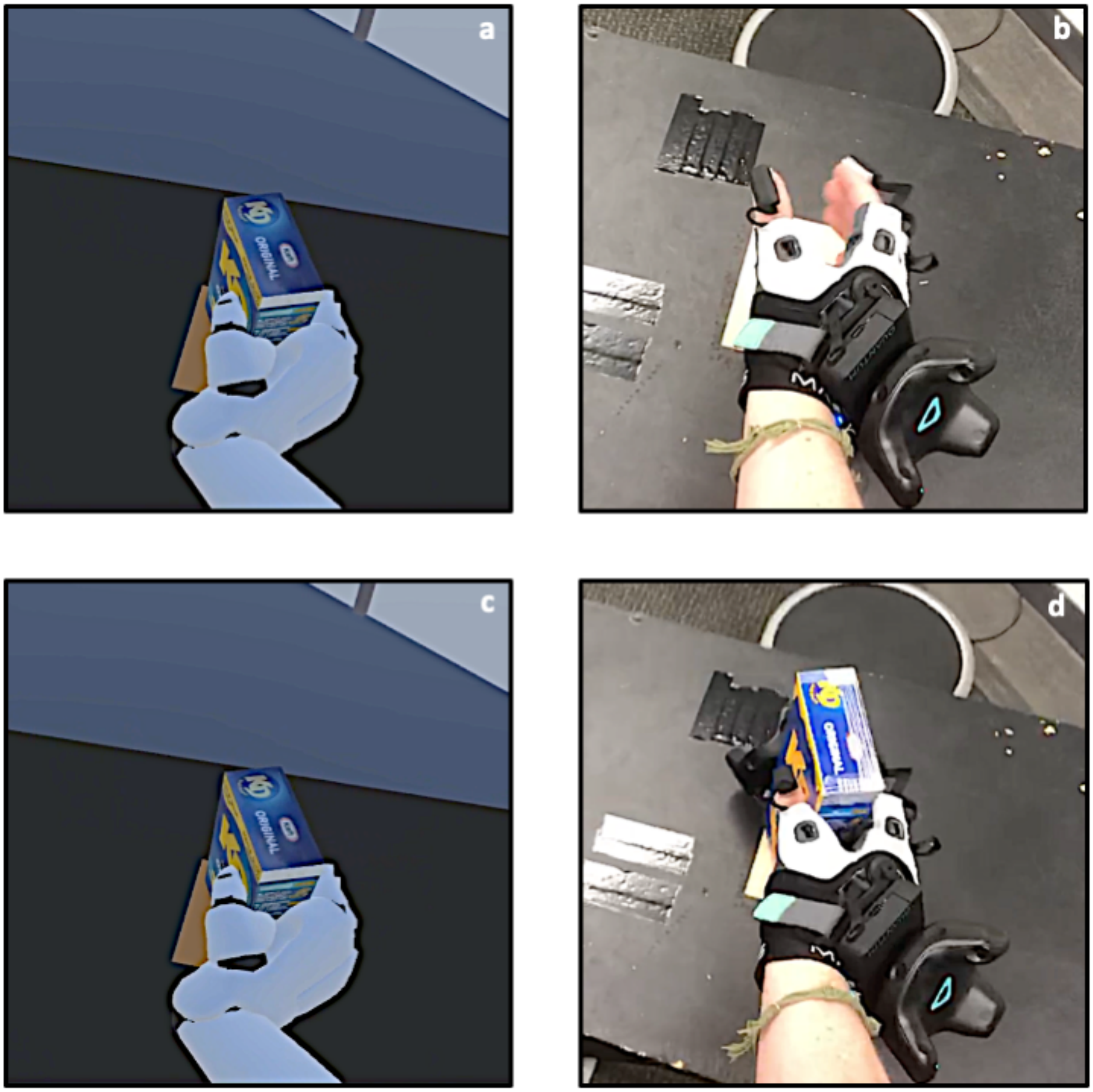

Figure 4.1: The virtual and real-world hands of participants in each of the two conditions during an interaction. In the No Haptic condition, participants saw a) virtual hands, and wore b) VR tracking gloves without a real pasta box. In the Haptic condition, participants saw c) virtual hands, and wore d) VR tracking gloves and felt a real pasta box.

4.3.3 Procedure

4.3.3.1 Setup

After providing consent for the experiment, participants provided their demographic data and had their wrist-to-wrist wingspan measured. This distance was used to customize the appearance of each participant's virtual avatar to ensure the virtual arms moved and appeared realistic once the participant donned the headset. Next, participants had the task explained to them using the real-world apparatus before being fitted with the HMD. The participant and experimenter worked together to find a comfortable fit before carrying out the Vive Pro Eye 5-point eye tracking calibration. This calibration checked to ensure the HMD was positioned properly, and the screens for each eye were the appropriate distance apart before instructing each participant to follow a blue ball as it moved into 5 locations in the field of view. As a validation of the calibration, each participant was then shown a virtual screen with grey circles that lit up blue when fixated. Rarely a circle did not light up blue when a participant fixated on it, and so the calibration was performed again. Next, participants donned the Manus Quantum Metagloves and had a tracker secured to the fingernail of each of their fingers with double-sided mounting tape. Each participant carried out a calibration of each glove (provided by Manus) that resizes the virtual fingers and hands to the appropriate size based on their hand and finger positions and locations.

For the Haptic condition, we ensured the highest degree of accordance possible such that when participants saw their virtual hand touch the virtual pasta box, they felt their real hand touch the real-world pasta box. To do so, we had each participant grasp the real-world pasta box with their right hand, and the experimenter shifted the spatial location of the virtual pasta box so that the virtual hand and fingers were positioned in a grasping position around the virtual box as closely as possible to each participant's real-world grasp. Experimenters used the position of the tip of the thumb on the real-world pasta box as the location to place the virtual thumb on the virtual pasta box without any space between the virtual box and virtual thumb, thus aligning their real and virtual grasping hands as closely as possible.

For the No Haptic condition, to account for the differences in hand and finger size and shape between participants, we needed to find a grasping mechanism that worked for each participant. The grasping mechanism required the pasta box to be within a 5 cm radius from the centre of the space created between the fingers and the thumb during a lumbrical grip. To trigger a grasp, we set a minimum grip aperture between the thumb and index finger for each participant. When the box was within the 5 cm radius and the grip aperture decreased below the set point, the box began to track with the movements of the virtual hand. When the grip aperture increased past the set point, the box stopped tracking with the virtual hand. For this condition, once the HMD was donned but before data collection trials began, the experimenter worked with each participant to modify the thumb-index finger minimum grip aperture that would initiate and terminate an interaction of the virtual pasta box. The experimenter had the participant carry out several practice object movements and used their feedback to set the minimum grip aperture setting. Once a setting was found that participants felt comfortable with, the collection trials began.

4.3.3.2 Task

Participants performed the object-movement task with their right hand. The task was designed to assess the coordination of gaze and movement during an everyday object interaction. Each trial was initiated with an auditory cue (500ms beep) and consisted of three sequential object interactions. First, participants moved the pasta box from the Start/End Target on a table on their right side onto the Mid Shelf Target in front of them (Figure 4.2(a)). Then, participants moved the pasta box from the Mid Shelf Target to the High Shelf Target by crossing the body's midline (Figure 4.2(b)). Finally, the pasta box was picked up from the High Shelf Target and placed back on the Start/End Target (Figure 4.2(c)). At the start and end of each trial and after each pasta box placement, participants touched the Home cube (pink rectangle in Figure 4.2(a,b,c)), and were instructed to visually fixate on a small grey sphere (Neutral position) before each trial began and after each trial was completed. In previous versions of this task, the Home position was flat to the level of the cart, while in this version of the task, it was elevated to aid in the visual alignment of the virtual and real-world hands to the apparatus.

Participants were instructed to move at a comfortable pace and interact with the pasta box on its long edge. There were colored targets indicating where the pasta box should be placed for each movement, and participants were instructed to place the box on the short edge within the boundaries of each placement target. Additionally, participants were to avoid dropping the pasta box, contacting the apparatus, hesitating, or making undesired movements (like scratching one's leg). If a rule was violated, participants were told to complete the trial to the best of their ability and an extra trial was added at the end of that group of trials. In the Haptic condition, participants carried out an average of 21.1 ± 1.33 trials with 19.8 ± 0.63 included in analysis, while in the No Haptic condition they carried out 23.0 ± 2.54 trials with an average of 20.0 ± 0.0 being included for analysis.

Once 20 error-free trials were collected, participants were instructed to remove the HMD to complete an Embodiment Survey consisting of 13 statements on a computer tablet (see Table 1, Longo et al., 2008). Participants were instructed to read the statements and rank their agreement with each one on a 7-point scale from Strongly Disagree to Strongly Agree. Before donning the HMD for the second condition, participants were offered to take a few minutes break if they so desired. Upon completing the second condition, participants completed another

Embodiment Survey at which point the experiment was complete and all equipment was removed.

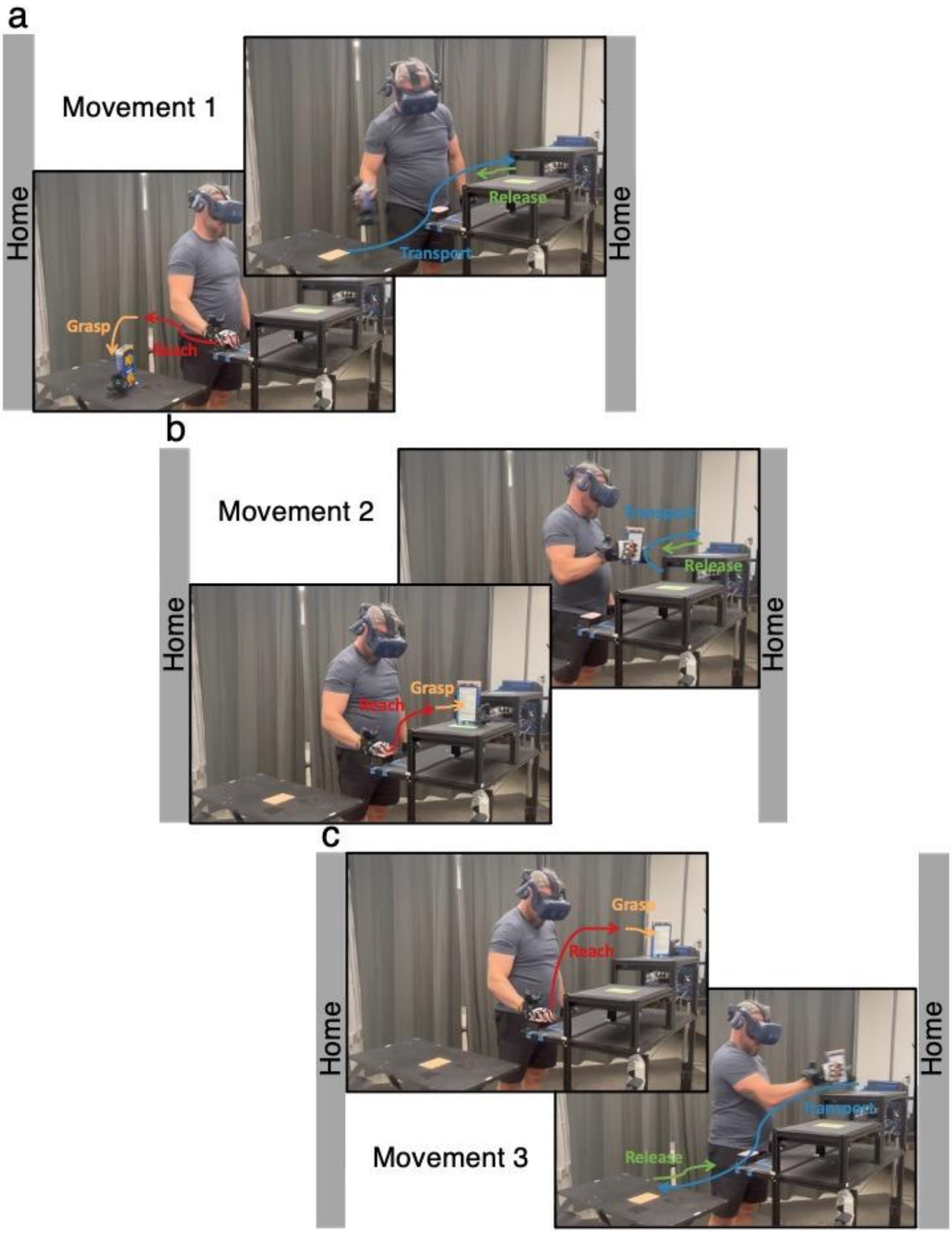

Figure 4.2: Participants wore a VR HMD and tracking gloves while doing the Pasta Box Task which includes the Reach, Grasp, Transport, and Release of a pasta box at 3 target locations. a) Movement 1: Grasp from side cart (Start/End Target) and Release on Mid Shelf Target. b) Movement 2: Grasp from Mid Shelf Target and Release on High Shelf Target. c) Movement 3: Grasp on High Shelf Target and Release on Start/End Target.

4.3.4 Data processing

Using custom C# scripts the 3D position and rotation of each Manus Quantum Metaglove, the HMD, pasta box, placement targets, and other relevant objects as well as the 3D position of the thumb and index finger, were recorded (90 Hz) on each trial. As well, the Vive Pro Eye gaze vectors for each eye and a combined vector were also recorded giving an estimate of the location each participant was looking at each frame of the experiment. Using a combination of hand and object velocities and positions each trial was segmented into its three object movements, with each object movement subsequently segmented into Reach (hand moving toward object), Grasp (hand starting the object interaction), Transport (hand moving object between locations), and Release (hand completing the object interaction and moving away) phases (see Lavoie et al., 2018 for full segmentation details and Figure 4.3 for sample segmentation). A fifth Home phase (when the hand was returning home after completing each movement) was also segmented from the data and used for the *Absolute Duration* analysis, but as it is task irrelevant will not be discussed. We then used the exact same segmentation procedure from the previous VR versions of this task (Chapter 3) to generate equivalent events and measures for each trial of each session of this dataset.

Because we are interested in overt fixations to areas relevant to object interactions, and since previous research has shown that participants rarely fixate on objects or areas irrelevant to the goal of a task (Hayhoe, 2000; Land, 2009; Land & Hayhoe, 2001; Lavoie et al., 2018; Tatler et al., 2011), we selected specific regions during each phase of movement for analysis. For this study, the areas of interest (AOIs) within each phase were defined as the current location being acted on by the hand (*Current*), and the hand itself or an object being moved by the hand when no other AOI is being fixated (*Hand in Flight*). A fixation to an AOI was said to occur when the distance between gaze vector and AOI was sufficiently small and the velocity from gaze vector to AOI was also sufficiently low. To account for blinks, any brief periods of missing data in each AOI fixation were filled in. Then, to avoid erroneous fixation detection (e.g., fly-throughs), any brief fixations were removed. Full details can be found in a previous publication (Lavoie et al., 2018).

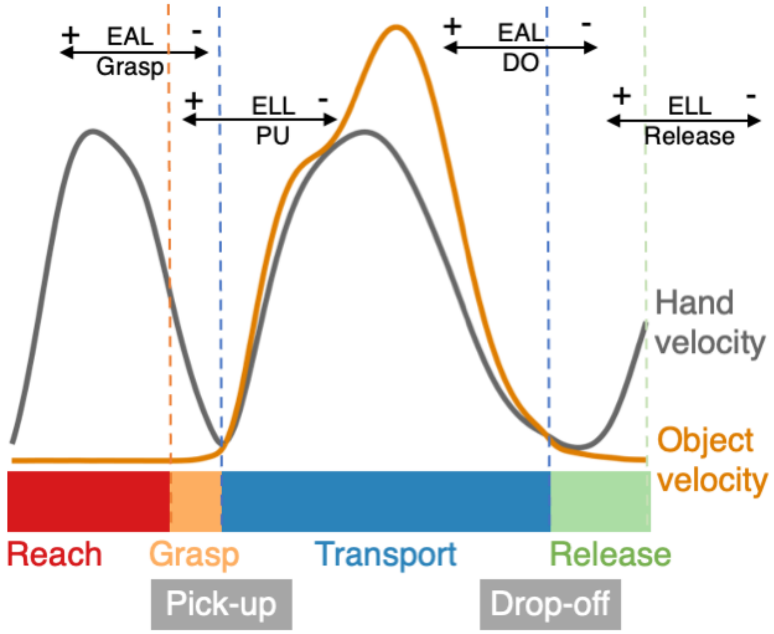

Figure 4.3: The segmentation of an object Movement into its Reach, Grasp, Transport, and Release phases is determined by the velocity of the object (orange trace), the velocity of the hand (grey trace), and distances to task relevant locations. Also shown are the approximate temporal locations defined by the terms Pick-up and Drop-off, and the Eye Arrival Latency (EAL) and Eye Leaving Latency (ELL) measures associated with each (adapted from Lavoie et al., 2018).

4.3.5 Dependent measures and predictions

The motivation of this study is to explore how eye-hand behaviour and feelings of embodiment change when there is or is not haptic feedback during an otherwise identical virtual object interaction. In this vein, we frame all predictions and results with respect to the question, “What does haptic feedback get you?”. The measures here are based on those from our previously published studies (Lavoie et al., 2018). To ensure consistency with our previous publication of this task, we maintain the same three statistical groupings (Families) to assess eye-hand coordination, and add a fourth group to assess participants’ feelings of embodiment. Family 1 includes the *Absolute Duration* and *Relative Duration* of each phase (Reach, Grasp, Transport, Release), and answers the question: “How long do people take?”. Family 2 includes the *Number of Fixations* and the *% Fixation Time* to the Current AOI in each phase and to the Hand in Flight AOI during the Reach and Transport phases, and answers the question: “Where do people look?”. For Family 3, we calculated the *Eye Arrival Latency* which measures when the gaze lands on a location around the time a Grasp begins and Transport ends (Drop-off), and also the *Eye Leaving Latency* which measures when the gaze leaves a location around the time when Transport starts (Pick-up) and when Release ends. These four latency measures were calculated for each object movement and answer the question: “When do people look?”. Family 4 is based on the 13 statement Embodiment Survey that each participant filled out upon completing each of the two data collection blocks, and answers the questions: “How do people feel?”.

4.3.5.1 Family 1: How long do people take?

- *Absolute Duration*
    - The time in seconds spent in each phase as determined by our segmentation.
    - The sum of the Absolute Durations of each phase equals the Total Movement Time for each of the three Movements
- *Relative Duration*
    - The percentage of time each phase contributes to the Total Movement Time determined by our segmentation.

In our previous study, controller-mediated VR participants took nearly twice as long to complete the task as their real-world counterparts, with increases in *Absolute Duration* in all phases of movement. However, there was a disproportionate increase in the Release phase in controller-mediated VR, and a disproportionate decrease in the Grasp phase. We predict that participants will move slower in the No Haptic condition yielding greater *Absolute Duration* values compared to the Haptic condition, but with disproportionately large values in the Grasp and Release phases, the moments when participants are initiating and terminating an object interaction with zero haptic feedback. As well, we expect the No Haptic condition to have larger *Relative Duration* values for Grasp and Release phases, and, as a result, smaller *Relative Duration* values for Reach and Transport phases. In brief, we expect a lack of haptic feedback will cause participants to move more similarly to the controller-mediated sample from our previous publication, and the return of haptic feedback will cause participants to move more similar to the normative population (Chapter 3).

4.3.5.2 Family 2: Where do people look?

- *Number of Fixations*
    - The number of distinct (separated by at least 100 ms) continuous (> 100 ms) fixations to an AOI in a given phase.
- *% Fixation Time*

    - The amount of time fixated on an AOI in a phase divided by the Absolute Duration of that phase, multiplied by 100.

Visual fixation patterns are expected to be considerably similar across the two conditions. That is, we predict participants will primarily direct their visual attention towards objects and areas that are directly involved in their ongoing or future interactions, while allocating minimal attention to objects and areas that are irrelevant to the task at hand (Hayhoe & Ballard, 2005; Land & Hayhoe, 2001; Lavoie et al., 2018). Our previous research revealed that controller-mediated VR participants dedicated much more *% Fixation Time to Hand in Flight*, and subsequently much less *% Fixation time to Current* (upcoming drop-off target) during the Transport phase, likely attributable to the absence of continuous haptic feedback, which necessitated the visualization of the object being grasped. Here, with a lack of haptic feedback, we anticipate an increase in fixations towards each participant's own hand and the object in their hand, accompanied by a decrease in fixations towards the upcoming drop-off target during the Transport phase. By returning haptic feedback to the participant, we expect a decrease in the fixation time to their own hand and an increase in the fixation time to the upcoming drop-off target during the Transport phase. In the same vein, we expect participants may increase their *Number of Fixations to Current* and to the *Hand in Flight* in the No Haptic condition to fixate back and forth on the object in their hand and the upcoming drop-off target, to be sure that the object is being successfully transported.

Finally, we think participants will have greatly reduced confidence in their ability to successfully start and end an object interaction during the No Haptic condition, due to its complete lack of haptic feedback. This will translate into increased *% Fixation Time to Current* during Grasp and Release during the No Haptic condition compared to the Haptic condition.

4.3.5.3 Family 3: When do people look?

See Figure 3 for a visual description.

- *Eye Arrival Latency at Grasp (EAL Grasp)*
    - EAL Grasp is defined as Grasp start time minus the time of eye arrival at the Grasp location.
- *Eye Leaving Latency at Pick-up (ELL PU)*
    - ELL PU is defined as Transport start time minus the time of the eye leaving the Pick-up location or object.
- *Eye Arrival Latency at Drop-off (EAL DO)*

    - EAL DO is defined as Transport end time minus the time of the eye arriving at the Drop-off location.
- *Eye Leaving Latency at Release (ELL Release)*
    - Eye Leaving Latency at Release is defined as Release end time minus the time of the eye leaving the Release location or object.

We hypothesize that disparities between the No Haptic and Haptic conditions will manifest in changes to the temporal dynamics of eye hand coordination. We expect participants will begin fixating on the pasta box at least half a second before their hand arrives to pick it up, leading to an *EAL Grasp* not significantly different between the two conditions. As well, we predict participants will begin fixating the drop-off target of the box for about the same amount of time prior to the box arriving in both conditions, yielding similar *EAL DO* measures. This 'just-in-time' phenomenon has been shown to be preserved in many studies and contexts (Ballard et al., 1995; Hayhoe & Ballard, 2005; Hebert et al., 2019; Land & Hayhoe, 2001; Lavoie et al., 2018; Ngo et al., 2022); Bertrand & Chapman, 2023; Chapter 3).

We expect the absence of haptic feedback will elicit prolonged fixations on the box during both pick-up and drop-off as a compensatory mechanism of ensuring a successful interaction. The return of haptic feedback will allow participants to behave with patterns closer to those found in the real world. Consequently, we predict the *ELL PU* and *ELL Release* values will be much larger in the No Haptic condition, because participants will need to use visual attention to ensure a successful object interaction has occurred. Again, these predictions are based on our previous study using hand-held controllers with limited haptic feedback, and upper-limb prosthesis user populations (Hebert et al., 2019; Marasco et al., 2021).

4.3.5.4 Family 4: How do people feel?

After each set of trials, participants ranked 13 statements on a scale from 1 to 7 (Strongly Disagree to Strongly Agree). 6 statements were Control statements where we expected 3 would be similar between the two conditions and 3 would be different. The remaining 7 statements were comprised of Ownership (2), Location (2), Agency (2), and Deafferentation (1) statements. These statements are listed in Table 1.

We included Control statements with expectations of being similar and different between the two conditions for added information about participants’ experience, as well as to check for technical problems or participant compliance. For instance, if participants in the No Haptic condition reported higher agreement with the statement “I could feel the edges of the objects with the virtual hand” than the Haptic condition, there would be grounds to assume that something was wrong with the experiment from a technical aspect or from a participant compliance aspect. From the experimental statements, we expected that participants would self-report higher values for the Ownership, Location, and Agency statements, as these are the three components that make up the feeling of Embodiment, while not self-reporting different values for the Deafferentation statement.

4.3.6 Overview of statistical analysis

With the large number of tests and the fact that we were only interested in differences between the two conditions, we used a modified procedure developed by Cramer and colleagues to correct for our large number of tests (Cramer et al., 2016). For the first three families listed above, we grouped the measures accordingly: Family 1 (How long do people take?), Family 2 (Where do people look?), and Family 3 (When do people look?), and listed the *p*-value (Greenhouse-Geisser corrected if available) of every repeated measures analysis of variance (RMANOVA) comparing the two conditions in descending order (most to least significant) within each Family. Using the formula: Adjusted α = [0.05] / [(# of tests) - (rank order - 1)], and selecting the tests whose calculated *p*-value were less than their Adjusted α, we had a conservative list of tests we would move forward with. Any Omnibus Repeated Measures ANOVA that showed significant interaction effects of Condition were followed up with a similar process in which each *p*-value from the post-hoc tests for this measure were listed in descending order. Using the same formula as above and the number of tests for this follow-up set, any significant main and interaction effects were found. From this, all possible pairwise comparisons of the relevant factors were conducted using a Bonferroni correction with a corrected $p < 0.05$ marking a significant effect. It should be repeated that only significant interactions or main effects of Condition were pursued as this study is focused on the differences between eye-hand behaviour in virtual reality with no haptic feedback and with full haptic feedback on the hands. Details about the effects of specific Movement and Phase effects of the task can be found in previous studies (Lavoie et al., 2018). For each participant in both conditions, each of the dependent measures was calculated for every trial, then averaged across trials.

For each of the 13 statements in Family 4 (How do people feel?), we ran a paired sample student t-test, and used an even more conservative formula (Bonferroni correction) to claim significance.

Below is a breakdown of the statistical analyses run within each Family of tests.

4.3.6.1 Family 1: How long do people take?

For both *Absolute Duration* and *Relative Duration*, we ran Condition (NH vs H) x Movement x Phase Repeated Measures ANOVAs, where there were 2 Conditions and 3 Movements. *Absolute Duration* and *Relative Duration* were split into 4 phases (Reach, Grasp, Transport, Release).

- Condition (NH vs H) x Movement x Phase Repeated Measures ANOVA
    - *Absolute Duration*: 2 Conditions, 3 Movements, 4 Phases
    - *Relative Duration*: 2 Conditions, 3 Movements, 4 Phases

Additionally, we tested whether there were learning effect differences between the two conditions by calculating the average *Total Movement Time* (sum of the *Absolute Duration* of all 5 phases, including Home) for the first 5 and last 5 trials for each participant in each condition. We ran a 2 x 2 Repeated Measures ANOVA of Trial Position (First 5 or Last 5) x Condition specifically searching for an Interaction Effect between Trial Position and Condition.

4.3.6.2 Family 2: Where do people look?

For both *Number of Fixations to Current*, *% Fixation Time to Current, Number of Fixations to Hand in Flight* and *% Fixation Time to Hand in Flight* we ran Condition (NH vs H) x Movement x Phase Repeated Measures ANOVAs. There were 2 Conditions, 3 Movements, and 4 Phases (Reach, Grasp, Transport, Release) for the measures to Current, while there were 2 Conditions, 3 Movements, and only 2 Phases (Reach, Transport) for the measures to the Hand in Flight. This reduction in phases during Grasp and Release is because the participant’s hand is at the pick-up or drop-off location and is indistinguishable from the target

- Condition (NH vs H) x Movement x Phase Repeated Measures ANOVA
    - *Number of Fixations to Current*: 2 Conditions, 3 Movements, 4 Phases
    - *% Fixation Time to Current*: 2 Conditions, 3 Movements, 4 Phases
    - *Number of Fixations to Hand in Flight*: 2 Conditions, 3 Movements, 2 Phases
    - *% Fixation Time to Hand in Flight*: 2 Conditions, 3 Movements, 2 Phases

4.3.6.3 Family 3: When do people look?

To compare the eye latency measures (*EAL Grasp*, *ELL PU*, *EAL DO*, *ELL Release*), we carried out a 2 x 3 Repeated Measures ANOVA of Condition (NH vs H) x Movement for each.

- Condition (NH vs H) x Movement Repeated Measures ANOVA
    - *EAL Grasp*: 2 Conditions, 3 Movements

- *ELL PU*: 2 Conditions, 3 Movements
- *EAL DO*: 2 Conditions, 3 Movements
- *ELL Release*: 2 Conditions, 3 Movements

4.3.6.4 Family 4: How do people feel?

To compare the self-reported Embodiment Survey between the two conditions we ran a paired samples t-test for each of the 13 statements with a Bonferroni correction yielding the following significance cut-off: Adjusted α = [0.05] / [# of tests] = [0.05] / [13] = 3.85×10^{-3}.

A critical component of this work is to show how measures of visuomotor performance change with participants' experiences of embodiment. Therefore, we ran a linear correlation analysis between the two most significant differences we found in the first three families, *% Fixation Time to Current* and *% Fixation Time to Hand in Flight* during Transport, against each of the significant experimental statements found in Family 4.

4.4 - Results

4.4.1 Family 1: How long does it take people to move?

4.4.1.1 Absolute duration shorter when haptic feedback present

The *Absolute Duration* of each phase of movement is greater in the No Haptic as compared to the Haptic condition. The most pronounced increase in *Absolute Duration* was found in the Grasp (NH = 0.63s, SD = 0.28s; H = 0.33s, SD = 0.12s; $p = 9.19 \times 10^{-7}$) and Release phases (NH = 1.04s, SD = 0.42s; H = 0.62s, SD = 0.22s; $p = 5.87 \times 10^{-10}$), with the Transport phase also increasing (NH = 1.89s, SD = 0.37s; H = 1.52s, SD = 0.37s; $p = 4.10 \times 10^{-10}$), and the least pronounced increase found in the Reach phase (NH = 0.99s, SD = 0.25s; H = 0.91s, SD = 0.29s; $p = 1.00 \times 10^{-3}$). See Figure 4.4(a).The only phase in which participants are not interacting with the pasta box is the Reach phase, and perhaps this explains why it is the only phase of movement that is not greatly extended in the No Haptic condition. This sheds some initial light on when during an interaction haptic feedback will most affect our object interactions.

As predicted, participants took much longer to complete the entire task in the No Haptic condition than in the Haptic condition (*Total Movement Time*: NH = 17.24s. SD = 3.32s; H = 13.26s. SD = 3.35s; $p = 1.04 \times 10^{-12}$). However, there was no evidence that this was driven by a differential learning effect as there was no significant interaction found between Trial Position and Condition when analyzing the first and last 5 trials separately (NH: First 5 = 18.25 s, SD = 3.52 s; Last 5 = 18.38 s, SD = 4.03 s; H: First 5 = 14.27 s, SD = 3.52 s; Last 5 = 13.63 s SD = 3.67 s).

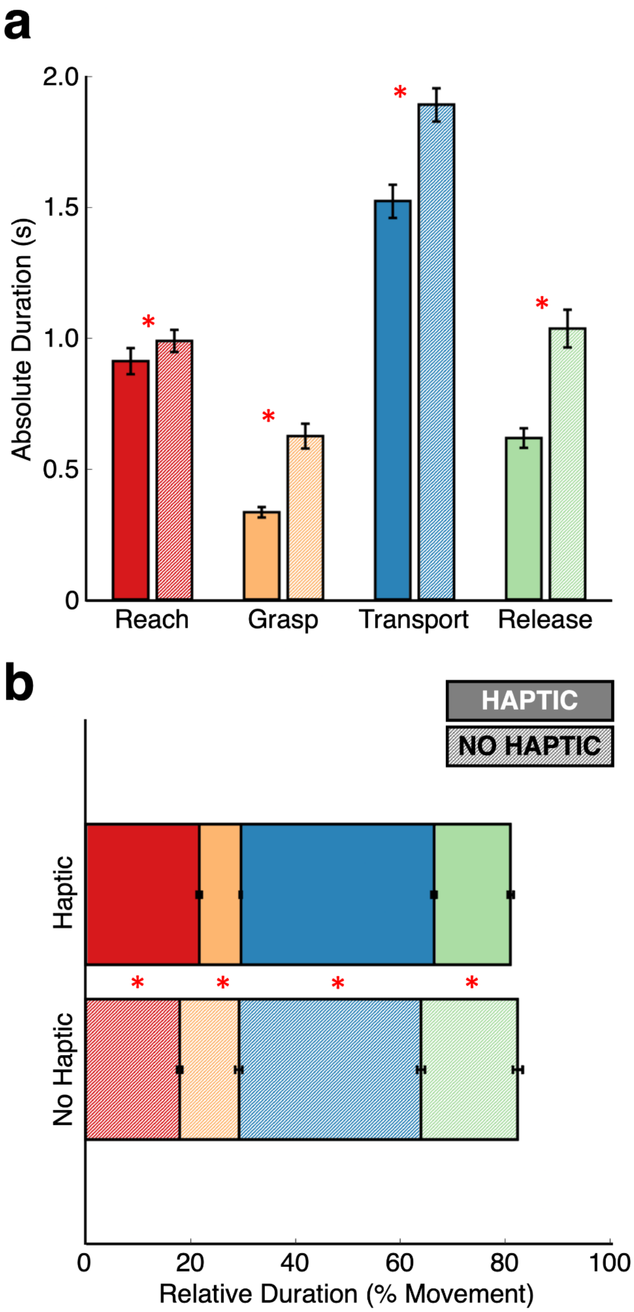

Figure 4.4: The average of all participants' a) *Absolute Duration* (s), and b) *Relative Duration* (%), of each phase of movement of the Pasta Box Task in the No Haptic (NH) and Haptic (H) conditions. Error bars represent standard error of the mean (SEM). In both a) and b) the Home phase is omitted as it is irrelevant to the object interaction.

4.4.1.2 Haptic feedback allows for much faster grasping and releasing

It must be reiterated that, overall, people move significantly slower in the No Haptic condition during all movement phases except for Reach. The results from *Relative Durations* suggest that the relative distribution of time over the course of an object interaction is still quite similar between conditions. Most relative time is spent Transporting the box in both conditions, with less time spent Reaching towards and Releasing the box, and even less time Grasping it. However, despite this general similarity the fact that the *Absolute Durations* during Reach and Transport were more similar while the *Absolute Durations* during Grasp and Release were less similar between conditions leads to commensurate differences in the *Relative Duration* measures, with subsequent effects to all phases of movement.

The *Relative Duration* measure is proportional, meaning that as one measure increases, another must decrease. Participants spend slightly more ($p = 8.68 \times 10^{-11}$) *Relative Duration* in the Reach phase in the Haptic (21.622%, SD = 2.93%) than in the No Haptic condition (17.88%, SD = 2.90%) and subsequently much less *Relative Duration* in the Grasp phase in the Haptic condition (NH = 11.29%, SD = 3.92%; H = 7.95%, SD = 1.17%; $p = 2.31 \times 10^{-5}$). *Relative Duration* is slightly lower ($p = 2.00 \times 10^{-3}$) in the Transport phase in No Haptic (34.75%, SD = 4.51%) compared to H (36.81%, SD = 2.95%) and higher ($p = 6.52 \times 10^{-6}$) in the Release phase in No Haptic (18.44%, SD = 5.31%) compared to H (14.65%, SD = 3.00%). The disparities between the Grasp and Release *Relative Durations* are the most pronounced. See Figure 4.4(b).

In summary, without haptic feedback, participants take more time to complete each phase of the task, with disproportionately greater time spent grasping and releasing the box than reaching and transporting it.

4.4.2 Family 2: Where do people look?

4.4.2.1 Visual fixation patterns during Grasp, Transport, and Release (but not Reach) affected by lack of haptic feedback

The visual fixation patterns found in both conditions followed the same characteristic trend we have found in all of our previous studies (Hebert et al., 2019; Lavoie et al., 2018), including controller-mediated VR (Chapter 3). When preparing to pick-up and move an object from one location to another, people almost universally fixate on the object for about half a second before their hand arrives at it. They then stay fixated on that object as they begin grasping it, ending the fixation and shifting their gaze towards the upcoming drop-off location once they’re confident the grasp will be successful. Their eyes then stay fixated on the drop-off location until their hand arrives with the object. Generally no fixations are made to areas or objects that are irrelevant to the task at hand.

When analyzing the differences in *% Fixation Time to Current* between the Haptic and No Haptic we found there to be no significant difference during the Reach phase (Reach to Box at pickup: NH = 76.60%, SD = 11.52%; H = 74.69%, SD = 11.95%). However, during the Transport phase of the Haptic condition, participants consistently spent a greater proportion of time fixating on the location they were about to drop the box off at (*% Fixation Time to Current*) compared to the No Haptic condition (Transport to drop-off location: NH = 57.86%, SD = 6.84%; H = 69.71%, SD = 8.51%; $p = 8.38 \times 10^{-13}$). This pattern was also evident in other parts of the movement where the, *% Fixation Time to Current* values were lower in the Haptic condition during both the Grasp (NH = 99.16%, SD = 2.55%; H = 93.25%, SD = 9.75%; $p = 1.21 \times 10^{-4}$) and Release (NH = 99.04%, SD = 3.21%; H = 95.81%, SD = 8.56%; $p = 1.00 \times 10^{-3}$) phases. See Figure 4.5(b).

Considering this pattern of *% Fixation Time to Current* in light of the *Absolute Duration* findings amplifies the differences between the two conditions. Not only are the *% Fixation Time to Current* values during Grasp and Release during the No Haptic condition larger than those in the Haptic condition (and get as close to 100% as one could possibly expect in a 34 participant sample), but also the Grasp and Release *Absolute Duration* values in the No Haptic condition are nearly twice as long as those in the Haptic condition. Participants’ eyes are glued to the hand as it grasps and releases the virtual pasta box when haptic feedback is absent, and this behaviour corrects when haptic feedback is returned.

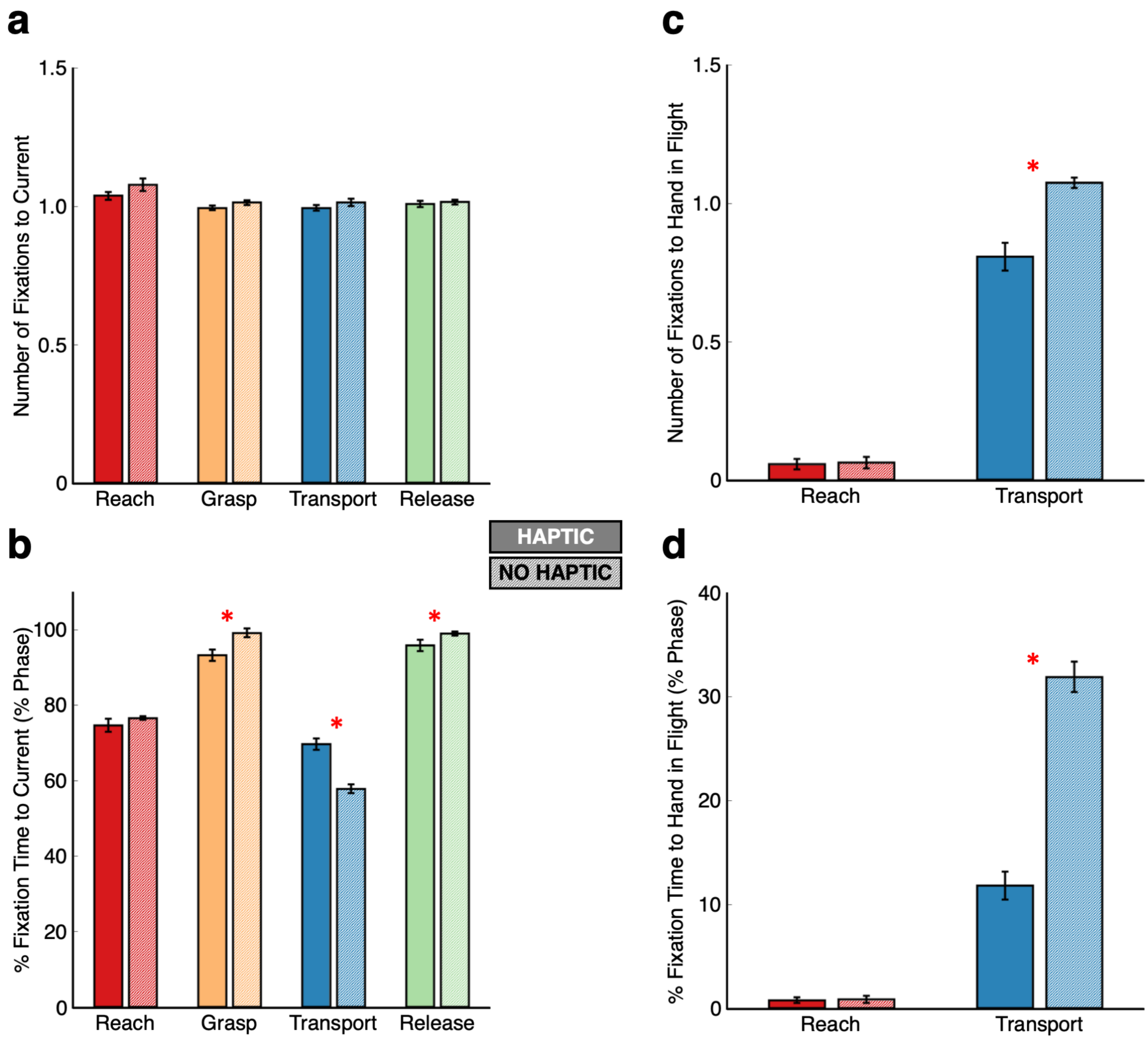

Figure 4.5: The average of all participants' a) *Number of Fixations to Current* (#), b) *% Fixation Time to Current* (%), c) *Number of Fixations to Hand in Flight* (#), and d) *% Fixation Time to Hand in Flight* (%) of each phase of movement of the Pasta Box Task in the No Haptic (NH) and Haptic (H) conditions. Error bars represent standard error of the mean (SEM).

4.4.2.2 Without haptic feedback, eyes fixate much more on hand in flight during Transport

Participants in the No Haptic condition looked more toward their own hand and the object in their hand while they were transporting an object compared to the Haptic condition. This occurred at the start of each Transport, which we interpret as participants using eye gaze in the No Haptic condition to ensure they'd initiated an object interaction successfully. The first evidence for this is an increase in the *Number of Fixations to the Hand in Flight* during the Transport phase (NH = 1.07, SD = 0.11; H = 0.81, SD = 0.29; $p = 5.29 \times 10^{-8}$). See Figure

4.5(c).Since this pattern was not seen in other movement phases (e.g. Reach) this is strong evidence that this difference is due to the level of haptic feedback participants received from the pasta box. This is also supported by the significant increase we found in the *Number of Fixations to Current* (Figure 4.5(a))in the No Haptic compared to Haptic condition. The most likely reason for this increase, and supporting another of our hypotheses, is that participants look back and forth between their hand and the drop-off location while transporting the object. The *% Fixation Time to the Hand in Flight* results follow a similar pattern. Participants spent much more (p = 2.33 x 10^{-14}) time fixating the Hand in Flight during the Transport phase in the No Haptic condition (31.89%, SD = 8.62%) than in the Haptic condition (11.82%, SD = 7.72%) while there were no statistical differences between condition for the other movement phase (Reach). See Figure 4.5(d).The importance of these *% Fixation Time to the Hand in Flight* results are amplified again when considering that the *Absolute Duration* values of the Transport phases in the No Haptic condition were longer than in the Haptic condition. Recall that participants in the No Haptic condition fixate significantly less relative time during Transport on the location they're transporting the object to compared to the Haptic Condition. This finding gains more clarity knowing that the reason for this is in part that participants are spending more relative time fixating on their own hand, or the object in their hand, during the No Haptic condition, and therefore less fixation time is dedicated to the drop-off location.

To summarize, without haptic feedback, participants fixate on the box or their own hand 100% of the time they are grasping and releasing. When haptic feedback is returned, not only does the time spent grasping and releasing shrink significantly, but participants spend less relative time fixating on the box or their own hand while this grasping and releasing is occurring. In addition, transporting the box without haptic feedback increases the number of fixations to the hand or the box in the hand, as well as to the drop-off location, likely due to back and forth fixations. In the same vein, the lack of haptic feedback causes participants to fixate much more on their own hand while it transports the box, and subsequently much less on the upcoming drop-off location. And finally, when haptic feedback is returned to participants, both the increase in fixation time on their own hand and the decrease in fixation time to the drop-off location reverse closer to the previous real-world values previously found (Lavoie et al., 2018; Chapter 3).

4.4.3 Family 3: When do people look?

4.4.3.1 In the absence of haptic feedback, visual fixation is glued to objects after pick-up and release

In chronological order, here we describe the similarities and differences between the 4 eye-hand latency measures in the two conditions. In other words, we explain these results in the order that they would occur as a participant fixes their gaze on the box before picking it up (*EAL Grasp*), moves their hand towards it, picks it up, shifts their gaze away from the pick-up location (*ELL PU*), fixates on the drop-off location (*EAL DO*), and then as they move the box to the drop-off location and finally shift their gaze away from the object being dropped off (*ELL Release*). The values discussed below can be visualized in Figure 4.6.

EAL Grasp measures the time the eye arrives at the object location prior to the start of an interaction. We see the pattern of at least 500 ms of advance looking time in both conditions along with a significant difference between the two (NH = 0.75s, SD = 0.18s; H = 0.65s, SD = 0.17s; $p = 2.50 \times 10^{-4}$). This is more evidence for the 'just-in-time' phenomenon found previously across a number of studies and testing environments (Ballard et al., 1995; Bertrand & Chapman, 2023; Hayhoe & Ballard, 2005; Hebert et al., 2019; Land & Hayhoe, 2001; Lavoie et al., 2018; Ngo et al., 2022). We hypothesize that the No Haptic condition was slightly greater than the Haptic condition because participants moved slower, leading to a longer period of time with the eyes fixated on the box before the hand arrived at it. Moreover, we note that the *EAL Grasp* values for both conditions here are slightly extended compared to the real world and controller-mediated VR results (Chapter 3). We hypothesize that this is the result of a slight change in the real-world apparatus, an elevation of the Home button into a cube shape. This Home button provided greater discriminatory haptic feedback than in all previous experiments, perhaps leading participants to not have to fixate on it to ensure their hand touched it. And thus, participants could maintain the fixation on the box after they dropped it off, touched the “Home” button without having to look at it, and then return their hand to the box to grasp it for the next interaction. This logic is supported by the fact that the first grasp for each condition is the only one that required participants to have their eyes fixated on a neutral target before initiating the grasp, and these values are much closer to the 500ms minimum (NH = 0.57s, SD = 0.12s; H = 0.52s, SD = 0.13s).

Moving forward, *ELL Pick-up* was significantly longer in the No Haptic compared to the Haptic condition (NH = -0.78s, SD = 0.34s; H = -0.30s, SD = 0.29s; $p = 1.77 \times 10^{-11}$), meaning participants stayed fixating on the object after they’d picked it up for nearly half a second longer when they did not have haptic feedback compared to when they did. This reinforces and refines our main point from the previous section. Not only does lack of haptic feedback cause participants to visually fixate more on the box during an interaction, but it also concentrates that increased visual fixation to the start of the interaction during the pick-up.

EAL Drop-off was not significantly different between the No Haptic and Haptic conditions (NH = 1.08s, SD = 0.22s; H = 1.04s, SD = 0.22s), except for at the final drop-off target (Movement 3: NH = 1.01s, SD = 0.21s; H = 0.83s, SD = 0.20s; $p = 1.93 \times 10^{-5}$). That is, participants visually fixated for a similar period of time in both conditions on the drop-off target before their hand arrived with the box to initiate the drop-off. We suspect that the difference found at the final drop-off target is the result of participants moving faster in the Haptic condition and is amplified enough to be significantly different here as this is the longest single movement in the task.

Finally, *ELL Release* in the No Haptic condition was longer than in the Haptic condition (NH = -0.59s, SD = 0.33s; H = -0.38s, SD = 0.27s; $p = 1.34 \times 10^{-6}$). In the Haptic condition, participants shifted their fixation away from the box much sooner after their hand finished releasing it, while in the No Haptic condition they stayed fixating on it for over half a second after the release was complete. We note that the *ELL Release* values in this study, like the *EAL Grasp* values, may be slightly impacted compared to previous iterations of the experiment as the Home button gave participants greater haptic feedback, likely decreasing their need to fixate it each time their hand was to touch it. This would increase the *ELL Release* values disproportionately in the Haptic condition for Movements 1 and 2, as participants could stay fixated on the box after they'd released it, as they would be interacting with the box immediately after touching the Home button. Movement 3 would not be affected as participants would be required to shift their gaze to the Neutral marker upon completing their final release. This is exactly what was found (H: Movement 1 = -0.49s, SD = 0.31s; Movement 2 = -0.51s, SD = 0.31s; Movement 3 = -0.13s, SD = 0.22s; $p = 6.96 \times 10^{-10}$) indicating that the haptic feedback provided by the pasta box allows participants to shift their gaze away from objects much sooner after releasing them.

In brief, when initiating a pick-up of the box, lack of haptic feedback necessitates participants' use of prolonged visual fixation as the transport begins. Similarly, when releasing the box without haptic feedback, participants' eyes lingered much longer on the box after their hand disengaged it. Once haptic feedback was returned, both of these prolonged fixations minimized, gravitating back towards values found previously in the real world (Lavoie et al., 2018, Chapter 3).

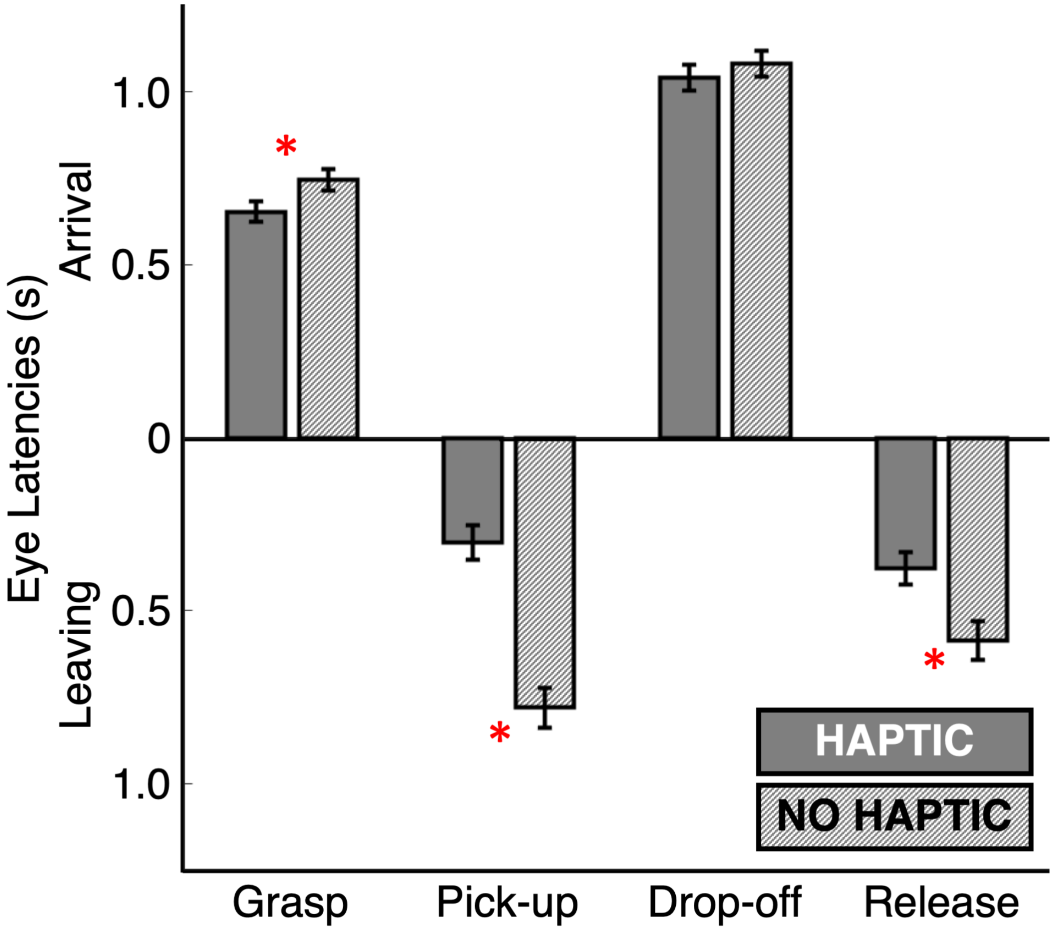

Figure 4.6: The average of all participants' *EAL Grasp* (s), *ELL PU* (s), *EAL DO* (s), and *ELL Release* (s) of the Pasta Box Task in the No Haptic (NH), and Haptic (H) conditions. Error bars represent standard error of the mean (SEM).

4.4.4 Family 4: How do people feel?

4.4.4.1 Haptic feedback increases feelings of Embodiment in VR

The second major motivation of this study is to explore how haptic feedback affects participants' feelings of embodiment. Although unsurprising, our findings add to previous literature that providing accurate touch feedback in VR increases feelings of embodiment to virtual limbs. Of the 13 total statements, 6 statements were Control statements where we expected 3 to be similar between the two conditions and three to be different. The remaining 7 statements were experimental, assessing for feelings of Ownership (2), Location (2), Agency (2), and Deafferentation (1). Reiterating from the Methods section, we ran a paired samples student t-test on each statement between the two conditions and used a Bonferroni correction to determine the significance cut-off to be 3.85×10^{-3}.

Statement	Category	No Haptic	Haptic	p-value
I found the experience enjoyable.	Control, similar	5.71, SD = 1.22	6.00, SD = 1.04	7.70×10^{-2}
I felt the touch somewhere between my hand and the virtual hand.	Control, similar	3.91, SD = 1.85	5.18, SD = 1.70	6.00×10^{-3}
There was very little lag between when I initiated a movement and when it began.	Control, similar	4,41, SD = 1.52	5.21, SD = 1.90	5.50×10^{-2}
It felt natural to pick up the pasta box.	Control, different	3.97, SD = 1.73	6.03, SD = 1.17	1.49×10^{-7} *
This task was no more difficult than it would be outside of virtual reality.	Control, different	3.47, SD = 2.00	5.56, SD = 1.81	1.22×10^{-7} *
I could feel the edges of the objects with the virtual hand.	Control, different	2.74, SD = 1.58	4.85, SD = 1.65	1.67×10^{-7} *
The virtual hand began to feel like a part of my body.	Ownership	4.71, SD = 1.57	5.56, SD = 1.50	3.00×10^{-3} *
It seemed like the virtual hand was part of my body.	Ownership	4.41, SD = 1.56	5.44, SD = 1.42	7.87×10^{-4} *
It seemed like the virtual hand was moving with my real hand.	Location	5.12, SD = 1.47	6.12, SD = 1.27	2.00×10^{-3} *
It seemed like the virtual hand was in the location where my real hand should be.	Location	5.41, SD = 1.28	5.97, SD = 1.19	3.70×10^{-2}
It seemed like I was in control of the virtual hand.	Agency	5.74, SD = 1.11	6.41, SD = 1.16	8.00×10^{-3}
It seemed like the virtual hand did what I wanted it to do.	Agency	5.21, SD = 1.20	6.35, SD = 0.85	3.85×10^{-6} *
It seemed like I couldn’t really tell where my real hand was.	Deafferentation	3.56, SD = 1.81	3.03, SD = 1.92	3.70×10^{-2}

Table 4.1: The 13 statements in the Embodiment Survey that participants rated their agreement with on a scale from 1 (Strongly Disagree) to 7 (Strongly Agree) after each of the No Haptic and Haptic conditions. The second column indicates the role of each statement, with 6 being control statements (of which, 3 were expected to be the same between conditions, and 3 were expected to be different), 2 for each of Ownership, Location, and Agency, and 1 for Deafferentation.

The three Control statements that we expected to be similar between the two conditions were not found to be significantly different between them. “I found the experience enjoyable”, “I felt the touch somewhere between my hand and the virtual hand”, and “There was very little lag between when I initiated a movement and when it began” were not rated significantly different by participants between the two conditions. The three Control statements which we expected to be different between the two conditions were found to be significantly different in the direction we expected. “I could feel the edges of the objects with the virtual hand”, “This task was no more difficult than it would be outside of virtual reality”, and “It felt natural to pick up the pasta box” were rated significantly higher in agreement in the Haptic condition. Although Control statements, these do shed light on the experience that participants had while doing the experiment. The experiment seemed to be enjoyable in both conditions without much lag, and the lack of haptic feedback made object interactions feel more difficult and less natural.

Four experimental statements were found to be significantly different between the two conditions. Participants rated both Ownership statements greater in the Haptic condition: “It seemed like the virtual hand was part of my body”, and “The virtual hand began to feel like a part of my body”. The Location statement, “It seemed like the virtual hand was moving with my real hand” was rated significantly greater in the Haptic condition. Assessing participants’ Agency, “It seemed like the virtual hand did what I wanted it to do” was rated significantly greater by participants in the Haptic condition. The three experimental statements that did not meet the significance cut-off were “It seemed like the virtual hand was in the location where my real hand should be” (Location), “It seemed like I was in control of the virtual hand” (Agency), and “It seemed like I couldn’t really tell where my real hand was” (Deafferentation).

4.4.4.2 Feelings of embodiment correlate with eye-hand coordination during object movement

In our previous work, when we manipulated visual feedback during object interactions in VR, we found that participants’ self-reported feelings of embodiment correlated with their movement differences during the same task done with hand-held controllers (Lavoie & Chapman, 2021). As outlined in the introduction, here we predicted we would see the same correlations when manipulating haptic feedback. Based on our previous work and on the strength of effects reported for gaze behaviours in this study, we chose as indicators of how participants controlled their gaze while transporting the box the *% Fixation Time to Current* and *% Fixation Time to Hand in Flight* during the Transport phase. Theoretically these two measures are directly tied to how much time you must spend fixating on the site of interaction versus being able to look ahead. For these two measures, we subtracted each participant’s mean value in the

Haptic condition from their No Haptic condition value. Then, we did the same for the values that each participant assigned to the 4 experimental statements that were significantly different between the two conditions on the Embodiment Survey. Finally, we conducted a linear correlation analysis between the difference in values between the two conditions. We predicted that participants who were able to look more toward the upcoming target with the return of haptic feedback would also be those that reported a higher degree of embodiment.

Together then, we ran a total of 8 linear correlation analyses. To be conservative, we used a Bonferroni correction, yielding a significance cut-off of: Adjusted $\alpha = [\ 0.05\ ] / [\ \#\text{ of tests}\ ] = [\ 0.05\ ] / [\ 8\ ] = 6.25 \times 10^{-3}$. Four of the correlations achieved this conservative level of significance and all of them went in the predicted direction. Figure 4.7 depicts these four correlation analyses. Specifically, a correlation between *% Fixation Time to Current* during Transport was found for both Ownership statements, "The virtual hand began to feel like a part of my body" ($\boldsymbol{\rho} = 0.442$, $p = 4.00 \times 10^{-3}$), and "It seemed like the virtual hand was part of my body" ($\boldsymbol{\rho} = 0.433$, $p = 5.00 \times 10^{-3}$). Additionally, a significant correlation was found between the Agency statement, "It seemed like the virtual hand did what I wanted it to do" and both *% Fixation Time to Current* ($\boldsymbol{\rho} = 0.535$, $p = 5.55 \times 10^{-4}$) and *% Fixation Time to Hand in Flight* ($\boldsymbol{\rho} = -0.477$, $p = 2.00 \times 10^{-3}$) during Transport.

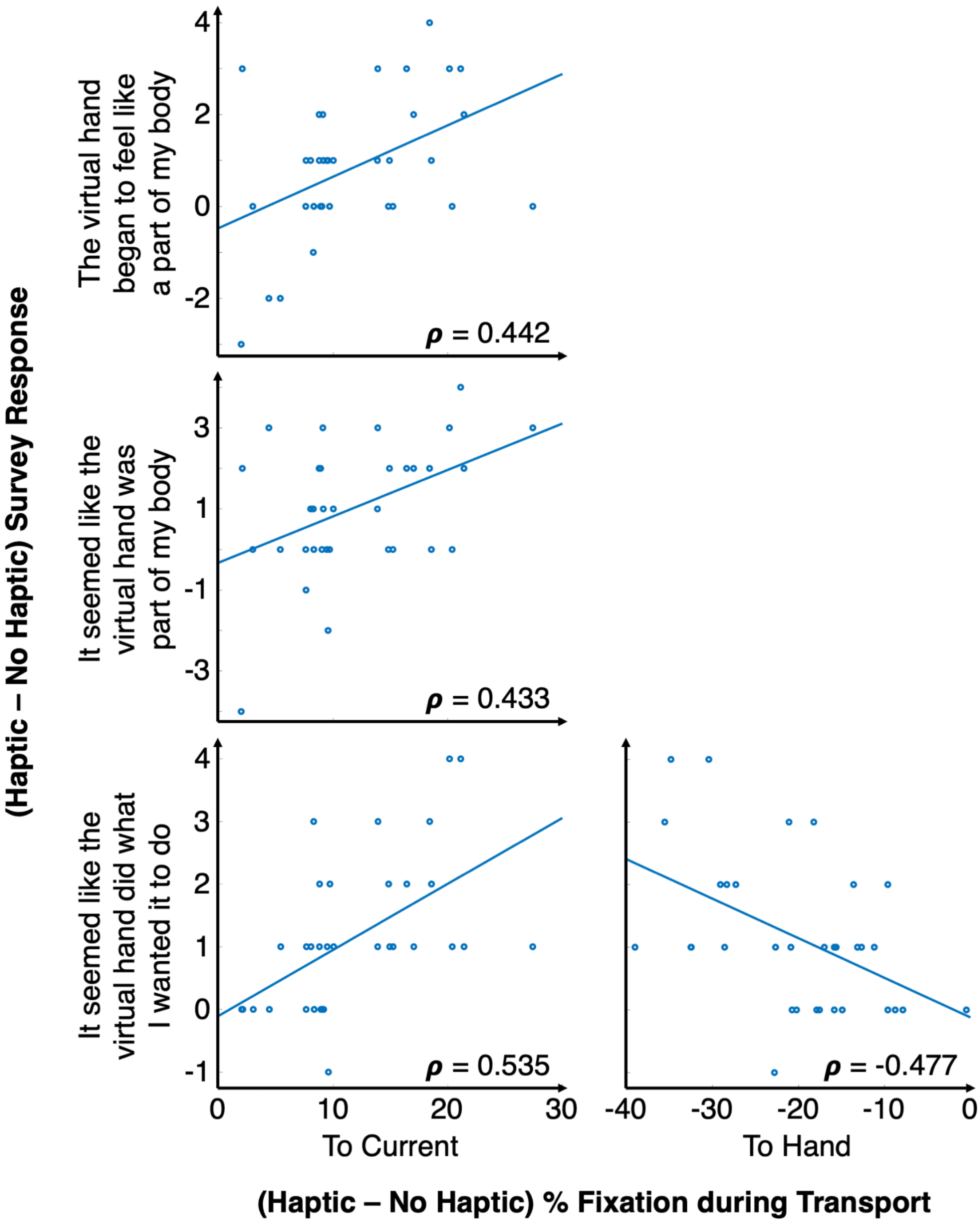

Figure 4.7: The correlational analyses showing that *% Fixation Time to Current* during Transport increases as three Embodiment statements increase and % *Fixation Time to Hand in Flight* during Transport decreases as one Embodiment statement increases, between the No Haptic and Haptic conditions.

4.5 - Discussion

Users and researchers of the two seemingly disparate domains of Virtual Reality and prosthetic limbs have arrived at the same conclusion: a lack of haptic feedback and a lack of embodiment of the device present major barriers to their adoption and utility. Testing for a link between these phenomena and examining what specific behaviours are impacted when you change haptic feedback and / or embodiment is notoriously difficult. After all, unlike vision, turning on and off a sense of touch is almost impossible, while altering a person's experience of their own body is equally challenging. Here, we overcome these challenges using advances in virtual reality motion and gaze tracking to overlay a virtual version of an object interaction task (Pasta Box Task, see Lavoie et al., 2018) onto its real-world counterpart while precisely measuring eye-hand coordination and recording participants' subjective experiences of embodiment. This allowed us to create two key conditions: a "Haptic" condition, where the virtual pasta box was coincident with a real-world pasta box such that a reach to grasp and move the virtual box gave full, authentic haptic feedback, and a "No Haptic" condition, where the real-world pasta box was absent, meaning a reach to grasp and move the virtual box yielded no sense of touch.

As predicted from previous work in both virtual reality (Lavoie & Chapman, 2021) and prosthetic limb users (Hebert et al., 2019; Marasco et al., 2021), when we deprived participants of haptic feedback they took much longer to complete the task, with disproportionately more time spent grasping and releasing the box. What's more, participants spent nearly all of this increased grasp and release time visually fixated on the pasta box. Impressively, in the "Haptic" condition when we put the real world box back in the scene participants not only decreased the time spent grasping and releasing, but also spent less of their time during grasps and releases fixated on the box. Returning haptic feedback returned key performance indicators of visuomotor confidence - rather than staying fixated on the site of interaction (both when picking up and dropping off the object) the eyes were free to look ahead to the next site of action, a hallmark of proactive planning. Importantly, these changes in visuomotor behaviour were commensurate with changes in the users' experiences of embodiment - in the "Haptic" condition participants reported greater senses of Ownership, Location and Agency.

These findings agree with one of the only other studies we are aware of that was also able to manipulate haptic feedback within the same individual while measuring their gaze and movement performance (Marasco et al., 2021). In that study, researchers demonstrated that returning haptic and proprioceptive feedback, along with intuitive motor control, to prosthesis-users, also shifted their gaze behaviour in the same direction we observe here - less time spent fixated on the site of interaction and more time spent looking ahead (Marasco et al., 2021), along with a decrease in stalled visual fixation during grasp and release (Hebert & Shehata, 2022). Again, in parallel to the current results, these changes in behaviour occurred alongside an increased sense of embodiment.

To further investigate the relationship between embodiment and visuomotor behaviours in the current dataset, we also conducted an exploratory analysis of the correlation between key parameters of gaze location and key expressions of embodiment in the survey. Put succinctly, we predicted that participants who reported larger changes in feelings of embodiment across the “Haptic” and “No Haptic” conditions would also show bigger changes in gaze distribution between these conditions. This is exactly what we found. Four of the eight correlations we tested survived conservative statistical correction and all of them showed the same result - an increasing sense of embodiment due to the return of haptic feedback was matched with an increase in the time spent looking ahead to the next site of action.

Taken together we believe the results from eye-hand coordination, experiences of embodiment, and their correlation allow us to draw two important conclusions from this study. First, visuomotor behaviours during object interaction should be held up as *the* benchmark behaviour to assess activities of daily living that center around motor control and visual and haptic feedback. Second, more provocatively, there is no divide between what researchers refer to as embodiment and the confluence of motor control and visual and haptic feedback. Tackling the first of these two claims, it is important to reiterate just how foundational and stereotyped eye-hand coordination is during object interactions. In short, our overt visual fixation can only be dedicated to one location at a time. During sequential, everyday object interactions, the eye leads the hand, preceding and predicting future manual actions (Land & Hayhoe, 2001; Lavoie et al., 2018). Gaze lands on an object to be picked up at least 500 ms before the hand arrives to grasp it. As long as we are going to act at another location, our gaze will then shift away from the grasp location coincident with when the hand arrives there. However, as soon as you alter the visual (Lavoie & Chapman, 2021) or haptic (current study) feedback a participant receives, this timeline is significantly and measurably disrupted.

This means we have a powerful new tool in our arsenal with which to test some of the most important theories in visuomotor neuroscience. For example, previous work has discussed how virtual objects are not treated in the same manner by the brain as real-world objects (Goodale & Milner, 1992; Harris et al., 2019; Snow & Culham, 2021). These researchers contend that our brains perceive interactable objects in the real world through the dorsal, vision-for-action pathway which is mostly imperceptible and used in real-time. Conversely, the ventral vision-for-perception pathway is more accessible to our awareness but less implicated in our actions. Extending this to VR, the authors have argued that virtual objects are just representations, or proxies, of real-world objects with many missing intricacies. This may cause human VR object interactions to be similar to pre-planned or delayed real-world object interactions, with an increase of the ventral, vision-for-perception pathway (Goodale et al., 1994). We argue that our results, and the use of detailed gaze and movement analysis during object interactions, will be key to testing this hypothesis. As an example, here we fully returned haptic feedback to participants in VR, yet they still moved substantially slower than our previous, real-world dataset (Lavoie et al., 2018), suggesting that indeed, there is still a gap between real-world interactions and those visually mediated through a headset.

An exciting extension of the utility of this class of tasks and measures is that, not only should it be used as a tool to test visuomotor theories and to measure the functional value of haptic feedback to prostheses and VR users, but it could also be an objective measurement of embodiment. That is, in two separate experiments we have shown that specific gaze and movement behaviors at the time of an object interaction predictably scale with individual participants' experiences of embodiment (Lavoie & Chapman, 2021). This ability to empirically quantify the elusive concept of embodiment is directly related to the second claim we want to make in this paper - that embodiment is *what it is to be* an agential actor in a world that receives predicted and synchronized sensory feedback.

To explain, one of the most popular models of motor control (e.g. the processes thought to govern things like eye-hand coordination) is optimal feedback control (Todorov & Jordan, 2002; Wolpert et al., 1995), which states that error values between actual and predicted movements are minimized to generate corrections in movement outcomes. This correction is calculated from outgoing motor signals and incoming sensory feedback (e.g. visual, haptic, proprioceptive). It’s been proposed that the feeling of agency (a core theoretical component of embodiment) is calculated in a similar way (Blakemore et al., 2000). The comparator model of agency states that our brains calculate an error value between actual sensory information and predicted sensory information (based on outgoing motor commands). When the prediction error value is zero, agency is said to occur (Blakemore et al., 2000). Finally, the sensorimotor contingencies model of VR embodiment states that our brains compare bottom-up sensory information and top-down cognitive information for embodiment to occur (Gonzalez-Franco & Lanier, 2017; Tsakiris, 2010). When a motor intention is made, it is copied and used to create predicted sensory outcomes of that motor intention. While this occurs, actual sensory information is returned, which is compared to the prediction. When the difference between the two is small, the greater the likelihood of accepting a VR embodiment illusion there is (Gonzalez-Franco & Lanier, 2017). Based on the results of the current study, we argue that all of these models are actually the same thing and are able to be read out from gaze and movement behaviours during object interactions. The moment that my hand makes contact with an object I want to interact with I am literally connected to that object through myriad sensory feedback signals. And in that moment, if those signals match those that my brain has evolved to predict, I will embody that movement and the natural control of gaze will move to the next site of action. But, if those signals are disrupted and run counter to expectation, then I will feel disembodied and my gaze will not be free to look ahead.

The potential impact of this work is wide-reaching. For example, with respect to VR, we've previously made the assertion that controller-mediated VR for skill training was far less optimal than other options that provide better haptic feedback (Chapter 3). Eye-hand coordination, especially for skill learning, is incredibly important. If a VR application teaches users incorrect visuomotor patterns, unintended consequences could occur in the real world. But how would you know? Here, we have provided a gold standard for the current state of the VR industry. A participant who moves quickly and efficiently with their eyes leading their hands throughout an object interaction is a strong indicator of a real-world visuomotor skill and is likely to also be fully embodied. For prosthetic users, these findings are equally important, as they confirm previous literature showing that the return of reliable, predictable haptic feedback will lead to major increases in device functionality (Hebert et al., 2019; Marasco et al., 2021). Going further, the aforementioned connection between visuomotor behaviour and feelings of embodiment could be used in a clinical setting to assess, not only prosthetic device functionality, but also each user's experiences of embodiment towards their device, allowing better fine-tuning of device specifications for each individual.

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5 - Discussion

As discussed in Chapter 1, from an evolutionary perspective, being situated in a body that we own and control may be the foundation to our conscious experience. Whether our ability to be conscious is the result of natural selection morphing one adaptation into another, “just as the feathers that originally played a role in thermoregulation subsequently gave rise to the possibility of flight” (Glasgow, 2018), or some other process, embodiment seems to be at its foundation. Moreover, embodiment is fundamentally connected to our ability to interact with our environment, which in turn relies on the successful integration of an array of sensory feedback including visual and haptic. The purpose of this thesis developed from these ideas, and resulted in a test of the connection between embodiment and sensory feedback. In fact, the more I ruminated on these ideas, the murkier the distinction between embodiment and dynamic behaviour became. Could embodiment be the synchronization of incoming sensory information and outgoing motor information into one unified experience? Could this unity be what creates the feeling we all have that our “body is the storm center” (James, 1905) of our experience? And, if this is the case, can we find a measurable, behavioural result that occurs when embodiment is altered while we are in dynamic interplay with our environment that shows these two concepts might be the same thing?

To do this, I used an object interaction task that had been thoroughly studied in both prosthesis-using (Hebert et al., 2019; Marasco et al., 2021; Williams et al., 2021) and normative populations (Boser et al., 2018; Lavoie, 2017; Lavoie et al., 2018; Valevicius et al., 2018, 2019), and built a replica of it in VR. By maintaining the same task, it allowed me the freedom to compare any alterations I made in the current experimental design to past iterations. The Pasta Box Task has participants move a box of pasta into and out of a set of shelves to and from three different locations. Participants carry out several repeated trials of the task, with each trial started with an auditory cue (500 ms). See Figure 1.10 for a visualization of the task. In the virtual versions of the task, participants wore an HMD and were visually presented with a virtual replica of the lab environment they were in. For each experiment, I changed participants’ feelings of embodiment by changing their visual and haptic feedback, and measured the resulting changes in their visuomotor behaviour during the task. Below, I revisit each of the three studies of this thesis in the context of previous literature, and follow with a general discussion.

5.1 - Thesis in Context Revisited

5.1.1 On Chapter 2: Altering embodiment through visual feedback changes visuomotor behaviour

Chapter 2 discusses an experiment in which I altered participants' body visualization during object interactions in VR and measured their movement and self-reported feelings of embodiment. In short, participants carried out multiple trials of the same object movement task (Pasta Box Task) in VR while seeing either a visualization of the plastic controllers they held in their hands, or a set of dynamic human-like limbs that extended into their torso area (see Figure 2.1). The interaction mechanism was exactly the same in both conditions. Initiating an interaction with the pasta box occurred when the trigger button on the controller was held down when it was in close proximity to it. The interaction ended when the trigger button was released. Profound differences were found in how participants positioned the controller during interaction initiation. When the controllers were visualized, participants simply extended the tip of the controller into the virtual box and held the trigger down, but when the dynamic limbs were visualized, participants oriented the virtual hand in a plausible grasping pattern around the box with the thumb and forefinger in opposition. To do this, participants necessarily had to move their real-world wrist into a biomechanically uncomfortable position. In addition, after each condition, participants rated their agreement with statements on an Embodiment Survey. Self-reported feelings of ownership were much greater when participants visualized the virtual limbs compared to the controllers, while measures of agency were equal. Most interestingly, a correlation between changes in movement between the two conditions and changes in feelings of ownership was found. That is, people who reported greater ownership over the virtual limbs compared to the controllers also had a greater difference in their movement patterns between the two conditions.

As stated in Chapter 2, the results from this study add to previous research findings showing that feelings of embodiment are separable (Kalckert & Ehrsson, 2012; Lin & Jörg, 2016; Longo et al., 2008; Synofzik et al., 2008). More specifically, in both conditions, participants maintained a high level of agency over their virtual end effectors, while feelings of ownership were reported as significantly higher when virtual limbs were being visualized. This goes against previous assertions that ownership is a necessary precursor to agency (Haggard, 2017). However, this may be explained by the possibility that in this study, the virtual controller did not replace participants' real-world limbs in their body schema, but rather became a tool to be wielded, like a hammer. In fact, it's been shown that visual discontinuity of an end effector to the body decreases feelings of ownership (Tieri et al., 2015), which could have contributed further to our findings. Thus, we argued that the virtual limbs did replace participants' real-world limbs in their body schema, resulting in the increase in feelings of ownership, while the virtual controller was treated more like a tool - something over which you feel you have agency but less ownership with respect to it being part of your body.

The significant correlation found between participants' movements and their feelings of ownership is another way in which we can show embodiment is not confined to the mind, but rather that it has influence outside the brain to the body. Proprioceptive drift, the well-studied phenomenon wherein a participant believes their real-world limb has gravitated in location closer to a rubber hand they've embodied, has been found to correlate with self-reported survey findings (Longo et al., 2008). Further research has shown that both the temperature, and tactile processing speed, of a participant's real hand will decrease when ownership increases in a rubber hand (Hohwy & Paton, 2010; Moseley et al., 2008), and that feelings of ownership towards a virtual limb increase when the color of the limb fluctuates in synchronization with respiration rate (Monti et al., 2020) and heart rate (Suzuki et al., 2013). To our knowledge, this study is the first to show a correlation between feelings of embodiment and functional changes during object interactions as a result of altered limb visualization. It affirms previous findings showing that embodiment extends outside the brain to the body, and pushes further showing that embodiment extends to our movement behaviour towards interactable objects in our environment.

Additionally, the fact that participants voluntarily oriented their wrist into an uncomfortable position in order to make the virtual hand orient into a grasping pattern contributes to another line of research. When moving a cursor on a screen, it's been shown that participants will move their hand in a curved trajectory to make the visual of this movement appear linearly (Flanagan & Rao, 1995). As well, the importance of real-time visual feedback for motor control has been discussed extensively (Wolpert et al., 1995), but our finding suggests that movement planning and updating is affected more by the visual appearance of the movement rather than the actual motor output or proprioceptive feedback. In fact, these findings support theories in which movements are planned and updated with visual feedback taking the dominant role in such a way that movements are updated in real-time with the aim of matching actual visual feedback to the predicted visual feedback of a movement. Taken together this finding changes how we think about the theory that movements are planned to maximize "end state comfort" (Rosenbaum et al., 2012, 2018). Instead of comfort being derived from a property of actual body position, it is instead based on whether or not visual feedback conforms to a position that *looks* comfortable.

5.1.2 On Chapter 3: Limited haptic feedback leads to altered visuomotor behaviour

Chapter 3 compares eye-hand coordination patterns during an object interaction task in the real world to the exact same task in VR with limited haptic feedback. The real-world dataset was collected from participants wearing a head-mounted eye tracker and upper-body motion capture markers and had been previously published (Lavoie et al., 2018). The VR dataset used here was the condition from Chapter 2 in which participants visualized a set of dynamic, human-like limbs that connected to their torso while they held a set of plastic controllers. In this condition, the haptic feedback that participants received was limited to a vibration of the controller when an interaction could be initiated. This vibration stopped once the interaction initiated. It was found that participants in both the real-world and VR conditions spent roughly the same relative amount of time reaching towards, grasping, and transporting the object. Visual fixation patterns were also similar in that participants fixated on objects and areas that were relevant to the task. Furthermore, participants exhibited a similar advanced visual fixation time (~ 500ms) before their hand arrived to interact with an object. However, there were also important and stark differences between the real-world and VR interactions. In VR participants took nearly twice as long to complete the task as real-world participants with a disproportionately large amount of time spent releasing the object. While transporting the object, VR participants spent more time visually fixating their virtual hand, or the object in it, and less time fixating on the upcoming drop-off area of the object compared to the real-world participants. Moreover, VR participants' visual fixation lingered longer on the object after it had been picked up and after it had been dropped off compared to their real-world counterparts, who immediately shifted their gaze to the future location of action.

As discussed extensively in Chapter 3, a major finding from this study is that the 'just-in-time' phenomenon was preserved in the VR condition. That is, in both the real-world and VR versions of this task, participants visually fixated the box they were about to pick up approximately half a second before their hand arrived at it. We've found this phenomenon to be present in humans moving a mouse cursor on a screen (Bertrand & Chapman, 2023), making a cup of tea (Land & Hayhoe, 2001), picking up a pasta box (Lavoie et al., 2018), and even in monkeys catching prey (Ngo et al., 2022). Fixating the object to be interacted with early enough allows eye movement information to be translated into appropriate motor commands of the arm and hand, and as the hand approaches the object, visual feedback allows for real-time fine-tuning of the hand movement (de Brouwer et al., 2018, 2021). This half a second of visual fixation may be the amount of time required for appropriate computations to take place to ensure a high enough probability of a successful interaction. Even in VR, with minimal haptic feedback, participants maintained the same amount of advanced fixation on an object before their hand arrived at it.

However, we observed extended visual fixations on the pasta box after participants in VR picked it up and dropped it off. In the real world, almost immediately after participants initiated a grasp or a release, their visual fixation shifted to the next area of action. In VR, participants' gaze lingered, as if to ensure the box did what they wanted it to. We attributed this to the lack of haptic feedback from the box in VR (the primary motivation and question tackled in Chapter 4), and this result adds to literature explaining which sensory modes are most dominant at specific times during an object reach. Revisiting section 1.1.5, researchers have confirmed that visual feedback is most important in guiding the hand to an object in the later stages of a grasp (Volcic & Domini, 2016), with this current study extending this line to show that haptic information takes the lead in allowing naturalistic visuomotor behaviour to occur the moment contact is made to the moment it ends (from the earliest point of the grasp to the latest stages of the release). As well, these results support similar evidence found in prosthesis-using populations where a lack of haptic feedback leads to increased visual fixation on one's own hand and decreased visual fixation on upcoming areas of interaction (Hebert et al., 2019), with the return of haptic feedback reversing this trend back towards normative values (Marasco et al., 2021).

5.1.3 On Chapter 4: Altered embodiment through haptic feedback correlates with visuomotor changes

Chapter 4 represents a real culmination in this thesis, in which I restored full haptic feedback during object interactions in VR, and compared visuomotor behaviour and feelings of embodiment against a condition with no haptic feedback. Here participants carried out multiple trials in two conditions of a version of the task used in each of the two previous studies. In both conditions, participants visualized the exact same thing - a virtual replica of the lab room they were in, with a set of shelves and a pasta box on those shelves. As well, participants were fitted with a set of VR tracking gloves that were calibrated to their own real-world hands and finger movements, such that a virtual set of limbs, hands, and fingers were appropriately sized and moved with their real-world movements (see Figure 4.1). In one condition, I aligned a real-world pasta box to the virtual pasta box participants saw, such that when they interacted with the virtual box with their hand, they received authentic and rich haptic feedback from a real-world pasta box. In the second condition, there was simply no real-world box at the location where the virtual pasta box was visualized and therefore participants received no haptic feedback. Combining techniques from the other two chapters of this thesis, here I recorded the same visuomotor behavioural measures as in the second study, and also had each participant fill out an Embodiment Survey similar to the first study. Briefly, I expected that a return of haptic feedback would liberate visual fixation from a participant's own hand, or the object in their hand, from the start to the end of a transport, with a correlative increase in their feelings of embodiment.

Briefly, participants needed much more time to complete the task without haptic feedback, with most of the increased time being used during grasps and releases. Participants without haptic feedback visually fixated on the box for almost all of their grasp and release time. With the return of haptic feedback, participants decreased their total task time, but specifically the time spent grasping and releasing, with decreases in the amount of time fixating on the box during these grasps and releases. Again, without haptic feedback participants spent much more time fixating on their virtual hand or the box in it during transport, and much less time fixating on the upcoming drop-off location. Upon the return of haptic feedback, less fixation time was observed on the virtual hand and the object in it while transporting, and subsequently more time was spent visually fixating the drop-off location. Furthermore, the lack of haptic feedback had participants maintain their visual fixations on the box much longer after they had picked it up and dropped it off compared to when haptic feedback was available. Parallel to the findings from Chapter 2, participants rated feelings of embodiment higher when haptic feedback was available, and more interestingly, a correlation was found between the level of embodiment participants reported and their visual fixation patterns while transporting the box. Now, across two separate studies, we have evidence that measuring gaze and movement behaviours provides an objective quantification of the elusive subjective experience of embodiment.

As I wrote this thesis, my mind kept coming back to the quote from William James that I provided at the start of section 1.2, “Where the body is is ‘here’; when the body acts is ‘now’; what the body touches is ‘this’; all other things are ‘theres’ and ‘thens’ and ‘thats’” (James, 1905). The more I deliberate on this statement, the more profoundly truthful it becomes. The reason we experience embodiment is that all our sensory experiences are synchronized and integrated to create a unified experience of being. We necessarily could not feel this unified sense of embodiment if the sensory information from the outside world had no rhyme or reason to its timing and organization. For example, if the incoming vision and touch information to my body had no correlation at all, I would have no way of confirming that the moving hand I see touching a box is in fact my own hand. In a dynamic world, in which we move and see and touch objects, it's the only way in which we can truly know what is 'us' and what is 'not us'. This is how we know our bodies are 'here' and 'now' and 'this', making everything else in the world 'theres' and 'thens' and 'thats'. The results from this study go a long way in providing confirmation of this. By removing haptic feedback during object interactions, visuomotor behaviour changed significantly, and people felt less embodied. When haptic feedback was returned, visuomotor behaviour improved and people felt more embodied. Even more, embodiment scores correlated with this changed visuomotor behaviour. It all makes sense in light of the above quote. When sensory information ceases to line up the way millions of years of evolution predicts it should, either due to synchronization issues or a complete lack of one sensory stream, we have to change the way in which we use our body, causing a decrease in feelings of embodiment.

For both the VR industry, and upper-limb prosthesis development, there seem to be two elephants in the room when it comes to drastically increased quality of experience: haptics and embodiment. That is, providing users with realistic haptics and increasing their feelings of embodiment are two major problems that are in need of solutions. But, what if these two elephants in the room are actually just one? The results from this study show that providing timely haptic feedback leads to increased feelings of embodiment, a finding that parallels prosthesis-users using advanced devices that can return a sense of touch (Marasco et al., 2021). It seems as though providing timely haptic feedback in both domains not only improves visuomotor function, but also improves embodiment. Put in its strongest and most speculative form - I argue that the experience of embodiment *is* the convergence of visual, haptic and all other forms of sensory feedback on an agent who is interacting with a dynamic world.

Given this bold claim, it is important to examine the results from Chapter 4 from another lens. Yes, returning haptic feedback moved the VR users toward real-world behaviours, but crucially, not completely. Why didn't VR users exhibit visuomotor behaviour completely in line with the real-world users from the previous dataset? One possible explanation is the previously discussed (see section 1.3.1) perceptual differences that humans may exhibit towards virtual objects compared to real objects (Snow & Culham, 2021). That is, virtual objects scale from low (2D lines on a screen) to high (3D, HMD display with haptic feedback) ecological validity, but are all proxies for actual, real-world objects. Humans recognize, remember, and attend to real-world objects better than virtual ones, with actability being the proposed reason (Snow & Culham, 2021). An additional, perhaps complementary hypothesis, also discussed earlier, proposes that object interactions in virtual environments stimulate the ventral, vision-for-perception pathway for visual information in the brain, leading to slower movements (Harris et al., 2019). Part of this hypothesis, however, rests on haptic feedback not being fully returned to users. In my Chapter 4 study, with full haptic feedback returned, this cannot be used as the reason for the dorsal stream being downregulated and the ventral being upregulated. It seems as if the virtual visual mediation is still introducing a fundamental shift away from the real world.

One way to further test this hypothesis would be to design a similar experiment where participants carry out repeated trials of the Pasta Box Task while using an augmented reality headset. In both conditions, participants would be able to see the real lab and shelving unit, along with their own real hands and limbs. In one condition, however, they'd see a real pasta box that they can feel with their hands, and in a second condition, they'd see a projected replica of that pasta box, but would not be able to feel it at all. Any differences in visuomotor behaviour that are found in this experiment should be attributable to the differences in haptic feedback. And thus, these results could be used as a comparator with this thesis to delineate which effects are due to the lack of haptic feedback, and which are due to the visual effects in the virtual environment. Whatever the case, in Chapter 4, we've shown that returning haptic feedback to VR users improves visuomotor behaviour and increases feelings of embodiment in a correlative manner. But, it does still beg the question: What else needs to be improved to push VR visuomotor behaviour into alignment with those of the real world?

5.2 - Visuomotor Behaviour during Object Interactions

This thesis was partly motivated by a larger series of studies focused on visuomotor behaviour during object interactions. As mentioned earlier, the first studies using the Pasta Box Task described the eye-hand coordination and movement patterns of able-bodied participants using a head-mounted eye tracker, and upper-body motion capture system (Boser et al., 2018; Lavoie et al., 2018; Valevicius et al., 2018, 2019). This task was then used to assess the differences that prosthesis-using participants exhibit compared to able-bodied participants (Hebert et al., 2019), and was later used to test the changes that occur when prosthesis-users have haptic feedback returned to them during object interactions (Marasco et al., 2021). And now, this thesis has broadened the library of visuomotor behaviour knowledge during object interactions in VR and with various levels of visual and haptic feedback. With this knowledge, I am able to describe, in detail, the roles that each of visual, haptic, and proprioceptive feedback play at different stages of a successful object interaction, and further, assert that changes in stereotypical visuomotor behaviour can be used to give insight into a person's feelings of embodiment.

Although differences in total task time, duration of each phase of movement, and visual fixation time to relevant areas all differ, in the interests of brevity and because ultimately I think I've shown it is the most critical, here I discuss only the eye-hand arrival and leaving latencies between the object interaction conditions mentioned above and in this thesis. Recall, the eye-hand arrival latency (EAL) is the duration between the participant's visual fixation arriving at an object or area and their hand arriving there, and the eye-hand leaving latency (ELL) is the duration between the participant's fixation ending at an object or area and their hand leaving. Here I describe the major EAL and ELL similarities and differences in each of the aforementioned Pasta Box Task conditions.

Before reaching out to initiate a grasp of the pasta box, participants in all conditions visually fixated the box at least a minimum of approximately half a second, supporting previous literature that describes a 'just-in-time' visual fixation behaviour during naturalistic action (Ballard et al., 1995; Hayhoe & Ballard, 2005). This hypothesis states that a minimum of half a second of real-time visual fixation of an object or area is necessary to compute the interaction grasp dynamics of the hand before it arrives. We've shown that not only do humans require about half a second during real-world grasps, but that this minimum half a second translates to VR object interactions using either plastic controllers with limited haptic feedback, and tracking gloves with both no haptic and full haptic feedback. As well, previous literature showed that prosthesis-users fixated about a full second before their prosthesis arrived at the box, an extended timeframe we attribute to the fact that prosthesis-users moved much slower than their able-bodied counterparts (Hebert et al., 2019). The major differences between haptic feedback in each of these conditions, combined with the fact that minimal differences were found in the EAL values of each, push the assertion that haptic feedback is not an important factor in the reaching stages of a grasp. Figure 5.1 shows each of the eye-hand latency averages for each condition. It's noted that the EAL Grasp values for the VR No Haptic and Haptic conditions are larger than previous iterations, and this is hypothesized to be due to an alteration of the physical apparatus, which is described below. This supports previously discussed research indicating that visual feedback takes precedence at the end effector approaches an object (Bozzacchi et al., 2014; Camponogara & Volcic, 2019; Volcic & Domini, 2016). In fact, the findings from the first study of this thesis support this. Recall that in the first study, participants used plastic controllers held in their hands, and either saw a virtual replica of the plastic controllers, or a dynamic set of human-like hands and limbs. The haptic feedback was the same in both conditions. That is, at the point where participants would be able to initiate an interaction, a slight vibration would occur in the plastic controller, at which point holding down the trigger would cause the object to be held by the end effector. Just by switching the visualization of the end effector, participants changed the orientation of their grasp.

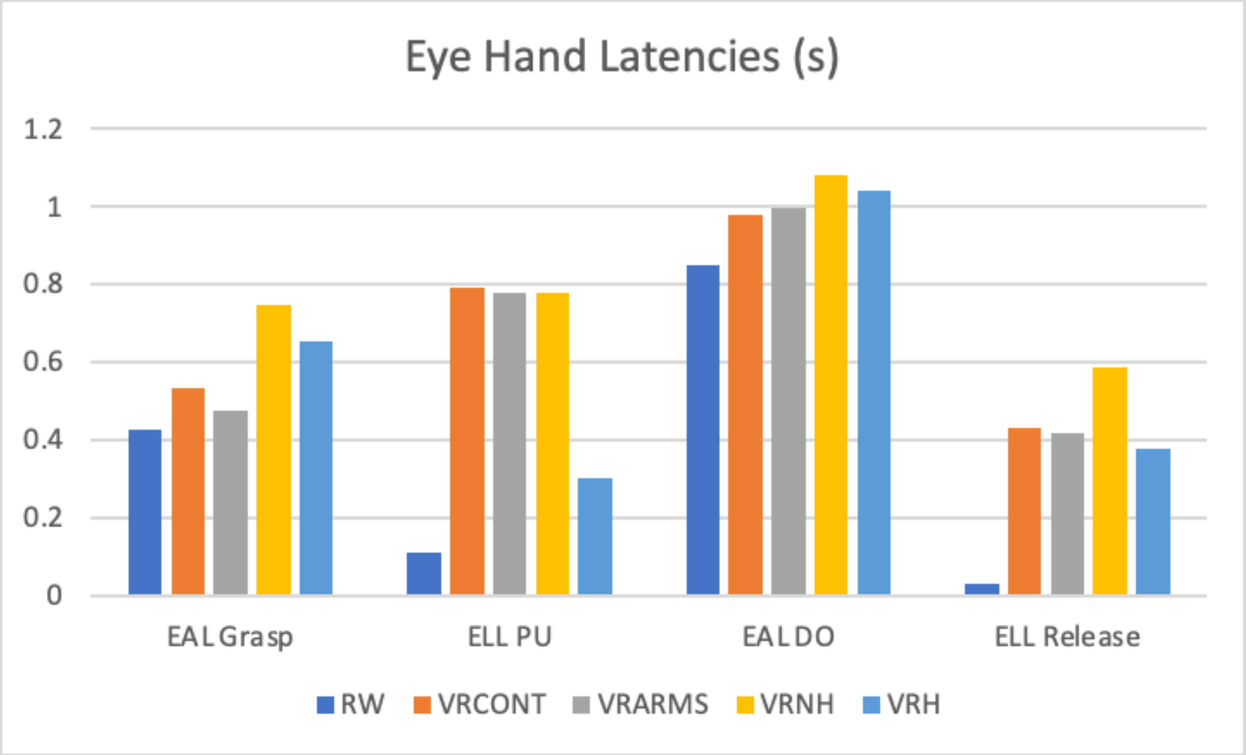

Figure 5.1: A comparison of the average eye-hand latencies (s) (*EAL Grasp, ELL PU, EAL DO, and ELL Release*) during the Pasta Box Task of all five conditions in this document: real world (RW), VR Controllers (VRCONT), VR Arms (VRARMS), No Haptic (VRNH), and Haptic (VRH).

Thus, I argue that up until the point when the end effector actually contacts, or needs to exactly conform to, an object a participant is relying on a largely stereotyped deployment of visual attention with an advanced fixation of at least 500 ms. But, there comes a crucial point during the interaction where participants expect some form of haptic feedback. This is where visual dominance gives way to haptic sensory feedback. In the real-world version of the Pasta Box Task, once a participant's hand initiated a grasp, their visual fixation shifted away from the pasta box being grasped to the next location. In stark and consistent contrast, we found that in the prosthesis-using population, controller-mediated VR population, and no-haptic VR tracking glove population, visual fixation lingered on the box much longer as the pick-up began causing an increased ELL. In short, having little to no haptic feedback during the grasp phase of an object interaction, forces users to continue to use visual feedback. This was tested and confirmed in the full-haptic VR tracking glove condition of Chapter 4, in which participants drastically decreased their ELL PU to almost the level of the real-world population. A similar trend of results was found in the ELL Release during the drop-off of the pasta box. In the real-world, participants almost immediately shift their fixation to the next area of action, whereas prosthesis-users, and controller-mediated and no-haptic VR participants all maintain visual fixation for much longer after the release has occurred. Once again, when full haptic feedback is returned to VR participants, their ELL Release decreases, but to a lesser extent, which is hypothesized to be due to slight changes in the task apparatus (described below).

The physical apparatus in Chapter 4 had one alteration that led to a change in the EAL Grasp and ELL Release values from previous iterations of the experiment. In the experimental design, to ensure the virtual hand was visualized without overlapping with the virtual shelving unit (which could break immersion and affect embodiment), we had to elevate the Home button from a flat surface to a cube shape. This ensured a participant's virtual hand was not sitting inside the virtual cart. An unexpected outcome from this was that participants, in both conditions in Chapter 4, could feel where the Home button was on the cart, and therefore did not require as much visual fixation in order to ensure their hand arrived at it in between each object movement. Specifically, we saw that there was much less urgency to acquire visual information from the Home button at specific portions of the task. When a participant had dropped off the pasta box at a location, and the next area they required visual fixation was going to the pasta box again, they oftentimes did not break their gaze after drop-off and before the next pick-up. This caused the EAL Grasp 2 and 3 values, and the ELL Release 1 and 2 values to be extended relative to previous iterations of this experiment. Figure 5.2 below shows the EAL Grasp values for each of the three Grasps, and the ELL Release values for each of the three Releases. This information allows for two assertions to be made. Firstly, the 'just-in-time' phenomenon is much closer to 500ms for both conditions in this experiment than the average of all three values shows, as evidenced by the EAL Grasp 1 in both conditions being much closer to 500ms than the other two locations. And second, that haptic feedback in the Haptic condition liberates the eyes to behave much more closely to the real-world values after release than the averages of this task show, as evidenced by ELL Release 3 being much smaller compared to the No Haptic condition than in ELL Release 1 and 2.

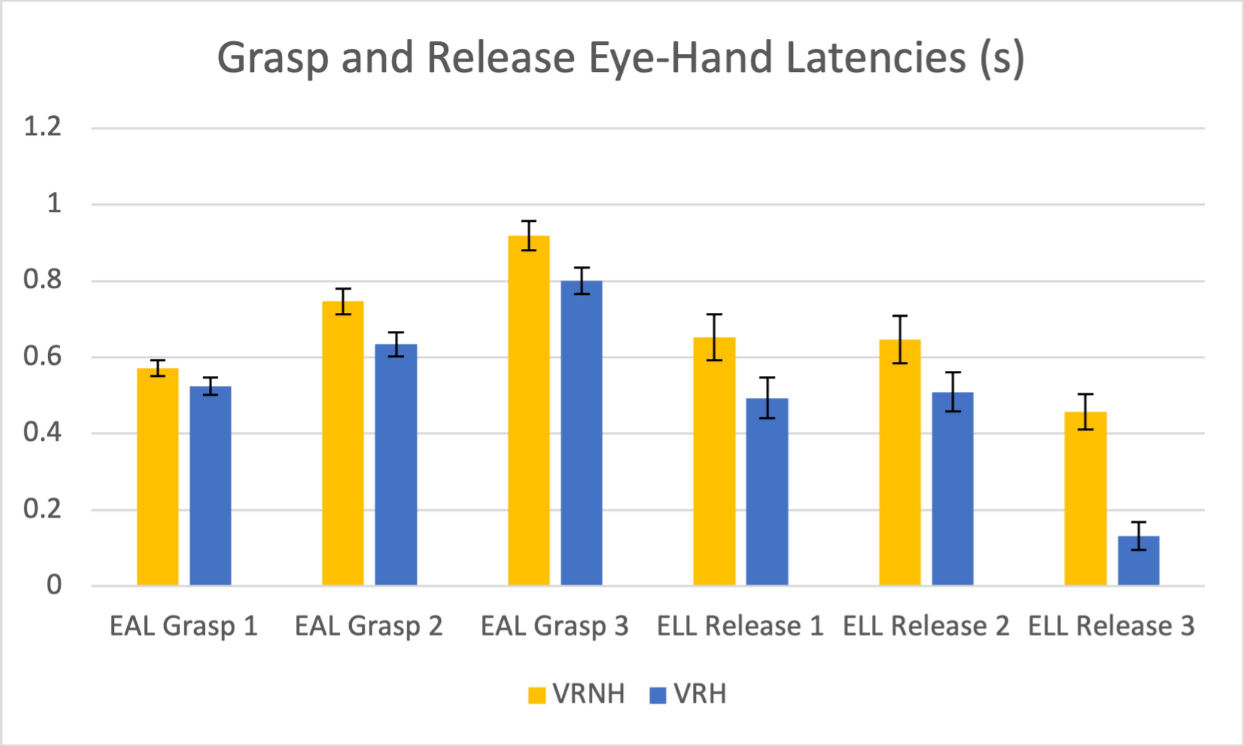

Figure 5.2: A comparison of the *EAL Grasp* (s) and *EAL Release* (s) averages for each movement of the No Haptic (VRNH) and Haptic (VRH) conditions in Chapter 5. Note that *EAL Grasp 1* is for both VRNH and VRH are much smaller than at the other two locations, and that *ELL Release 3* during VRH is substantially lower than either of the other two locations. Error bars represent standard error of the mean (SEM).

Even in light of this difference in the physical apparatus, there are still further differences between the Haptic condition and the previous real-world dataset that are unaccounted for. There are several theories in which these findings could be attributed to. Firstly, the limited haptic feedback found in prosthesis-users and controller-mediated and no-haptic VR participants could be decreasing the dorsal visual stream activation, and increasing the ventral stream (Goodale et al., 1994; Harris et al., 2019), with any residual differences between the full haptic feedback condition and the real-world results being attributed to the differences in how our brains deal with virtual and real objects and environments (Snow & Culham, 2021). Additionally, the changes in haptic feedback obviously impact the way in which overt visual attention is dispersed over the course of the task. But, under the radar, covert attention must also be impacted by the increased demands placed on the visual system because of the lack of haptic feedback (Baldauf et al., 2006; Baldauf & Deubel, 2008a, 2009, 2010). Previously, coauthors and I proposed that covert attention is continuously and fluidly being dedicated to relevant areas of an ongoing task in such a manner that the highest area of attention holds overt attention, and then covert attention rises and falls at other relevant areas of the task (see Figure

1.4). In this way, during the Pasta Box Task in the real world, participants are visually, overtly fixated on the box as the hand is reaching towards it, and then covert attention is small, but dedicated to the upcoming area of drop-off. As the hand gets closer to the box, the covert attention to the drop-off target increases. Eventually, as the hand makes contact with the box, the covert attention at the upcoming target now supersedes the need for visual attention at the box, causing a saccade of overt visual attention to the drop-off target. The key here is that haptic feedback from the box on the hand allows the release of visual fixation from the box to be dedicated to the next location of action. Importantly, when haptic feedback is either limited or nonexistent (prosthesis-users, controller-mediated VR, no-haptic VR), visual fixation cannot be released, forcing a lag in visual fixation on the box. In essence, the lack of haptic feedback inhibits the natural, fluid flow of visual attention.

5.3 - Embodiment as the Foundation of Consciousness

Returning to the themes at the beginning of this document, I hope I've been able to convince you of the importance that our body plays in human behaviour. The chain of millions of years of human evolution occurred with the foundation of embodiment. In this thesis, I've shown that how we move, how we visualize the world and our own bodies, and how we interact with our environment, connects to our feelings of embodiment. Our being situated within bodies directly impacts the conscious experience we have, and our experience would not be the same from an evolutionary perspective or an individual perspective without our body. Although VR can simulate somewhat "real" bodies, it's still no match for what we experience in the real world. When I wake up in the morning, my body's sensory capabilities are different compared to when I've had my third coffee of the morning. VR obviously can't simulate the grogginess I feel through my eyelids as they struggle to stay open. In fact, it can't simulate any altered sensory experiences except through visual (and very basic haptic) input. The fact that we are in bodies, and that we experience our consciousness through bodies is often overlooked by major theories of consciousness. Embodied cognition is undeniable and needs to be embedded as a primary role in the study of human consciousness.

In brief, higher-order theories of consciousness separate the brain into lower and higher order areas (Lau & Rosenthal, 2011). For a mental state to be conscious, a correct combination of higher order areas must target lower order areas to create a specific meta-representation of those lower order neural signals (Seth & Bayne, 2022). Global workspace theories of consciousness state that mental states are thrust into conscious awareness in a fronto-parietal network through a neural ignition process (Baars, 2005; Seth & Bayne, 2022). Evidence for this ignition process comes from differences in anterior cortical brain regions after the onset of a stimulus that is either consciously perceived or not (Dehaene & Changeux, 2011). Both higher-order theories and global workspace theories of consciousness are met with arguments that the importance put on anterior brain regions may be more linked to abilities to report an experience (cognitive access) rather than consciousness itself (Seth & Bayne, 2022). Integrated information theory states, quite differently, that consciousness is dependent on the ‘cause-effect power’ afforded to an entity by the amount of information it generates as a whole compared to that created by the sum of its parts (Tononi, 2008). It is not just that a system is processing information that makes it conscious, but that it has the ability to influence itself with the information that it produces (Tononi et al., 2016). This generalized claim, supported by mathematical models that would require several years for me to understand, allows the application of integrated information theory to already existing inorganic systems (Tononi & Koch, 2015). Both re-entry and predictive processing theories of consciousness rely on the minimization of prediction errors between top-down and bottom-up neural information streams (Hohwy & Seth, 2020; Lamme, 2006). That is, top-down sensory predictions and actual bottom-up sensory signals are compared in real-time yielding a prediction error (see Figure 5.3). The minimization of this error allows for the generation of mental states. These theories are supported by the influence that top-down signals seem to have on perceptual experience (mostly visual examples) (Lamme et al., 2000), and the fact that expectations impact many aspects of our conscious perception (de Lange et al., 2018).

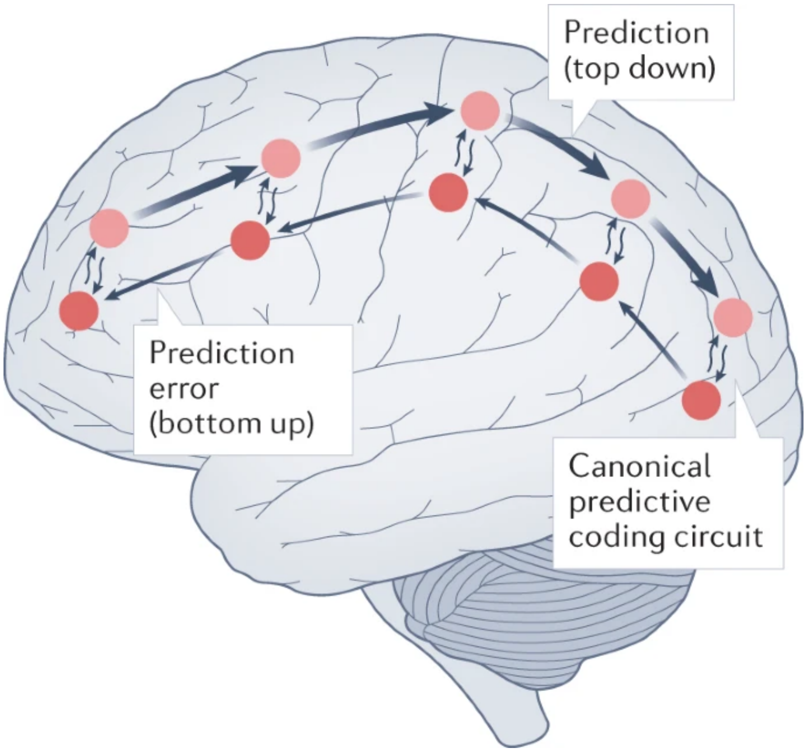

Figure 5.3: A visualization depicting the top-down prediction information stream and the bottom-up prediction error stream associated with conscious mental states in re-entry and predictive processing theories of consciousness. Borrowed from Seth & Bayne, 2022.

To me, the only group of consciousness theories that truly take into account the evolutionary impact of evolving within a body embedded in an environment, are the re-entry and predictive processing theories (Park & Tallon-Baudry, 2014; Seth, 2013; Varela, 1993). Predictive processing was not developed with the goal of describing consciousness, but rather to explain the general function of brain and body, and was later branched to the study of consciousness. In fact, feedback models of brain and behaviour like optimal feedback control (Todorov & Jordan, 1998, 2002), comparator model of agency (Blakemore et al., 2000), and sensorimotor contingencies model (Gonzalez-Franco & Lanier, 2017), align quite closely with the predictive processing theory, providing additional evidence. Personally, it's not a coincidence that the best theory we have to explain and predict how we use feedback to control our bodies is strikingly similar to the best theory about how we became embodied conscious agents. Although my own personal opinions about consciousness align with predictive processing within an embodied entity (Shapiro, 2019), it's obvious that we have much to learn about how it's possible that we all experience our own private, inner worlds while simultaneously being situated in, and sharing a 3-dimensional space with everything else we know of in the universe. This "hard problem" of consciousness continues to elude philosophers and scientists alike

(Chalmers, 2017), and has pushed some researchers to ask for more stringent guidelines on theories of consciousness because “imprecise constructs can generate only vague and imprecise predictions” (Seth & Bayne, 2022). I couldn't agree more.

I believe the type of consciousness that humans experience could only come to be through an evolutionary process within bodies. Being inside a body, forced to survive with only certain abilities to impact the outside world is a stringent set of limitations. But, the limitations we have is what created the affordances we have. Limitations of being confined to a body produced the rules of engagement for us as beings. When it comes to building artificial consciousnesses, could we recreate the exact limitations and abilities that allowed for the development of our conscious experience? No. But, could we develop a different set of limitations that could lead to a different type of consciousness? Possibly. Instead of one of the major limitations being embodiment, perhaps a different set of limitations could be implemented to focus the development of selfhood. For humans, our bodies situate us in time and space. Other entities may not have this sense if their limitations don’t create it for them. For example, if an AI was developed across a network of computers around the globe, could we readily say that it would experience three-dimensional space in the same way that a human does? I also believe that to be conscious, an entity must be able to sense and act with the world outside of them, and be able to know what changes in the sensation they receive is due to their own actions. For the fictional AI entity above, perhaps this “sensing” and “acting” is not moving objects around in a 3D environment. It could be moving finances in the stock market and then observing the changes in the human housing situation over several years. Perhaps we may create (or have already created) a type of consciousness that we cannot even fathom, or are even aware of.

5.4 - Future Directions and Final Remarks

I’m fortunate to have had the time and guidance to immerse myself in the topics I present here. It’s apparent to me what the future of visuomotor behaviour, embodiment, and VR research requires. I’ve mentioned several times that although VR is starting to look more and more like the real world, visual stimulation is just one aspect of how humans sense our environment. Haptics, of course, synchronized with appropriate visuals of a virtual body will create illusions for users that will go a long way in creating a sense of embodiment, and will allow researchers more avenues to probe the depths of human consciousness. More sensory streams, like olfactory stimulation, and better motor outputs, like real-world walking on multi-directional treadmills (see Ready Player One), mouth movement and even verbal recognition, are being added. As discussed in this document, it's important to measure and document behavioural changes that occur as technological development progresses along the never-ending journey towards 100% virtual embodiment. This path is never-ending because, of course, a proxy is always a substitute for the real thing, and thus necessarily falls short of what it tries to emulate. As this journey continues, standardized tasks like the Pasta Box Task should be used to categorize the impact that each additional sensory and motor component makes on human behaviour and embodiment, probing ever further the depths of the human conscious experience.

As I continue on with my medical training, I can't help but see the immense potential that VR technology and behavioural assessment can bring to the field. Briefly, I envision future medical classes being supplemented with VR training simulations, perhaps even replacing traditional instructor-focused lectures with one-on-one AI-led virtual learning sessions. Instead of an instructor showing 2D slides of images of rare pathologies, students will be able to don their VR headsets and see high fidelity simulations of these pathologies, and even act in these simulations to learn best practices. As mentioned earlier, surgical training is one obvious area of opportunity for VR technology, but combining eye-hand coordination metrics into learning assessments is low-hanging fruit that will decrease surgical learning time for trainees. The faster a trainee can perfect a surgical technique, the sooner they can start performing these surgeries on patients in need. If we could train the world's surgical residents to become proficient even 10% faster, how many more patients could be served by their care? Rehabilitation and patient assessment is one more area that VR and AR technologies will drastically improve. Not only can physicians and other healthcare providers personalize rehabilitation exercises in these platforms in a gamified manner, but we can also collect user data that can be analyzed in real-time to provide ongoing assessment. Imagine the benefit that could be provided to a stroke patient if every day they could see just how much faster and more coordinated their movements were becoming as they completed their prescribed exercises. Not only that, eye-hand coordination assessments could be used to diagnose early stages of diseases that may be missed by a physician's naked eye. Consider a fully functional elderly patient who comes into their doctor's office for their annual physical. As part of the exam, the patient could don a VR headset and carry out a simple object movement task while their eye and hand movements are tracked with millimetre accuracy at high frequency. The patient may move all the objects in a normal duration, but perhaps their eye or body movements are similar to a large dataset of patients in the very early stages of Parkinson's disease? Early diagnosis allows physicians the opportunity to provide patients with earlier treatment which can maintain quality of life for longer, even with many degenerative conditions.

Descartes astutely stated, “cogito, ergo sum”, which translates to, “I think, therefore I am” (Descartes, 2009), in response to his own doubts about nearly everything he experienced. The statement came about as he reflected on hallucinations of the mind, and arrived at this ultimate question. What can we be assured is *actually* real? The answer he arrived at was that our ability to think or experience something with our minds is the only thing we can be assured of to be true. Everything else could be part of a simulation. The unfortunate reality of simulation theory is that we could even be part of a simulation within a simulation, with evermore layers. Our conscious experience could be “turtles all the way down” (an expression, interestingly, attributed to a William James lecture, Ross, 1967). The reality of this, is that at the bottom of whatever line of turtles I am a part of, necessarily has to be the fact that I have a mind. However possible, I’m skeptical of simulation theory based on much of what’s been discussed in this document. For one, the timing and precision of the synchronicity of incoming sensory and outgoing motor information necessary to create the unified experience of embodiment that I have, connects my conscious experience seamlessly with that which is not me. The requirements of a simulation able to provide these specifications would be unfathomable for my mind to comprehend. And, if we truly are in a simulation that powerful, the result changes nothing about our lives.

Simulation theory creates another uncomfortable possibility. Solipsism. Perhaps the only true conscious entity that exists, or has ever existed, is me, and everyone else around me, including my closest friends and family, are all non-conscious entities, figments of whatever simulation I am in. Logically, solipsism is a real possibility. My true conscious experience resides within me, and even those closest to me, who know me better than anyone else, are never privy to the raw experiences of my mind. However, we may be physically separate from others, and the goings on inside my mind may be forever private, we are all still connected. We share proxies of our inner feelings in a multitude of ways, sometimes when we would much rather our feelings remain private. We are affected by the signals from those around us. We can tell when someone is happy or sad, when they are in pain or content, and we can feel these feelings when others outwardly express them to us. We could be in a simulation, but there’s just no doubt within me that the joy-filled laughter my nieces and nephews express when we spend time together is anything other than a beautiful, real experience. A much more reasonable assertion is that my conscious experience is one of many others like it, that evolved through a process of natural selection over a long period of time.

In this vein, humans are much more similar to one another than we are different. As much as we could potentially be a part of a simulation, it seems as though we are all products of the same millions of years of evolution to the brains and bodies that we now possess. We all have slight variations in the spectrum of these characteristics, but without being too cliche, what’s important is that our similarities are so much greater than our differences. The greatest similarity is that we all possess a remarkable, beautiful, one-of-a-kind, inner world that is ours and ours alone. One’s beliefs about how or why this is the case should always be superseded by the miracle that it is. What stems from this miracle, for me, is that I have an obligation to something. Whatever that ‘something’ may be, I am obliged to it for being gifted consciousness. Some call it God, others the Universe, but the terminology is of little importance. The realization that I’ve been gifted consciousness has developed within me a personal debt to it, which is paid by doing my best to increase quality of life and decrease suffering.

5.5 - References

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