# Examining The Effects Of Perceptual-Motor Variability On The Perception Of Action Capabilities In Virtual And Real Environments

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# Declaration

I declare that this thesis is my own work completed solely by myself under the supervision of Dr. Sally A. Linkenauger, and that it has not been submitted in substantially the same form for the award of a higher degree elsewhere.

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# Thesis Abstract

Successful interactions within the environment are contingent upon the perceiver's ability to perceive the maximum extent over which they can perform actions, commonly referred to as action boundaries. Individuals are extremely sensitive to their action boundaries, and the perceptual system can quickly and flexibly recalibrate to changes in the size of action boundaries in the event of physiological and/or environmental changes. However, action boundaries are learned over time from perceptual-motor feedback across different environmental and physiological contexts, the information upon which action boundaries are based must inherently be characterised by variability. As a result, the judgement of one's action boundary is more likely based on probability distribution rather than an immutable, exact borderline. Hence, the question then arises as to where on that distribution do people decide that an action is possible.

This thesis, therefore, seeks to understand how the perceptual system accounts for overt perceptual-motor variability in motor performance and recalibrate to new action boundary following changes in one's action capabilities. In 11 experimental studies, this thesis examined (1) how the perceptual system accounts for overt perceptual-motor variability in motor performance for different actions, and (2) whether the perceptual system employs different strategies to determine action boundary to accommodate demands arisen from the consequences and costs-benefits ratios of a particular action.

The findings of this thesis suggest that the point on the distribution that acts as the judged action boundary varies as a function of task. Specifically, the strategy in which the perceptual system employs to determine action boundary after experiencing overt perceptual-motor variability in motor performance is specific the action, and the consequences and/or cost-

benefits ratios of the outcome of a particular action but not the context. By using different approaches for different actions on an ad hoc basis to determine action boundaries, the perceptual system would be able to maximise the efficiency of information processing in the event of perceptual motor uncertainties, while minimising the exposure to potentially dangerous situations and aversive consequences. These findings of this thesis have broader theoretical and practical implications for future research in affordance perception and perceptual-motor recalibration.

# Chapter 1: Literature Review

## 1.1 Introduction

Perhaps one of the most striking characteristics of everyday actions is the range of actions that we are able to perform successfully. From passing a thread through the eye of a needle to navigating through a crowd in a cluttered terrain, humans have a remarkable capacity to generate accurate and adaptive motor behaviours under changing and at times unpredictable environmental conditions. This ability to perform everyday motor behaviours with minimal errors relies on an accurate perception of affordances. Gibson (1966; 1979)'s ecological theory of visual perception posits that the primary function of visual perception is to perceive affordances. Affordances are the possibilities for action in a given environment for an animal. Affordances can be considered as the meaningful relationship between the phenotypical properties of the perceiver and how the environment allows for actions to be performed as a result of those properties. However, here, I find it important to differentiate between the existence of an affordance and the perception of one. Affordances are relational properties between the features of the environment and the observer that exist regardless of whether they are being perceived by the observer or not, whereas the *perception* of affordances is the observer's perception of whether an action is feasible with respect to their action capabilities and/or intentions.

The selection and the perception of affordances are in part determined by the perceiver's action capabilities and intentions (Gibson, 1966; 1979; Chemero, 2003). The environment simultaneously provides a multitude of affordances, and any given affordance reflects the current compatibility between the features of the perceiver and the environment (Stoffregen, 2003; Warren, 1984). For example, if a surface has a greater rigidity relative to the weight of an individual, the surface affords traversing or standing. Similarly, if an object's width is smaller than an individual's handspan, the object affords grasping. An arm's reach for a small child is not the same as an arm's reach for an adult, affordance is relative to the body and action capabilities of the individual. An action is only possible if the perceiver possesses a certain behavioural repertoire that satisfies the requirements to act on those action-relevant properties in the environment.

To perform actions successfully, the perceiver must be able to identify the boundaries of their action capabilities with respect to those behaviourally relevant properties in the environment. These boundaries can be considered as a defining characteristic of the affordance. The body's functional morphology and physiology limit the extent to which an action can be accomplished, and the maximum extent of one's capability to perform an action is referred to as an action boundary (Fajen, 2007, Proffitt & Linkenauger, 2013). An action boundary is the transitional point between possible and impossible actions. An action is possible if it falls within one's action boundary and impossible if it is beyond one's action boundary. For example, the maximum distance over which one can reach is referred to as the action boundary for reaching. To determine whether an object affords reaching, the perceiver must relate the visual information specifying the distance to the object, to information about the maximum distance over which one can reach. The ability to accurately perceive one's action boundaries in relation to environmental constraints is fundamental to the perception of affordances and the successful performance of all visually guided actions. Additionally, it is important to differentiate between the perception of action boundary and the action boundary itself. As mentioned previously, action boundaries are the limits of one's action capabilities given their phenotypical and dynamic properties (Proffitt & Linkenauger, 2013). An action boundary is a categorial function: you either can or cannot perform an action, depending on whether the action falls within or beyond this boundary. On the contrary, the *perception* of action boundary or perceived action boundary are an observer's judgement of the limits of their action capabilities, and perceived action boundaries are learned overtime through past perceptual-motor experiences across various context, which in turn leads to variability in the perception.

Over the past few decades, empirical studies of affordance perception have developed on Gibson's idea and demonstrated that people are highly accurate at perceiving the boundaries of their action capabilities and could adaptively recalibrate to changes in their action boundaries. For example, individuals are remarkably accurate at judging the maximum height of steps that they could climb, and irrespective of body height, individuals consistently judge the climb-ability of steps as approximately 0.88 of leg length (Warren, 1984). Other studies have investigated individuals' ability to perceive the maximum boundary of their action capabilities for a variety of tasks, such as passing through doorways (Warren & Whang,1987), grasping (Linkenauger, Witt & Proffitt, 2011), and reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, 2009). Furthermore, individuals are able to recalibrate to new action boundaries following changes in their action capabilities, such as updating their maximum sitting and stepping height by wearing blocks under their feet (Mark, 1987), adjusting their judgement of passability when fitting one's hand through an opening when wearing a prosthesis (Ishak, Adolph, & Lin, 2008), and updating their reachability judgement when their arm's reach has been extended or constricted in a virtual environment (Linkenauger, Bulthoff, & Mohler, 2015).

As a consequence of learning and our extensive experience interacting with the environment, perception and action become coupled into a relatively stable system, thus providing a reliable reference for the selection and execution of action possibilities. However, with any action that is learned over time, variability in the outcome is always present, however small. Moreover, our actions are generated by a nervous system that is inherently noisy, which introduces additional uncertainty and variability to how the brain processes and generates movements. Hence, regardless of how consistent an action's outcome may appear, the perceptual-motor information specifying action boundaries must be characterised by variability. Action boundaries are binary categories, but the judgement/perception of one's action boundaries is based on learning previous perceptual motor information across various contexts, and because the information upon which our one's action boundaries perception is subject to variability, the perception of one's action boundaries must also be subjected to variability. As a result, the judgement of one's action boundary is more likely based on a probability distribution rather than a borderline. The question then arises as to where on that distribution do people decide that an action is possible. This thesis, therefore, seeks to understand how the perceptual system accounts for overt perceptual-motor variability in motor performance and recalibrates to new action boundaries following changes in one's action capabilities.

This thesis is organised in the following way. In this chapter, I will first review Gibson's affordance theory, in particular how perceivers use information about their action capabilities to adaptively interact with their environment and how they recalibrate to changes in action capabilities and environmental constraints. Then the literature regarding the sources and nature of motor variability will be reviewed and empirical evidence that demonstrates individuals taking variability into account when making judgements about their action capabilities will be discussed. Lastly, literature and evidence from the optimising and satisficing approaches on motor decision making will be reviewed, and possible mechanisms by which the perceptual system accounts for perceptual motor variability when determining one's action boundaries will be proposed. Chapters 2-5 present 11 experiments that investigate how the perceptual system determines action boundaries after experiencing overt perceptual-motor variability in motor performance for different actions. Particularly, I am interested in whether following variable perceptual-motor experience, the perceptual system employs different strategies to determine action boundaries to accommodate demands arising from the consequences and/or costs-benefits ratios of the outcome of a particular action. The first set of experiments examines the effect of random and systematic variability in horizontal reaching experience on the perception of action boundaries for reaching using virtual reality. The second set of studies explores whether the consequences of failure incurred from the environmental context in which the action occurs, and the consequences associated with failing the particular action would influence the strategy which the perceptual system employs to determine action boundaries under conditions of uncertainty. The third set of studies first examines the effect of optic flow and walking speed calibration on the perception of leaping and jumping ability, in order to determine whether optic flow could be used to specify an action boundary when calibrated or scaled to actions such as leaping and jumping. Then, finally, I investigated how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping. The last study investigates whether the perceptual system utilises the same strategy in a real-world situation as in virtual environments. Chapter 6 is a general discussion of the results and their implication for how action boundaries are selected in the event of perceptual-motor variability.

## 1.2 Affordances

Gibson (1966;1979) argues that the primary role of visual perception is to promote adaptive interactions with the environment by generating and detecting information pertaining to uncovering of affordances. The concept of affordances is one of the central tenets of Gibson’s ecological approach to perception. It describes the reciprocal relationship between a given observer and their environment in the identification of the perceiver’s action capabilities. Affordances are the opportunities for action available within a certain environment for a particular animal given phenotype. No relevant environmental properties can be perceived independently of a perceiver, and the perception of affordance must be relative to environmental constraints and the action capabilities of a particular perceiver.

The environment provides an infinite number of affordances, and any given affordance reflects the current fit between the action capabilities of the perceiver and the behaviourally relevant properties of the environment that makes a given action possible (Gibson, 1979; Chemero, 2003; Turvey, 1992). For example, if a horizontal surface has a greater density relative to the weight of an individual, the surface affords traversing or standing. Similarly, if an object's width is a lesser proportion of an individual's handspan, the object affords grasping. The surrounding environment is constantly changing and the opportunities for action emerge and disappear on a moment to moment basis, likewise, the perceiver's action capabilities fluctuate, and their intentions change over time (Turvey, 2004; Turvey & Shaw, 1999). Affordances are inherently dynamic, and any given action is only possible if the perceiver intends to act on and possesses a certain behavioural repertoire that satisfies the requirements to actualise those action-relevant properties in the environment at a given moment.

### 1.2.1 Body-scaled affordance and action-scaled affordances

Empirical studies of affordance perception have demonstrated that people are remarkably accurate at perceiving a vast number of affordances, including but not limited to reaching (Carello et al., 1989; Mark et al., 1997; Rochat & Wraga, 1997; Gardner et al, 2001; Pepping & Li, 2000), passing through aperture (Warren & Whang 1987; Bhargava et al., 2020; Franchak & Adolp, 2012), passing under barriers (van der Meer, 1997; White & Shockley, 2005; Wagman & Malek, 2008), bipedal step climbing (Warren, 1984; Wraga, 1999), and grasping (Newell et al., 1989; Linkenauger et al., 2009;2012). Affordances are generally divided into two categories (Fajen et al., 2009), namely body-scaled and action-scaled. Body-scaled affordances are action possibilities that are determined by the geometric properties of one's body, such as leg length, arm length and shoulder width. For instance, Warren (1984) showed that people scaled the height of a step to their leg length to determine whether a step is climbable or not. While short and tall individuals perceived the maximum step height that they could climb at different heights, however, the boundary between climbable and non-climbable step height varied as a function of leg length, in which both tall and short individuals perceived the maximum step height that affords bipedal climbing as approximately 0.88 of their leg length. Similarly, other studies have demonstrated that people used the geometric properties of their body to determine their affordances threshold for a variety of actions, such as using one's arm length to determine whether an object can be reached (Carello et al., 1979), using one's eye height and shoulder width to determine whether they can walk through an aperture  (Warren & Whang, 1987), using one's hand span to determine whether an object can be grasped (Newell et al., 1989). On the other hand, action-scaled affordances are those constrained by one's action capabilities (e.g., the amount of force they can generate with their muscles), which are determined by dynamic factors such as muscle strength, balance, and flexibility. For instance, to catch a fly ball, the perceiver's ability to catch the flyball is determined by their maximum running speed (Oudejans et al., 1996).

Nevertheless, most affordances do not fit into these dichotomous categories, but are determined by both geometric and dynamic properties. For example, for bipedal step climbing, the maximum step height that one can climb a step bipedally is partly determined by their leg length (e.g., Waren, 1984), but it is also constrained by additional factors such as muscle strength and hip flexibility (Konczak et al., 1992; Cesari et al., 2003) For instance, Comalli et al., (2013) found that young adults and older adults were both accurate at judging their action boundaries and their affordance judgements corresponded closely to their actual ability to perform the action. Young adults perceived steps to be climbable when the riser height was 93% of their leg lengths, whereas older adults perceived steps to be climbable when the riser height was 67% of the leg lengths. However, when comparing the height of steps they actually climbed, young adults attempted climbing steps that were 100% of their leg lengths while older adults attempted climbing steps that were 74% of their leg lengths. These findings suggested that while both groups of adults were accurate at the affordance judgments and took their own biomechanical and action limitations into account, older adults made significantly more conservative motor decisions and were more likely to refuse actions that are well within their action capabilities.

### 1.3 Recalibration

Perception and action are inextricably linked. To perform action successfully, perceptual information about the possibilities for action must be appropriately scaled to one's action capabilities. However, the environment and one's action capabilities are not exactly immutable but could vary over different timescales. Action capabilities and body dimensions could change over a long period of time through naturally occurring changes in body and perceptual-motor capabilities associated with growth, pregnancy or ageing (e.g., Franchak & Adolph, 2004; Koncazk et al., 1992); whereas, short term changes could occur due to factors such as fatigue, injury, change in posture or tool use (e.g., Pijpers et al., 2007; Wagman et al., 2014; Witt et al., 2005). These changes could alter the availability of affordances, as a result, actions that were once possible could become impossible, and conversely, actions that were once impossible now become possible, making it necessary for the mappings between perception and action to be recalibrated to enable accurate perception of affordances. The process of recalibration is imperative to the alignment between perception and action and allows one to adapt to changing environments and possibilities for action.

In addition to people's remarkable ability at discerning affordances, it has also been shown that people are also capable of perceiving affordance accurately even when their body dimensions and action capabilities have changed. For example, Mark (1987) had participants make judgments about the maximum climbable step height and maximum seat height with blocks placed underneath their feet. Information about the climb-on-ability of steps or sit-on-ability of seat is scaled to one's body dimensions such as leg length and standing eye height (Warren, 1984). By standing on the blocks, participants' eye-height information for step/seat height scaling was raised and the same step/seat height was of a smaller proportion of their new standing eye height, and this information must be recalibrated to allow an accurate perception of action possibilities. Results demonstrated that following a brief experience of walking around with the blocks underneath their feet, participants' subsequent affordance judgements were consistent with the changes in body dimensions (i.e., eye height). These results suggested that individuals could rapidly re-learn their action capabilities after a small amount of practice and recalibrate to accommodate overt changes in their action capabilities. Similar patterns of results have shown that individuals are able to recalibrate the relations between perception and action to accommodate changes in their action capabilities for other behaviours, such as making judgements about the passability of apertures while wearing a pregnancy pack that altered the dimensions of their torso (Franchak & Adolph, 2004) or whilst holding a horizontal bar that widens their body width (Yasuda et al., 2014); making judgements about their jumping ability whilst being encumbered by ankle weights (Lessard et al., 2009), adjusting their judgements of whether they can fit their hand through an opening when their hand width has been altered by a prosthesis attached to it (Ishak et al.,2008), updating their reaching ability judgements when their reach has been extended via tool use or when their reach has been restricted by wearing weights on their arm (Wagman, 2012; Witt et al., 2005; Rochat & Wraga, 1997).

## 1.4 Action boundaries

To perceive affordances, one must be able to distinguish between possible and impossible action, and this point of transition between possible and impossible action is typically referred to as the *critical point* (Mark, 1987; Warren, 1984), *affordance threshold* (Franchak, van der Zalm & Adolph, 2010; Ishak, Adolph & Lin, 2008; Lin, Rieser & Bodenheimer, 2015), or

*Action boundary* (Fajen,2007; Connaboy et al., 2020; Smith & Pepping, 2010). Studies of affordance typically involve participants making judgments on the maximum or minimum extent over which they can perform a given action in an environment. For example, the highest step height one can climb bipedally (Warren,1984), the narrowest doorway one can pass through without rotating their shoulders (Warren & Whang, 1987), the largest object one can grasp with their hand (Linkenauger, Lerner, Ramenzoni & Proffitt, 2012), or the furthest object one can reach (Carello et al., 1989). It should be noted that hereafter, this transitional point will be referred to as the *action boundary* for the sake of coherence and simplicity. Action boundary (Fajen, 2005) defines the maximum (and minimum) extent over which one can perform an action, and action is possible if it is within one's action boundary and impossible if it is beyond one's action boundary. Possibilities for action are scaled to one's action boundaries relevant to performing a given action. For instance, the maximum distance over one can reach is the action boundary for reaching, and the maximum extent over which one can grasp is the action boundary for grasping, and so on.

The aforementioned studies have shown that people are able to perceive their action boundaries and affordances with a high level of accuracy in a vast range of tasks. However, it has also been shown that the perception of action boundaries can be influenced by internal state variables such as fatigue and anxiety. For example, Pijpers et al., (2007) examined the influence of fatigue on individuals' perception of their overhead reaching ability in the context of climbing. They induced fatigue in participants by having them engage in a climbing task that gradually increased exertion, after that, they had participants estimate their maximum reaching ability. Findings showed that individuals' internal state influences both their perception of action boundaries and their actual action capabilities, specifically as participants became progressively exhausted, their actual reaching ability declined as a result of fatigue, which led to a decrease in their perceived action boundary size for reaching. Similarly, Pijpers et al.,

(2006) had participants climb across a horizontal route on a climbing wall that was either 0.3m above the ground or 3.60m above the group. Participants have reported feeling more anxious while climbing on the route that was high on the wall, compared to the route that was low on the wall. Findings showed that participants' actual reaching ability and their perceived action boundary for reaching were lower in the high anxiety condition compared to the low anxiety condition, and they were also more conservative with their climb by using more holds in the high anxiety condition. These findings suggest that an increase in anxiety led to a reduction in both the perceived and actual reaching ability in individuals, as well as changes in their motor behaviours. Taken together, these studies indicated that not only individuals' action capabilities were not fixed, but their perception of action boundaries was also not fixed, and the perception of action boundaries should be conceptualised as a continuum rather than discrete categories.

Affordances are binary functions; you either can or cannot perform an action. However, the perception of affordance is unlikely to be binary as the information which the perception of the affordance are based upon is probabilistic. We **learn** what we can or cannot do by doing, and action boundaries are learned over time through perceptual-motor experience via motor explorations in the environment. Infants generate spontaneous exploratory movements from birth in order to identify their action boundaries. (Adolph & Berger, 2013). Twelve-month-old novice walkers traverse roughly 297 metres per hour (Adolph et al., 2012); five-month-old babies produce 100-250 spontaneous exploratory hand and finger movements every ten minutes (Wallace & Whishaw, 2003). As a result of these movements, infants learn the visual information that specifies their action boundaries. Despite this massive amount of experience, our current environment is never the same as the past, and our body and action capabilities are not fixed, even from moment to moment. Indeed, actions cannot be performed with perfect consistency, even under the same task conditions. Hence, the information upon which we judge our affordances has a certain level of uncertainty. As a result, the perception of affordance should be characterised as a probabilistic function rather than a categorical one in order to account for the variable nature of action performance (Franchak & Adolph, 2014a).

Take reaching for example, while one's body dimensions and action capabilities are relatively stable over time, however, there may be situations where one's ability to carry out an action fluctuates to an extent that the previously learned action boundaries no longer serve as a reliable frame of reference to determine whether an action is possible or not. Even in normal circumstances a slight degree of variability exists as our abilities are never completely stable. However, consider the more drastic example an individual recovering from a broken arm. During recovery, bouts of pain, weakened muscles, swelling and stiffness would cause the individual's reachability to vary from one moment to another, resulting in uncertainty. In this case, the success and failure to perform a reach would then vary probabilistically, and the judgement of one's action boundary would be based on a probability distribution rather than an exact, immovable borderline (see Figure 1).

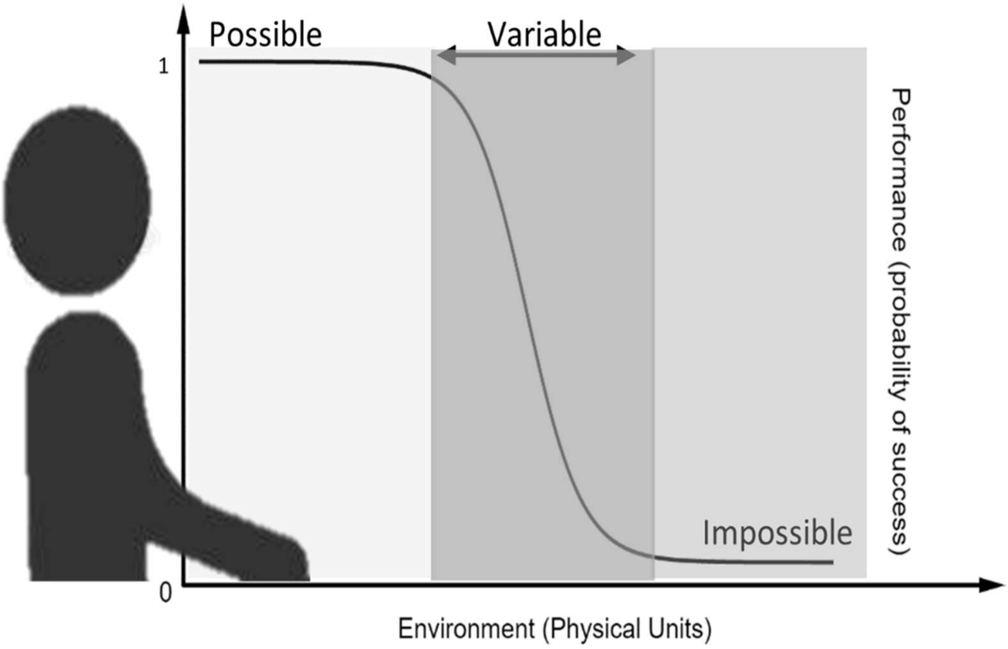

Figure 1. A schematic depiction of an individual whose reaching ability varied as a probabilistic function, in which the probability of success decreases as a function of increased physical units.

Given that the perceptual-motor systems are evolved to extract and process information that facilitates adaptive interactions with the environment, the system of affordances must also be evolved to account for this variability. However, how individuals decide whether they can or cannot perform an action when they have experienced variability and uncertainty in their action capabilities remains unclear.

## 1.5 Perceptual motor variability

Variability is an intrinsic feature of human motor performance. Broadly speaking, motor variability can be defined as the variations or deviations of movement that take place across successive attempts of motor action, or as Bernstein (1967) described this with the phrase “Repetition without repetition”. No matter how hard we try or how much practice we had in perfecting a movement, within each iteration of a movement, there are always some variations in the generation and outcome of motor action. An absolute repetition of any given movement is virtually impossible, due to the intrinsic variability and the dynamic complexity of both the internal environment of our bodies and the external environment in which we act.

Variability in motor performance is often construed as an index of performance quality and proficiency, whereby low levels of variability indicate skilled and controlled performance, and high levels of variability indicate weak and unstable performance (Harris & Wolpert, 2008; Schmidt et al., 1979). Hence, the process of acquiring and improving motor skills typically involves the progressive reduction and ultimately the elimination of performance variability through extensive task-specific practice (Fitts & Peterson, 1964; Ericsson et al., 1993). Nevertheless, while experts of a particular domain or motor skill typically exhibit lower levels of variability, there is always some residual variability even in the simplest and well-learned movements (Komar et al., 2015).

The primary reason for this is because our movements are generated by a nervous system that is inherently ‘noisy’, and variability or noise could happen at any point throughout the motor systems, from the generation and transmission of signals at the cortical planning level (Faisal et al.,2008 ; Renart & Machens, 2014), to the activation of muscles, force production, and the generation of movements at the movement execution level (Hamilton et al., 2004 ; van Beers et al., 2004). Motor variability has been studied extensively in research on motor control and skill acquisitions (Slifkin & Newell, 1998; Chen, Mayer-Kress & Newell, 2005). Until recently, research on motor variability has been heavily influenced by information theory (Shannon, 1948; Shannon & Weaver, 1949; Broadbent, 1958), in which variability in motor performance is typically considered as the result of signals that had been polluted or interfered by random noise or errors during transmissions that underlie perceptual-motor processes. According to this traditional perspective, variability in motor performance is considered a hindrance and is detrimental to motor performances (Newell 2001; Stergiou & Deck, 2011), and variability is something that needed to be attenuated or countered in order to improve the accuracy and stability of motor performance (Harris & Wolpert, 1998). Whereas contemporary views of motor variability suggest that variability provides a window into the working of the motor systems, and that variability plays a critical and functional role in motor learning (Herzfeld & Shadmehr, 2014), by providing the opportunities for one to explore new or alternative movement patterns or strategies in order to discover the optimal or the most stable or efficient way to generate a given movement. Motor variability thus represents the flexibility or adaptability within the motor systems that enable perceivers to accommodate changing external constraints and task demands (Kelso, 1984; Kelso et al., 1980; David et al., 2004).

The exact nature or status of motor variability remains a contentious topic both within and beyond the field of motor control research (Newell & Corcos, 1993). Be it hindrance or necessity, there is little doubt that variability in motor performance exists and has consequences for both ongoing and future motor performance. Although variability in motor performance has received relatively little attention in affordance research (Franchak & Adolph, 2004), some studies provide indirect evidence to suggest that the information about one's motor variability is indeed taken into account when people make decisions about the limits of their action capabilities.

Snapp-Childs and Bingham (2009) used participants' determinations of their ability to step onto or over barriers to provide evidence that people scale their actions not only to the geometric properties of their bodies, but also take into account movement variability to determine their action boundary. They found that young children tended to exhibit higher levels of movement variability and higher toe clearance (i.e., lifting their foot higher as they approached the barrier) when crossing barriers; whereas, adults exhibited a lower level of movement variability and lower toe clearance when crossing barriers. Compared to adults, young children are more variable when generating movements, hence they leave a greater margin of safety when crossing barriers, which suggests that children as young as 4 years old are sensitive to their performance variability and increased the margin of safety in order to compensate for the task-relevant variability and their level of motor competence. Similar findings were reported for aperture passing, in which children and elder adults have been shown to exhibit a high level of motor variability and leave a greater margin of safety when judging whether an aperture affords passing to avoid collision, and they also rotate their shoulders to a greater extent for a given aperture size compared to younger adults (Hackney & Cinelli, 2011; Wilmut & Barnet, 2010;2011). The presence of a larger margin of safety suggests that people take into account their action capabilities and task-relevant movement by making move conservative action boundary judgements.

The aforementioned studies support the notion that individuals make affordance judgements that reflect their own task-relevant movement variability and provide some evidence that information about one's motor variability is taken into account when people make decisions about the limits of their action capabilities. However, in these studies, only individual variability in natural postural sway and shoulder/trunk movement during gait were taken into account. As mentioned in the prior sections, not all perceptual-motor variability is large enough to be detectable when learning action boundaries, but in some instances, perceptual-motor variability is quite evident; perhaps a larger degree of perceptual-motor variability is required when learning or calibrating to new action boundaries in the event of perceptual-motor variability. Furthermore, these studies do not provide direct evidence of the *strategies* by which individuals have used to account for overt perceptual-motor variability in motor performance and recalibrate to new action boundaries following changes in their action capabilities, nor do they provide evidence as to whether a blanket conservative approach is employed to account for motor variability in all motor actions or whether different strategies will be employed for different actions and/or environmental constraints.

## 1.6 Determining action boundary under perceptual-motor uncertainty

Regardless of whether variability is a hindrance or necessity, the human perceptual-motor systems have evolved to extract and process information that facilitates adaptive interactions with the environment, hence there must be a system or some kind of mechanism in place that is designed to address this variability/uncertainty across different actions, types of actions, and environmental contexts. Indeed, making decisions under uncertainty is ubiquitous in our everyday lives, and how humans make decisions under uncertainty has intrigued economists, statisticians and psychologists for decades if not centuries. As a result, many theories and models have been proposed to seek to understand and capture the different strategies people used to make judgements and decisions under various levels of uncertainty and risk (e.g., Savage, 1972; Kahneman & Tversky, 1979; Simon, 1956; Gigerenzer & Todd, 1999 ) and amongst the many models proposed, at the opposite ends of the spectrum are the two decision making approaches, namely, optimising and satisficing.

The underlying assumption of the optimising approach to decision making is that we live in a world full of uncertainties, and the information and inputs from sensory modalities that are available to us are limited or ambiguous. To overcome this, inferential processes are used to weight and integrate information from multiple sources with prior knowledge and/or previous experiences according to their relative reliability and probability of occurrence to compute the best possible solution or strategy for behaviours under uncertainty, essentially generating a statistically optimal solution similar to a weighted average, wherein difference sources of information or input are weighted in proportion to their reliability, and those that are more reliable are attributed with higher weighting in the final solution (Kersten, Mamassian & Yuille, 2004; Deneve & Pouget, 2004).

The perceptual system could determine the appropriate action boundary from a variety of perceptual-motor experiences that conflict in terms of the indication of the observer's action capabilities by using something akin to a weighted average. One could assign a weighting to action boundaries based on the probabilistic information associated with each action boundary they have experienced during perceptual-motor experience. For instance, consider an individual who has experienced two different action boundary sizes (large and small) during their reaching experience, in which they experienced the large action boundary half of the time and the small action boundary half of the time (See Figure 2A). Given that they have experienced both action boundaries with equal probability, they could then take the average of the action boundary experienced, which would be similar to the mean. Alternatively, if they have experienced the large action boundary 75% of the time, and 25% of the time they experienced the small action boundary (See Figure 2B), then more weight would be assigned to the large action boundary as it was encountered more often than the other action boundaries, and the selected action boundary would be closer to the large action boundary (but not as large). Hence, by incorporating probabilistic information in the selection of action boundaries, we would expect individuals' action boundary estimates to reflect a systematic shift in size depending on the weighting attributed to each action boundary experienced.

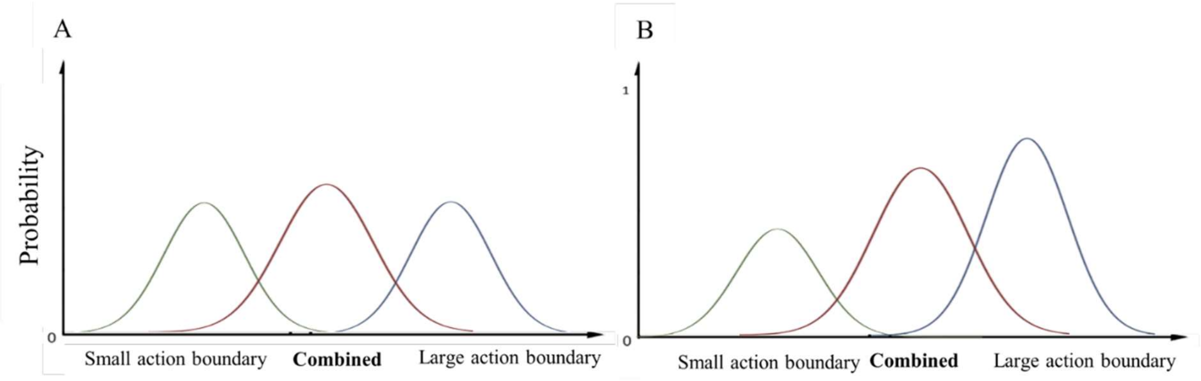

Figure 2. Possible action boundaries selection using a weighted average

Presumably, one would expect the perceptual system to employ such a logical and optimal approach to process information because the human brain is one of the most advanced and powerful information processing systems. Yet, the brain is the most energy-consuming organ in the human body, and both human cognitive and bioenergetic resources are limited (Clarke & Sokoloff, 1999; Niven & Laughlin, 2008; Broadbent, 1958; Mink, Blumenschine, & Adams, 1981), determining action boundaries using this approach would be both time and energy-consuming due to the amount of information processing involved (Howarth, Peppiatt - Wildman & Attwell, 2009).

Evolutionary approaches have characterised the optimising processes underlying such computations as inefficient given that human cognitive capacities are necessarily limited, and some have argued that perceptual systems function to satisfice and produce adaptive behaviours rather than to optimise. For example, research on human decision making has found that individuals rarely make optimal decisions, instead, they make decisions using heuristics (Simon, 1972; Tversky & Kahneman, 1975). Indeed, heuristics are more accurate and adaptive than complex statistical models in real-world decision-making scenarios (Gigerenzer & Gaissmaier, 2011).

Hence, when tasked with selecting the appropriate action boundary using inconsistent perceptual-motor information, the perceptual system could rely on heuristics for the sake of simplification and efficiency by disregarding probabilistic information and limiting the potential options by exploring fewer alternatives. One possible heuristic would be to select the action boundary using the most liberal reach experienced (See Figure 3C), the liberal would allow the perceiver to maximise the number of successful attempts, but at the same time, it may also result in the highest number of unsuccessful attempts. Thus, this approach would only be appropriate in the absence of negative consequences associated with failed attempts.

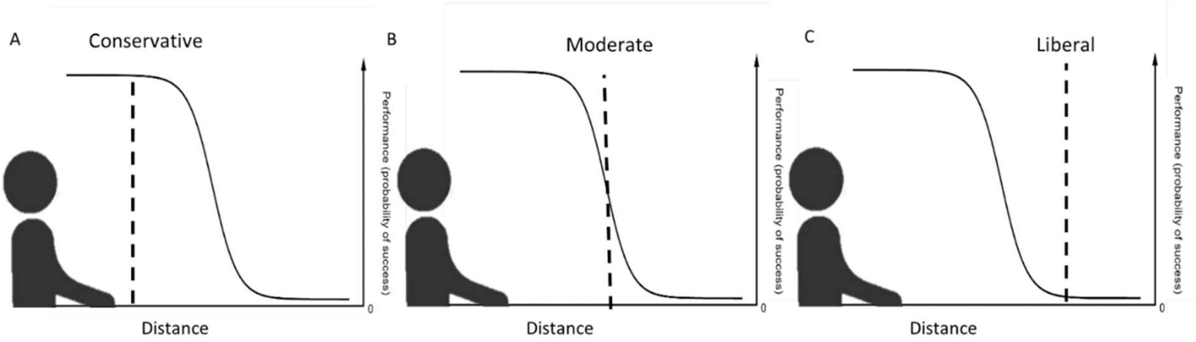

Figure 3. Possible action boundaries selection using the heuristic approach.

The second possible heuristic would be to use the most conservative reach experienced regardless of the variability (See Figure 3A). This approach would be in the perceiver's best interest, especially when making motor decisions in situations in which motor errors are associated with negative consequences. However, this approach would also result in the smallest number of successful attempts. The third possible heuristic would be to select the action boundary using the moderate/medium-sized reach experienced (See Figure 3B), selecting an action boundary size that is in between the most liberal and most conservative action boundary would allow the perceptual system to balance the number of successful attempts with the number of unsuccessful attempts. Taken together, it is reasonable to postulate that, to maximise efficiency, the perceptual system would utilise different strategies on an ad hoc basis to determine perceived action boundaries under conditions of uncertainty.

# Chapter 2: The Influence of Perceptual-Motor Variability on the Perception of Action Boundaries for Reaching

Despite an abundance evidence demonstrating that individuals are extremely sensitive to their action boundary and can flexibly recalibrate to changes in the size of action boundaries in the event of physiological and environmental changes. However, it remains unclear as to how does the perceptual system accounts for perceptual-motor variability in motor performance and recalibrate to new action boundary following changes in one's action capabilities. The current set of studies was framed as a test between optimising versus satisficing approaches, and our hypothesis was not based on ecological approaches of visual perception, but rather evolutionary approaches. In this series of experiments, we used large and observable changes in arm's reach during the perceptual motor calibration phase in order to assess how individuals account for overt perceptual motor variability in motor performance and recalibrate to new action boundary following changes in their action capabilities. Had individuals used a Bayesian-like approach, then they would learn or detect the distribution or probabilistic information associated with the reach lengths they have experienced during the calibration phase and use this information to inform their selection of action boundary size, and we would expect their reachability estimates to reflect a systematic shift in size depending on their weighing of each arm's reach experienced.

# Abstract

Successful interactions within the environment are contingent upon the perceiver's ability to perceive the maximum extent over which they can perform actions, commonly referred to as action boundaries. Individuals are extremely calibrated to their action boundaries, and the perceptual system can quickly and flexibly recalibrate to changes in the size of action boundaries in the event of physiological and/or environmental changes. However, because even the most basic motor activities are subject to variability over time, the information upon which action boundaries are based must also be subject to variability. In this set of studies, we examined the effect of random and systematic variability in reaching experience on the perception of action boundaries for reaching using virtual reality. Participants were asked to estimate their reachability following experience reaching with either a long virtual arm, short virtual arm, or a virtual arm that varied in size. Overall, we found that individuals tended towards liberal estimates of their reachability; however, individuals can be influenced to be slightly more conservative after a higher percentage of short reaches. Consequently, when anticipating our reaching capability in the event of perceptual motor variability, individuals employ a liberal approach as it would result in the highest number of successful attempts.

***Keywords*:** perception, action boundaries, perceptual-motor calibration

# The Influence of Perceptual-Motor Variability on the Perception of Action Boundaries for Reaching

One of the primary functions of visual perception is to guide our actions, as well as to detect and select affordances available in the environment. Affordances refer to possibilities for action for an individual in the given environment (Gibson, 1966; 1979). Affordances signify the reciprocal relationship between the perceiver and the environment, and the selection and the perception of affordances are determined by the perceiver's action capabilities and intentions. The environment provides a countless number of affordances, and any given affordance reflects the current compatibility between the features of the perceiver and the properties of the environment (Gibson, 1979; Warren, 1984). For example, if a surface has a greater rigidity relative to the weight of an individual, the surface affords traversing or standing. Similarly, if an object's width is a lesser proportion of an individual's handspan, the object affords grasping. An action is only possible if the behaviourally-relevant properties of the environment possess certain qualities that satisfy the perceiver's requirements to carry out intended actions. However, it is not enough to be able to perform an action; the perceiver must be able to perceive those behaviourally-relevant properties in the environment with respect to their action capabilities.

Differences in body morphology lead to differences in individual's action capabilities, and individuals use the action-relevant parts of their bodies as perceptual metrics to decide whether the environment affords a particular action (Proffitt & Linkenauger, 2013). The body's morphology and physiology place limits on the extent to which an action can be performed, and the maximum extent of one's capability to perform an action is referred to as an action boundary (Fajen, 2007). An action boundary can be conceptualised as the limit between possible and impossible actions. An action is possible if it is within one's action boundary and impossible if it is outside one's action boundary. For example, the maximum distance over which one can reach is referred to as the action boundary for reaching or the maximum extent over which one can jump is referred to as the action boundary for jumping. The ability to accurately perceive one's action boundaries is fundamental to the perception of affordances and the successful performance of visually guided actions.

Successful interactions with the ever-changing environment are dependent on the perceiver's ability to detect changes in the availability of affordances in the environment. The perceptual system is extremely sensitive to the boundaries of action capabilities, and individuals are very capable of closely estimating their actual ability to perform the action (Fajen, Riley & Turvey, 2009). For example, individuals are highly accurate at judging the maximum height of step that affords climbing bipedally. Regardless of differences in body heights, individuals judge the climb-ability of steps as a constant proportion of leg length (Warren, 1984). Such high degree of accuracy in the perception of action boundaries is found in a variety of actions, such as walking through doorways (Warren & Whang, 1987; Franchak & Adolph, 2012), fitting hands through apertures (Ishak, Franchak & Adolph, 2014), grasping (Linkenauger, Lerner, Ramenzoni & Proffitt, 2012; Linkenauger, Witt, Stefanucci, Bakdash & Proffitt, 2009), and reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Linkenauger, Witt, Bakdash, Stefanucci & Proffitt, 2009). Furthermore, individuals can flexibly adjust their affordance judgements and motor decisions to accommodate changes to their body dimensions, such as reaching through aperture with prostheses attached to their hands (Ishak, Adolph & Lin, 2008), walking through doorways while wearing a pregnancy pack (Franchak & Adolph, 2014), and climbing while wearing blocks under their feet (Mark, 1987).

Perceiving an affordance involves detecting the relation between the perceiver's action capabilities and behaviourally-relevant properties in the environment, and the detection of such relations requires learning (Gibson, 2000). Affordances change throughout life span; these changes are caused by changes in body morphology and perceptual-motor capabilities associated with growth or aging. Hence, action boundaries must be learned over time through perceptual-motor experience via motor exploration in the environment. From birth, infants are constantly initiating spontaneous exploratory movements in order to discover their action boundaries (Adolph & Berger, 2013). When alert, 12 months-old novice walkers travel approximately 297 metres per hour (Adolph et al., 2012); Infants as young as 5 months of age make approximately 100-250 different spontaneous hand and digit movements every 10 minutes (Wallace & Whishaw, 2003). These movements result in infants learning the optical information that specifies the maximum extent of their action capabilities. Over the course of their development, the range of action possibilities expand as a result of increased motor proficiency and action capabilities. Through their interactions with the environment, individuals learn and calibrate their action boundaries to identify potential action possibilities in the environment, as well as to utilise more efficient strategies to navigate their surroundings (Adolph & Tamis-LeMonda, 2014).

Experience with one’s action capabilities is accumulated since infancy, and upon entering adulthood, one’s body morphology remains relatively stable over time. Hence, the perceptual motor feedback specifying an action boundary is often consistent, thus providing a reliable frame of reference for the selection and performance of action possibilities. However, with an action that is learned over time, variability in the outcome is always present however small. Hence, regardless of how consistent an action’s outcome may appear, the perceptual motor feedback specifying action boundaries is always characterised by variability. Indeed, individuals have been shown to make affordance judgements that reflect their own task-relevant movement variability. For instance, young children and elderlies leave greater margin of safety for tasks such as aperture passing and stepping up compared to adults, suggest that they are taking their own action capabilities and movement variability into account by making more conservative affordance judgements (Wilmut & Barrnet, 2010; 2011; Snapp-childs & Bingham, 2009; Hackney & Cinelli, 2011).

Additionally, in certain contexts, the perceptual motor feedback specifying an action boundary is much more inconsistent due to changes in the body and action capacities, which introduces a large amount of variability into the perceptual-motor feedback which specifies action boundaries. Factors such as injuries, illness, level of fitness/fatigue, or even as simple as carrying additional weight, can lead to changes in body, and consequently, inconsistent fluctuations in the perceptual motor feedback specifying one's action capabilities (Franchak & Adolph, 2014). For instance, consider an individual recovering from a broken arm. Pain, weakened muscles, swelling and stiffness would cause the individual's reachability to vary from one moment to another. If the maximum extent over which one can reach is constantly fluctuating, which sized action boundary will the perceptual system calibrate to in order to ensure successful performance of action?

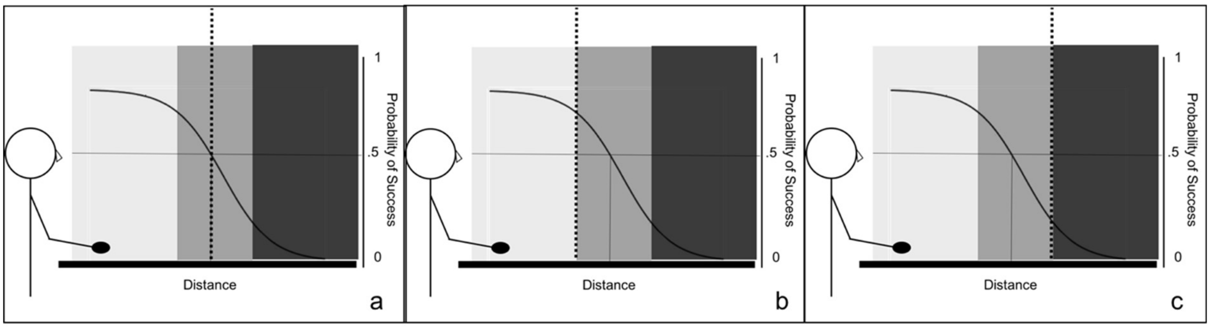

Figure 1. Possible action boundaries in the event of perceptual motor variability for reaching.

Consider Figure 1, wherein each panel is an illustration of an individual whose reaching capabilities has been subject to variability. Due to the variability in action experience, there is a probability distribution in which the central shaded grey area represents the degree of uncertainty. Specifically, the actor has learned through variable perceptual motor experience that the maximum extent of their reach varies randomly within the central grey area so that there is an equal probability that their maximum reach will be at the intersection between the light grey and central grey area as it will be at the intersection between the central grey and dark grey area. After experiencing this variability, how do individuals consequently determine their action boundaries?

It is possible that the perceptual system would select action boundary size using the average experienced reach to generate optimal perceptual decision with respect to increasing successful attempts while minimising failed attempts (Körding & Wolpert, 2006). For instance, consider a perceiver who can fully extend her arm and execute reaches that are 100% of her normal reach half of the time, and the other half of the time, she can only partially extend her arm and execute 50% of her normal reach. When deciding whether a target is reachable with such inconsistent information, the perceptual system could take the average of all the reach lengths experienced, which is approximately 75% of normal reach, and use it as the action boundary, see Figure1a, where the dotted line represents the average action boundary.

Intuitively, one would presume the perceptual system would employ such highly efficient and optimal approach to process information, since the human brain is arguably the most intricate information processing system and has impressive processing power. However, it is also the most energy consuming organ in the human body and has a limited capacity (Mink et al., 1981; Broadbent, 1958). Alternatively, it has been suggested that natural selection has shaped perceptual system to be satisficing rather than optimising (Gigerenzer & Goldstein, 1996; Hoffman, Singh & Prakash, 2015). This hypothesis is not based on ecological approaches of direct perception (as most action boundaries are not optically specified), but rather evolutionary approaches which characterise optimising processes as inefficient. For example, research on human decision making has found that individuals seldom make optimal decisions in everyday lives, instead they make decisions that are just ‘good enough’ and their patterns of decision making reflect a reliance on heuristics (Tversky & Kahneman, 1975; Simon, 1957). Indeed, simple heuristics have often been found to be more accurate and adaptive than complex statistical models in real world situations (Gigerenzer & Gaissmaier, 2011). With that being the case, when tasked with selecting the appropriate action boundary using inconsistent perceptual-motor information, the perceptual system could possibly rely on heuristics for the sake of simplification and efficiency. One such heuristic would be to use the most conservative reach experienced regardless of the variability. In this case, it would be in the perceiver's best interest to err on the side of caution when making motor decisions especially under conditions of uncertainty, which might be indicative of injury, see Figure 1b where the dotted line indicates the most conservative action boundary.

Alternatively, perceivers could also use a heuristic in which the action boundary is decided using the most liberal reach experience. This option would benefit the perceiver in the absence of consequences associated with a failed action, because it would result in the highest number of successful attempts, see Figure 1c, where the dotted line indicates the most liberal action boundary.

Unfortunately, introducing a large degree of *controlled* perceptual motor variability into one's perceptual motor feedback is near impossible to investigate in the real world, due to the consistency of the body morphology (or inconsistency at times). Alternatively, a small degree of variability would result in a difficulty in detecting an effect in the dependent measure. However, by using virtual reality and motion capture technology, in virtual environments (VEs), individuals can experience a self-representing avatar from a first-person perspective (which appears as their virtual body) whose movements are animated by the user's own movements in real time. Individuals experience a strong sense of body ownership over their virtual limbs following this sensory motor synchrony between the physical and virtual body parts (Argelaguet et al., 2016), even when their bodies are represented by virtual bodies that differ substantially from their own (Kilteni, Bergstrom & Slater, 2013). The visual feedback from individuals' virtual bodies following the movement of their physical bodies can be controlled and manipulated in a structured manner.

Studies using virtual reality have found that individuals react to and interact with the virtual environment and treat their avatar bodies as if they are real. For example, individuals with paranoid tendencies have reported persecutory beliefs about virtual avatars (Freeman, et al, 2003; 2005), exhibited biases towards virtual avatars with dark skin-tone that mirror real-world racial biases (Rossen et al., 2008), and exhibited behavioural and physiological responses that were indication of distress when instructed to electrocute a virtual avatar (Slater et al., 2006). Lastly, in a study that employed virtual reality to examine the effect of perceptual-motor experience on perceived action boundary size on perceived distances has obtained results consistent with manipulations of perceptual-motor experience on perceived action boundary size for reaching in real world. In this study, participants perceived the distance to target to be closer when they were calibrated to long virtual arm compared to when they were calibrated to a short virtual arm (Linkenauger, Bülthoff & Mohler, 2015). This is consistent with findings reported by Witt et al. (2005), in which participants perceived targets to be closer when their reachability was extended with a tool in the real world. Taken together, this technology permits the manipulation of perceptual-motor couplings that would result in outcomes that are comparable to those occurring in the real world.

In addition to manipulations in the sizes of perceptual motor couplings, this technology also allows us to assess how introduction of variability in those perceptual-motor couplings influences perceived action boundaries. In a series of studies, we examined the effect of random and systematic perceptual motor variability on the perception of action boundaries using virtual reality and motion capture technology. Participants engaged in a calibration phase where they executed a series of reaches to targets of various distances with either a long virtual arm, short virtual arm, or a virtual arm that varied in size across the reaching trials. After the calibration phase, participants estimated their maximum reachability.

# Experiment 1

In this experiment, we investigated the effect of random variability on the perception of action boundaries. In a virtual environment, participants estimated their maximum reachability after being calibrated with either a long virtual arm, a short virtual arm, or a virtual arm that varied in size randomly.

## Method

### Participants

GPower software application (Faul, Erdfelder, Lang, & Buchner, 2007) was used to perform an a priori power analysis to estimate sample sizes required to achieve adequate power. The required power was set at $1- \beta = .80$, and the level of significance was kept at $\alpha = .05$. We expected a large effect size of .4 based on Linkenauger, Bülthoff & Mohler (2015) in Experiment 1, where a similar paradigm was used, and participants were asked to make distance judgements following experience reaching with either a long virtual arm or a short virtual arm. In this study, an f value of .83 was obtained using a sample size of N = 12. For the frequentist tests provided, a power analysis indicated that a sample size of N = 15 would be sufficient to achieve a power of .80 and an alpha of .05. Our sample sizes also matched those used by Rochat and Wraga (1997) in Experiment 5, where participants were asked to make reachability judgements without limiting degrees of freedom and engaged their whole body, which was similar to the paradigm used in the current set of studies in which participants were able to reach and make reachability judgement on the basis of multiple degrees of freedom that are normally available to execute similar reaching motion. Taken together, we have increased our sample sizes to 20 with one extra (N = 21) due to the possibility of technical failure with this type of equipment.

Twenty-one participants (21 Females) between 18 to 25 years of age ($M_{age}$ = 19.00 years, $SD_{age}$ = 1.48 years) were recruited from Lancaster University through opportunity sampling. All participants but one was right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

## Stimuli and Apparatus

The experiment was conducted in front of a table and a chair was placed in front of it. A laptop was placed on the table and a keyboard was placed on the right of the participant. Participants wore an Oculus Rift CV1 head-mounted display (HMD) that displayed a stereoscopic image of the virtual environment with a resolution of 2160 x 1200 pixel and a frame rate of 90Hz. The position of participants' arms and hands were tracked using a Leap Motion hand tracking sensor mounted on the front of the Oculus HMD. The leap motion fully animates the arm and individual finger movements in real time based on the movements of the user.

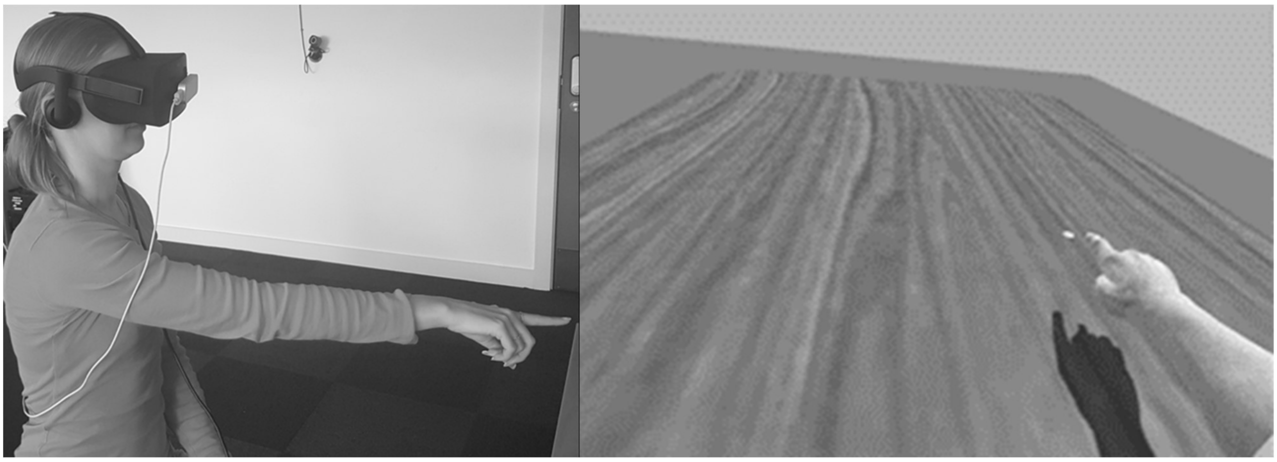

Figure 2. Left panel: Illustration of a participant completing a calibration trial. Right panel: Image of what the participant would see while completing the calibration trial.

The experimental program and environment were created using Unity 3D© Gaming Engine with the Leap Motion plugin. For the virtual environment, a 3D model of a room was used. A table was placed in the middle of the room in the virtual environment, the 3D camera and virtual avatar were placed in front of the table. A pink dot (2cm in diameter) was placed on the edge of the table directly in front of the core of the participant's core. This dot served as a reference point and represented the egocentric location of the participant. Participants were seated. The 3D camera was placed at eye-level of the avatar enabling the participant to perceive the virtual environment in a first-person perspective, and they were positioned in the virtual environment so that they were seated directly in front of the virtual table, see Figure 2. The movement of the participant's head was tracked, and the perspective of the participant was updated as the participant looked around in the virtual environment when moving their head. The movement and position of participant's tracked hands were mapped onto the virtual arm and hand in real time, so that the movement of the virtual hand was congruent with the movement of participant's actual hand. The avatar hands that we used were taken from the realistic human hand models provided by the Leap Motion V2 SDK. Three different virtual arm sizes were used: the original arm model was used for the normal arm's reach; the length of the original arm model was mapped onto the physical model derived from actual arm length of each participant. For the extended arm's reach, the virtual arm was scaled as 50% longer than the original arm model, and for the constricted arm's reach, the virtual arm was scaled as 50% shorter than the original arm model.

## Procedure

After providing their informed consent, participants were asked to sit facing the table. They were given instructions for both the calibration and estimation phases of the experiment. After donning the Oculus HMD, participants completed three experimental conditions, which were counterbalanced across participants. In the extended reach condition, the virtual arm was 50% longer than the participant's normal arm and was made to reach 50% farther than their physical reach. In the constricted reach condition, the virtual arm was limited to 50% of participant's physical reach with the arm being 50% shorter than the participant's normal arm. In the variable reach condition, the virtual arm varied randomly between the extended arm's reach, the constricted arm's reach and the normal arm's reach across calibration trials. In this study, Participants experienced all reaches with equal probability.

Each condition consisted of two parts: calibration and estimation. The calibration phase consisted of 54 trials in which a green dot was presented on the left, right or in front of the participant. Participants were instructed to reach and touch the green dot with their virtual hand. If the dot was too far for the participants to reach, they were instructed to point towards it instead. Participants were told that it is okay if they could not reach the dot, as long as they have tried their best. After they reached out and touched the dot, the dot disappeared and another green dot at a different location appeared. The dots were presented at one of the three horizontal distances from the reference point (20, 40 or 60 cm) and the dots were either presented directly in front of the participant or 50 cm to the left or right of the reference point, for a total of nine possible dot locations each presented six times for a total of 54 trials with dot location being presented in random order.

Participants engaged in the estimation phase after completing the calibration phase. Participants were wearing the HMD and could not see the keyboard, therefore at the beginning of the estimation phase, the experimenter placed the participants' fingers on the arrow keys. If participants could not find the arrow keys at any point during the experiment, the experimenter would reposition their fingers back to the arrow keys. The estimation phase consisted of 12 trials, in which participants were instructed to use the arrow keys to move the position of a blue dot (estimation dot) so that the dot was just within their reach. The left arrow key moved the estimation dot away from the participant and the right arrow key moved the dot towards the participant. Each button press moved the blue dot 1 cm towards or away from the reference dot. For half of the trials, the estimation dot originated at the same location as the reference dot (directly in front of the participant). During these trials, the virtual hand was removed from the scene so that participants had no visual feedback about their arm length. For these trials, participants moved the estimation dot away from them. The dot moved in one of 3 directions: ipsilateral, contralateral and straight. In order to control for hysteresis, for the other half of the trials, the estimation dot's starting position was a 1m horizontal distance and the participant moved the dot towards them. For these trials, the estimation dot started directly in front or .5m to the left or right (these dots moved diagonally towards the reference point). Hence, the dots either started close to or far away from the participant and were either presented (or moved to) on the left or right, or in front of the participant, for a total of six locations each presented twice for a total of 12 trials, see Figure 3. Participants were instructed to make as many fine adjustments as they needed until they were satisfied with their estimate of their reaching ability. After they were satisfied with their estimate, the dot disappeared, and the next trial began.

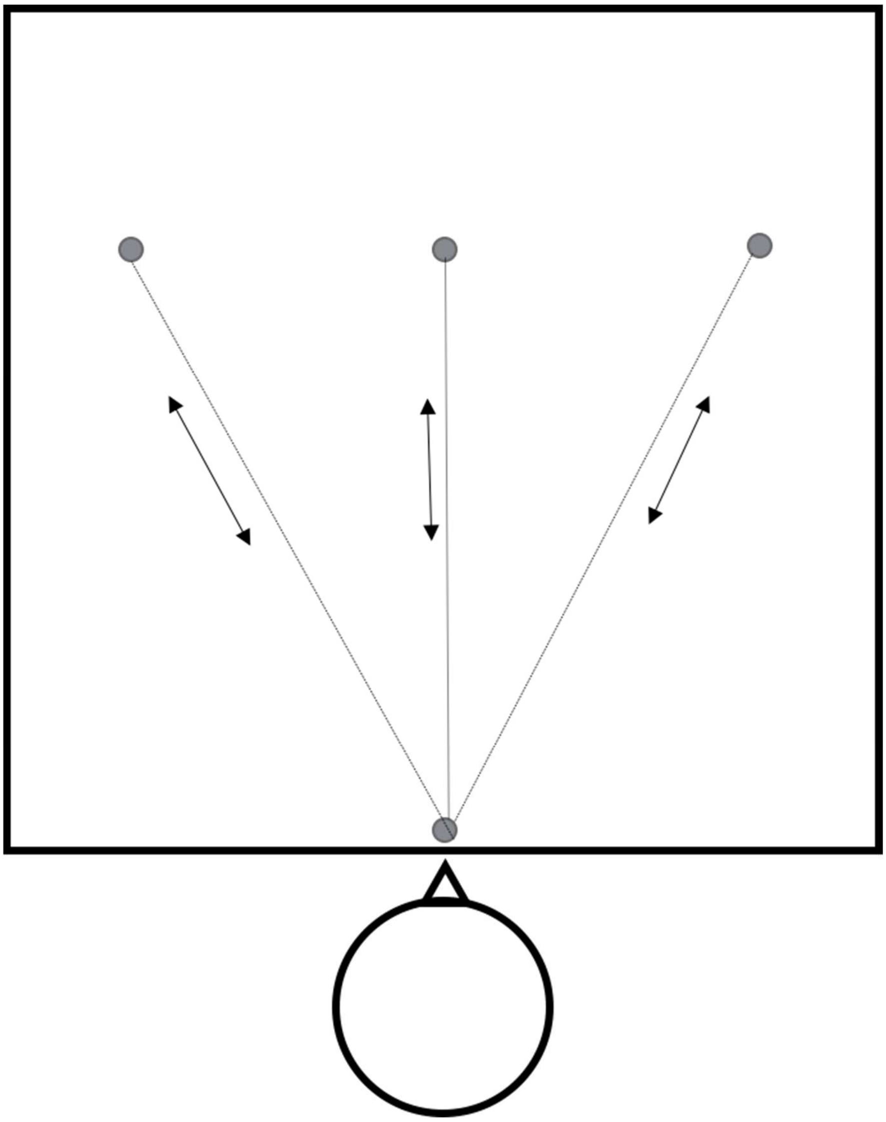

Figure 3. Diagram of the estimation phase. The grey dots represent the initial dot positions and the arrows and dotted lines represent the axis upon each dot moved.

## Data Analysis

We report repeated-measure ANOVAs, and Bayes factors alongside p-values for all one degree-of-freedom tests of key hypotheses. Our analyses are interpreted with regards to Bayes factors, which measure the probability of the data assuming one hypothesis (e.g., the experimental hypothesis, H1) relative to another hypothesis (e.g., the null hypothesis, H0). Bayes factors thus provide a continuous measure of relative evidence, in contrast to the p-value which attempts to control type 1 error rates (for a discussion and comparison of Bayes factors and p-values, see Lakens, McLatchie, Isager, Scheel & Dienes, 2018). The experimental hypothesis was specified using a scale of effect of 0.1m as Linkenauger, Mohler and Bülfhoff (2015) found a difference of roughly .05m in a similar virtual environment experiment with different virtual arm lengths, except instead of estimating affordances, participants estimated perceived distance. As differences between reaching capability estimates tend to be more sensitive and result in larger effects (see Linkenauger, et al., 2009), we anticipated up to double the magnitude of the effect reported by Linkenauger et al (2015). Bayes factors were calculated using the Dienes and McLatchie (2018) R script calculator, and robustness regions (RR) are provided to indicate the smallest and largest effect size that could be used to specify H1 that still yield the same conclusions. Bayes factors greater than 3 and 10 are interpreted as moderate and strong evidence respectively for the experimental hypothesis, while Bayes factors less than .33 and .10 are interpreted as moderate and strong evidence respectively for the null hypothesis. Bayes factors between .33 and 3 are interpreted as weak and inconclusive evidence. Note that these thresholds are simply to aid interpretation, and to make transparent the thresholds used to make decisions for all three studies, but that the Bayes factor itself is a continuous measure.

# Results

To analyse the influence of reaching condition on reachability estimates, where reachability was defined as the farthest extent to which participants estimated they could reach. We employed a repeated measures ANOVA with reaching condition (extended/ constricted/variable) and direction (left/right/centre) as within-subjects variables and the estimated reachability as the dependent variable.

The analysis provided Greenhouse-Geisser corrected degrees of freedom to account for possible violations of sphericity, therefore the degrees of freedom were not always integers. As predicted, analysis showed effects of reaching condition on estimated reachability, $F(1.23, 24.56) = 12.04$, $p = .001$, $\eta_p^2 = .38$. Bonferroni post-hoc analysis showed that participants estimated the extent of their reach as being farther in the extended reach condition ($M = .67$m, $SE = .03$m) than in the constricted reach condition ($M = .50$m, $SE = .03$m, $p < .001$, $B_{H(0, 0.10)} = 4.67 \times 10^4$, $RR[0.008, 57.29]$). They also estimated their reachability to be farther in the variable condition ($M = .63$m, $SE = .03$m, $p = .04$, $B_{H(0, 0.10)} = 16.94$, $RR[0.03, 1.24]$) than in the constricted reach condition. However, the evidence for the difference between the variable and extended reach condition was inconclusive ($B_{H(0, 0.10)} = 1.80$, $RR[0, 0.58]$, $p = .39$). These results suggested that there was strong evidence for a difference between the variable and constricted condition but that this evidence was lacking for the difference between the variable and extended conditions, see Figure 4.

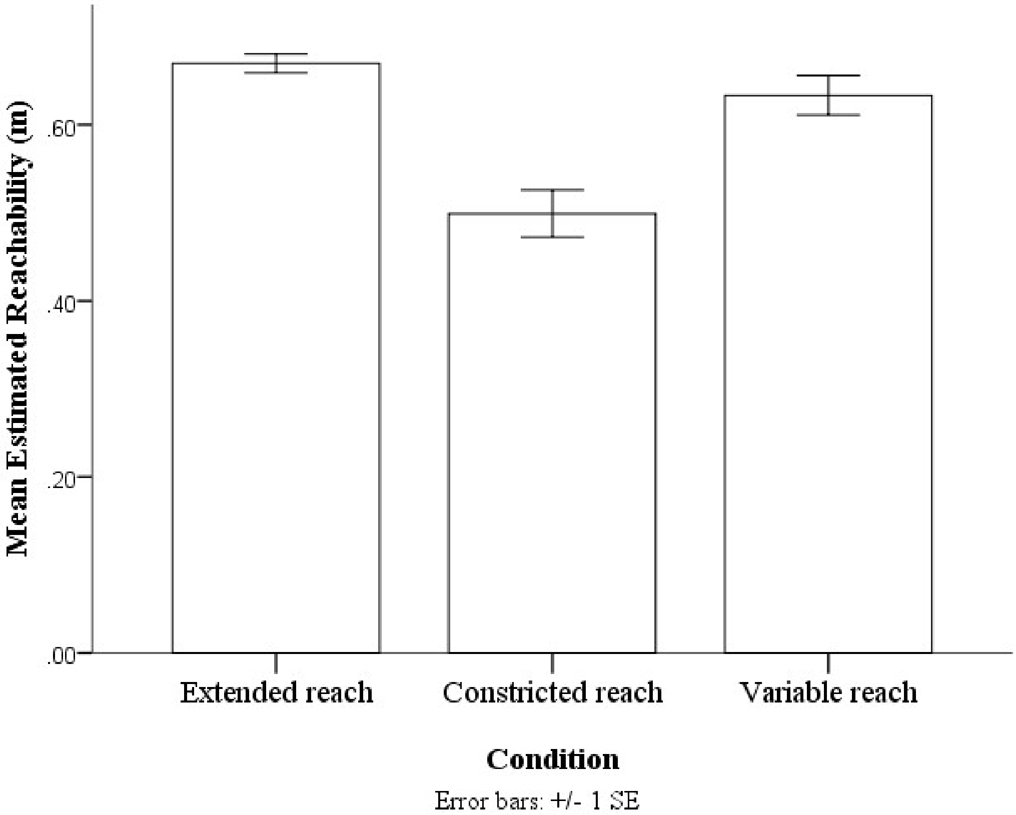

Figure 4. The mean estimated reachability of the three reaching conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

Direction significantly influenced estimated reachability, $F(1.44,28.80) = 26.16$, $p < .001$, $\eta_p{}^2 = .57$. Participants estimated their reachability for targets on the left, ($M = .63$m, $SE = .03$m) to be farther than targets on the right ($M = .58$m, $SE = .03$m, $p < .001$, $B_{H(0, 0.10)} = 1.39 \times 10^{10}$, $RR[0.002, 18.59]$) and those in the centre ($M = .59$m, $SE = .03$m, $p = .001$, $B_{H(0, 0.10)} = 3.90 \times 10^4$, $RR[0.002, 13.48]$). The evidence was inconclusive for the estimated reachability of targets on the right and in the centre, $p = .19$, $B_{H(0, 0.10)} = 0.57$, $RR[0, 0.17]$, see Figure 5. The interaction between reaching condition and direction was not significant, $F(4,80) = .60$, $p = .67$, $\eta p^2 = .03$.

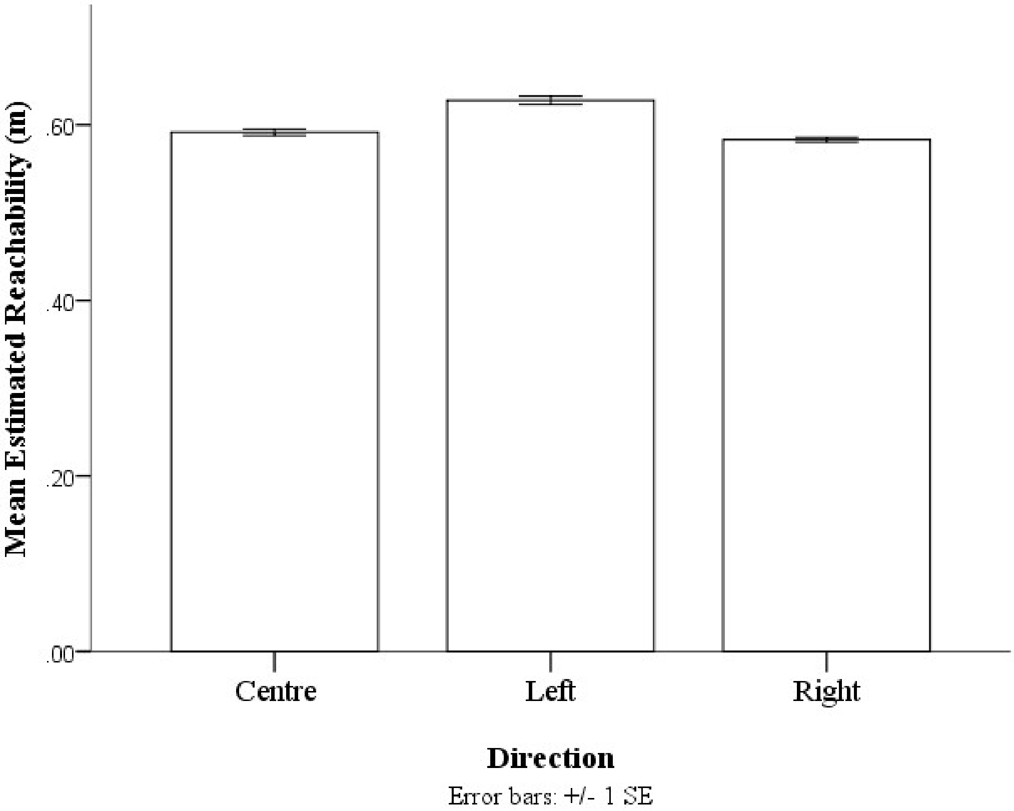

Figure 5. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

# Experiment 2

Findings from Experiment 1 showed that when all reaches were experienced with equal probability, individuals were more liberal with their reachability estimates than one would expected if they were using a weighted average of their experience. Therefore, it is possible that when faced with random variability, the perceptual system would select the action boundary using heuristics in which the action boundary is decided using the most liberal reach experience. To explore this further, Experiment 2 investigated how individuals select their action boundaries when the perceptual motor experience is systematically weighed in that individuals experienced the farther reach substantially more often than the other reaches; and whether individuals would favour an even more liberal action boundary if they have more experience with the farther reach.

## Method

### Participants

Twenty-one participants (16 Females) between 18 to 49 years of age ($M_{\text{age}}$ = 22.62 years, $SD_{\text{age}}$ = 6.90 years) were recruited from Lancaster University through opportunity sampling. All participants but one were right-handed. All participants provided informed consent. All participants had normal or corrected-to-normal vision. This study was approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experimental set-up was the same as in Experiment 1. Participants estimated their maximum reachability after being calibrated with either a long virtual arm, short virtual arm, or a virtual arm that varied in size systematically.

### Procedure

After giving their informed consent, participants were asked to sit facing the table. They were given instructions to the visual matching task and put on the Oculus HMD. Participants completed three experimental conditions, which were counterbalanced across participants. In the extended reach condition, the virtual arm was 50% longer than the participant’s normal arm and was made to reach 50% farther than their physical reach. In the constricted reach condition, the virtual arm was limited to 50% of participant’s physical reach with the arm being 50% shorter than the participant’s normal arm. In the variable reach condition, the virtual arm varied between the extended arm’s reach, the constricted arm’s reach and the normal arm’s reach across calibration trials. In this study, 50% of their reaches had the extended arm's reach, 25% of the reaches had the constricted arm's reach, and 25% of their reaches had the normal arm's reach; all reaches were experienced in a randomised order.

## Results

A repeated measures ANOVA was conducted with reaching condition (extended/ constricted/variable) and direction (left/right/centre) as within-subjects variables and the estimated reachability as the dependent variable.

There was a main effect of reaching condition on estimated reachability, *F*(2, 40) = 10.12, $p < .001$, $\eta p^2 = .34$. Participants estimated their reachability to be farther in the extended reach condition (*M* = .65, *SE* = .04) than in the constricted reach condition (*M* = .49, *SE* = .05, $p = .003$, $B_{H(0,\ 0.10)} = 512.57$, *RR*[0.02, 43.53]). They also estimated their reachability to be farther in the variable condition (*M* = .62, *SE* = .04) than in the constricted reach condition ($p = .01$, $B_{H(0,\ 0.10)} = 16.94$, *RR*[0.03, 1.24]), see Figure 6. Furthermore, we found weak, inconclusive evidence for there being no difference between the extended and variable reach conditions ($B_{H(0,\ 0.10)} = 0.75$, *RR*[0, 0.24], $p > .99$).

These results suggest that, after having more experience with the extended arm's reach than the normal and constricted arm's reach during the calibration phase of the variation reach condition, participants were liberal with their estimations, but no more than when all reaches were experienced with equal probability.

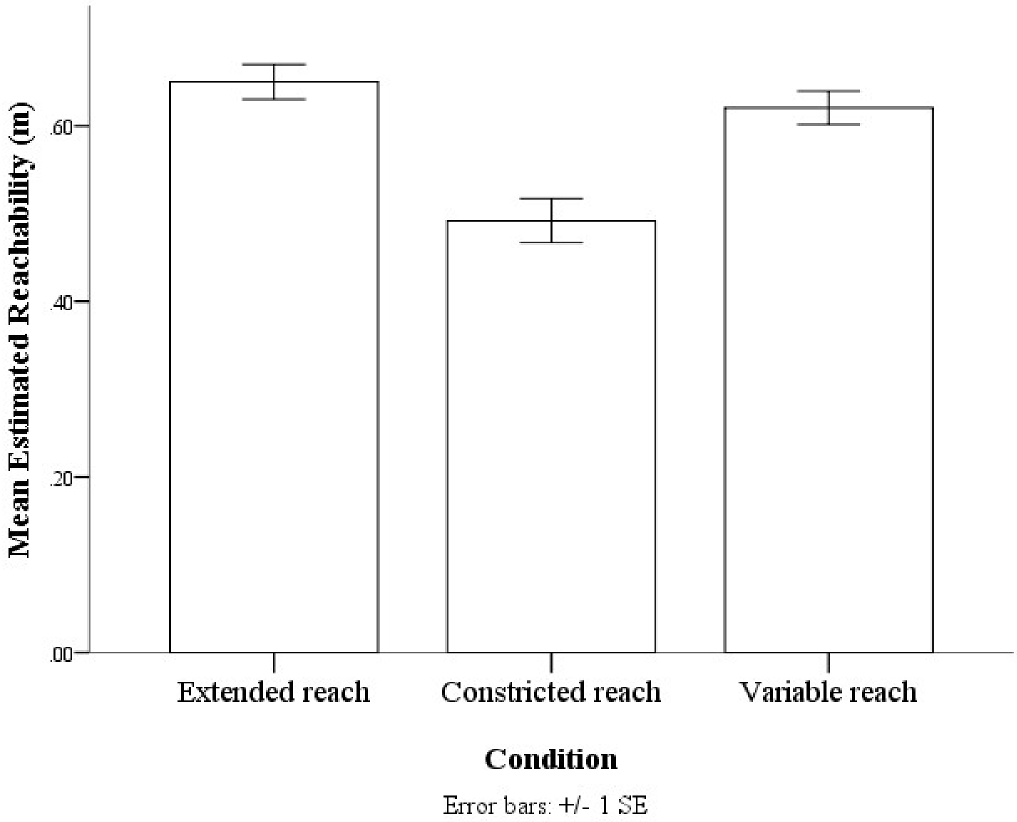

Figure 6. The mean estimated reachability of the three reaching conditions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

There was a significant effect of direction on estimated reachability, *F*(2, 40) = 15.12, $p < .001$, $\eta_p^2 = .43$. Bonferroni post-hoc analyses revealed a difference in estimated reachability between the different directions. The estimated reachability for targets on the left, (*M* = .61m, *SE* = .04m), was longer than those on the right (*M* = .58m, *SE* = .04m, $p < .001$, $B_{H(0,\ 0.10)} = 3.03 \times 10^4$, *RR*[0.002, 10.10]) and those in the centre (*M* = .58m, *SE* = .04m, $p = .001$, $B_{H(0,\ 0.10)} = 6.09 \times 10^6$, *RR*[0.001, 10.76]). The data also provided strong evidence for the null hypothesis when comparing the estimated reachability for targets on the right and in the centre, $p > .99$, $B_{H(0,\ 0.10)} = 0.07$, *RR*[0.02, ∞]. The interaction between reaching condition and direction was not significant, *F*(4,68) = .66, $p = .62$, $\eta_p^2 = .04$, see Figure 7.

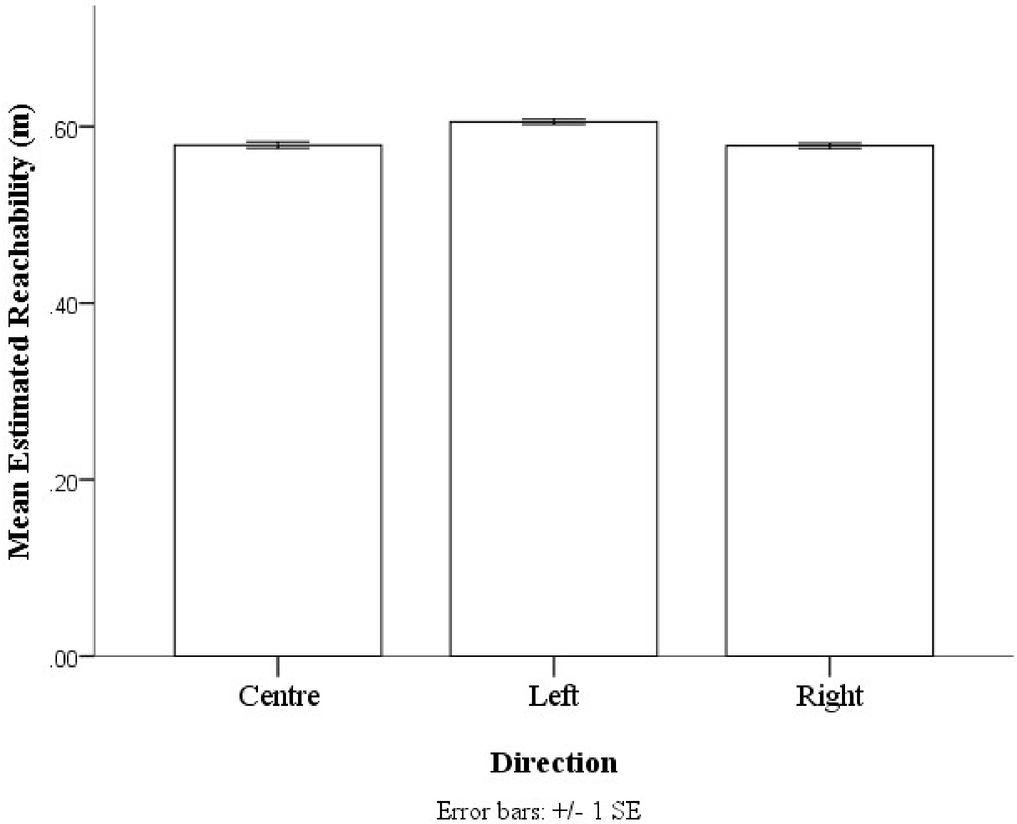

Figure 7. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

# Experiment 3

Findings from Experiment 1 and 2 showed that regardless of whether they have experienced all reaches with equal probabilities or whether their perceptual motor experience was systematically weighed in that they experienced the farther reach substantially more often than other reaches, participants selected the action boundary using the most liberal reach experience. To provide more clarity, in Experiment 3 we sought to investigate how individuals select their action boundaries when they experience the constricted reach substantially more often than the other reaches. If participants use the most liberal sized action boundary as their perceptual metric, the reachability estimations in the variable condition would be similar to those in Experiment 1 and 2. However, it is also possible that while participants have the tendency to use the most liberal sized action boundary as a perceptual metric, having more experience with the constricted reach could lead individuals to decrease their estimates of their reaches to a more conservative size.

## Method

### Participants

Twenty-six participants (21 Females) between 18 to 22 years of age ($M_{age}$ = 19.46 years, $SD_{age}$ = 1.24 years) were recruited from Lancaster University through opportunity sampling. All participants but three were right-handed. All participants had normal or corrected-to-normal vision.  All participants have given informed consent. This study has been approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experimental set-up was the same as in Experiment 1 and 2. Participants estimated their maximum reachability after being calibrated with either a long virtual arm, short virtual arm, or a virtual arm that varied in size systematically.

### Procedure

After giving their informed consent, participants were asked to sit facing the table. They were given instructions to the visual matching task and put on the Oculus HMD. Participants completed three experimental conditions, which were counterbalanced across participants. In the extended reach condition, the virtual arm was 50% longer than the participant's normal arm and was made to reach 50% farther than their physical reach. In the constricted reach condition, the virtual arm was limited to 50% of participant's physical reach with the arm being 50% shorter than the participant's normal arm. In the variable reach condition, the virtual arm varied between the extended arm's reach, the constricted arm's reach and the normal arm's reach across calibration trials. In this study, 25% of their reaches had the extended arm's reach, 50% of the reaches had the constricted arm's reach, and 25% of their reaches had the normal arm's reach, all reaches were experienced in a randomised order.

## Results

A repeated measures ANOVA was conducted with reaching condition (extended/ constricted/variable) and direction (left/right/centre) as within-subjects variables and the estimated reachability as the dependent variable[1].

There was a main effect of reaching condition on estimated reachability, $F(2, 50) = 22.00$, $p < .001$, $\eta p^2 = .47$. Participants estimated their reachability to be farther in the extended reach condition ($M = .70$, $SE = .04$) than in the constricted reach condition ($M = .49$, $SE = .04$, $p < .001$, $B_{\mathrm{H}(0, 0.10)} = 7.24$ x 105, *RR*[0.008, 75.43]). They also estimated their reachability to be farther in the variable condition ($M = .62$, $SE = .03$, $p = .001$, $B_{\mathrm{H}(0, 0.10)} = 1943.48$, *RR*[0.009, 40.64]) than in the constricted reach condition. Furthermore, we found evidence for a difference between the extended and variable conditions ($B_{H(0, 0.10)} = 28.12$, *RR*[.02, 1.29], $p = .02$). The results therefore indicate that there was strong evidence for a difference between the variable condition and both the extended and constricted conditions, although the magnitude of the obtained effects indicates that participants tended to provide more liberal than conservative estimates, see Figure 8.

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[1] The p-values in this section should be interpreted with caution. We initially recruited 21 participants for Study 3, but recruited 5 more participants following an initial review of the manuscript. See Sagarin, Ambler & Lee (2014) for a discussion of how recruiting participants after peeking at the results can inflate the type 1 error rate.

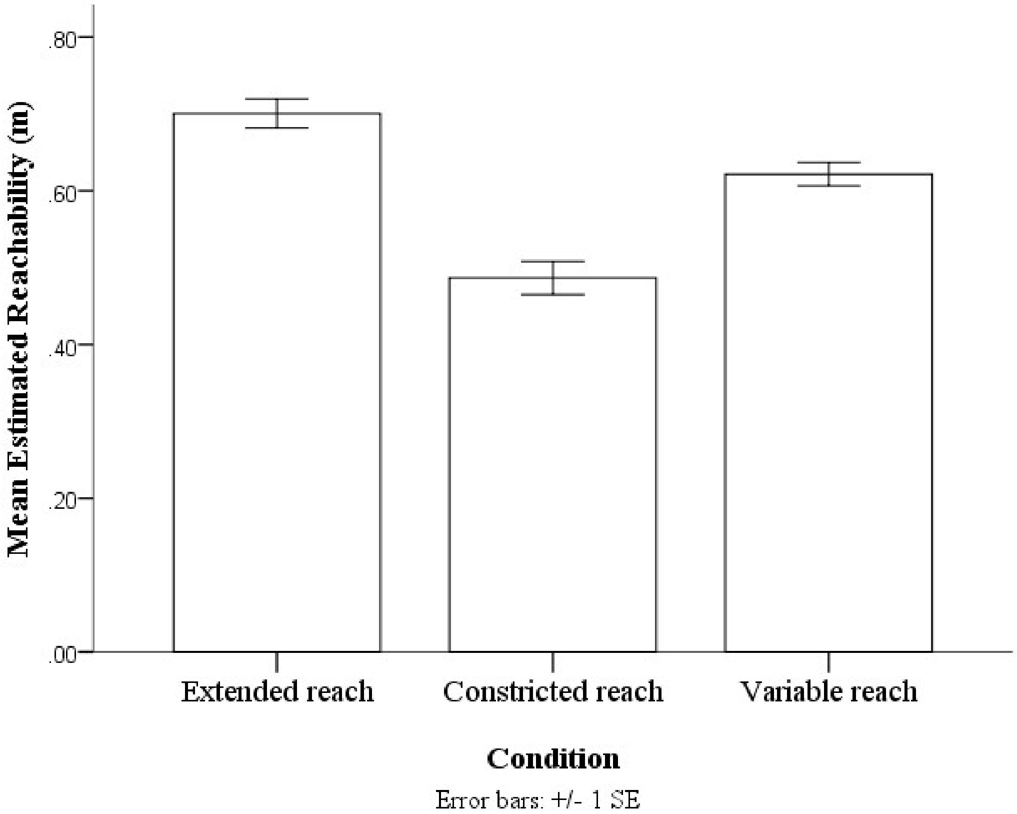

Figure 8. The mean estimated reachability of the three reaching conditions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

There was a significant effect of direction on estimated reachability, $F(2, 50) = 34.97$, $p < .001$, $\eta_p^2 = .58$. Bonferroni post-hoc analysis revealed differences in estimated reachability between different directions. The estimated reachability for targets on the left, ($M = .63$m, $SE = .03$m), was longer than those on the right ($M = .58$m, $SE = .03$m, $p < .001$, $B_{H(0, 0.10)} = 2.99 \times 10^{16}$, $RR[0, 17.22]$) and those in the centre ($M = .60$m, $SE = .03$m, $p = .001$, $B_{H(0, 0.10)} = 3795.81$, $RR[0.002, 7.41]$). Participants also estimated their reachability for targets on the centre to be farther than targets on the right, $p = .003$, $B_{H(0, 0.10)} = 96.94$, $RR[0.001, 3.02]$, see Figure 9. The interaction between reaching condition and direction was not significant, $F(4,100) = .83$, $p = .51$, $\eta_p^2 = .03$.

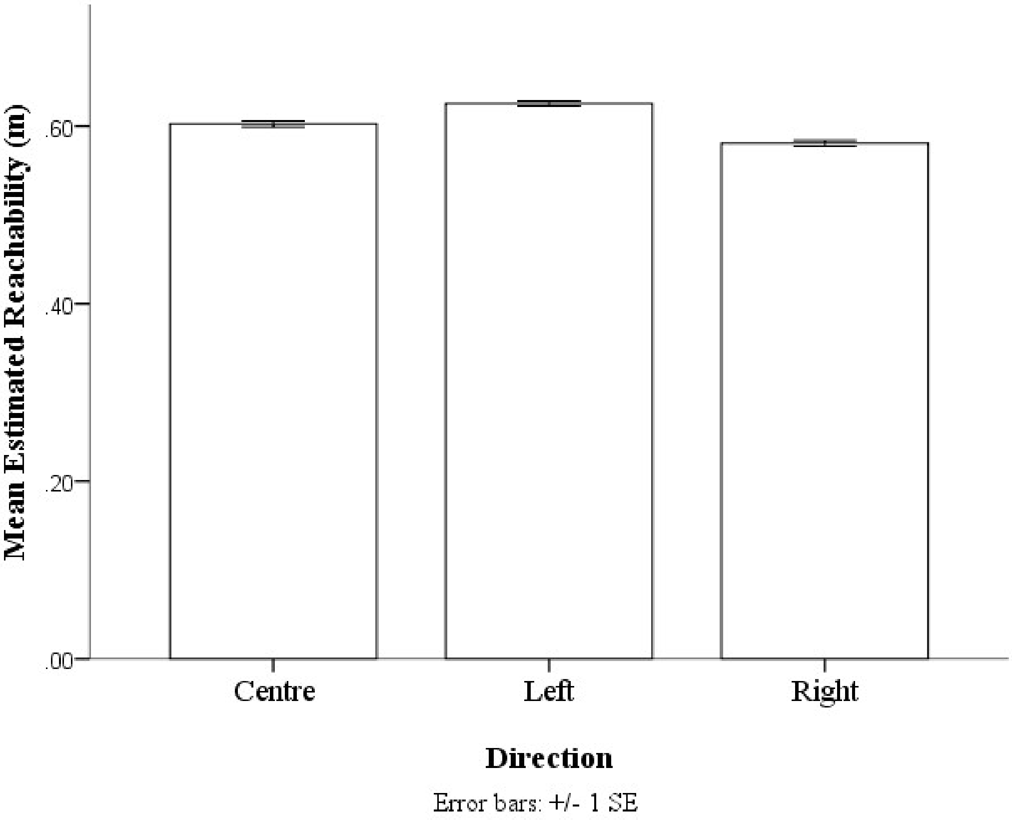

Figure 9. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

## Across All 3 Experiments

Although we found evidence for the difference between constricted reach and variable in all 3 experiments, we found inconclusive evidence for the differences between extended reach and variable reach in Experiments 1 and 2, although the evidence was strong in Experiment 3. However, the means across all 3 experiments in all three conditions were almost exactly the same in that we found small differences between the variable and the extended reach conditions, and larger differences between the constricted and variable reach conditions. Hence, we collapsed across all 3 experiments and analysed the combined data to get a better idea of the relationships between the three conditions.

For each participant in each condition, we created two difference scores. We created one difference score by subtracting the mean variable reach estimate from the mean extended reach estimate (FV), and the other difference score was created by subtracting the mean constricted reach estimate from the mean variable reach estimate (VN). We did not use absolute values as this would have merely given us an estimate of overall variability, and we wanted to keep the directionality associated with the estimates. By subtracting variable reach from extended reach and then constricted reach from variable reach, we equated degree of difference by making all differences in each hypothesised direction positive (and the alternative direction negative) while maintaining differences in directionality. *Importantly,* if participants took a weighted average, then we should expect no difference between the FV and VN conditions as all 3 experiments combined would equal themselves out to random variability (this is due to the notion that variable conditions in Experiments 2 and 3 had the exact opposite systematic distributions of extended and constricted reach trials).

In order to assess the relationship between the differences scores, we conducted a repeated measures ANOVA with difference score (FV versus VN) as a within-subjects variable and experiment (1, 2 and 3) as a between-subjects variable. We found an effect of difference scores with the FV scores ($M$ =.05, $SE$ = .02) being smaller than the VN scores ($M$=.13, $SE$ =.02), $F(1, 65) = 6.71$, $p = .012$, $\eta p^2 = .09$, $B_{H(0,\ 0.10)} = 12.55$, $RR[.02,\ 1.21]$, indicating that estimates in the variable reach condition were closer to the extended reach estimates than the constricted reach estimates, and therefore participants in the variable reach condition estimated liberally and not conservatively. We found no significant effect of experiment, F(2, 65) = .63, *p* =.54, with Bayes factors providing weak to moderate evidence for the null hypothesis across post-hoc tests (0.32 < *B*s > 0.73). There was also no significant effect for the interaction between experiment and difference score (e.g.., that the effect of difference score differed depending on the experiment), *F*(2, 65) = .205, *p* =.82, see Figure 10. In order for one experiment to drive the pattern in the data, we should expect a clear, strong significant interaction between experiment and difference score.

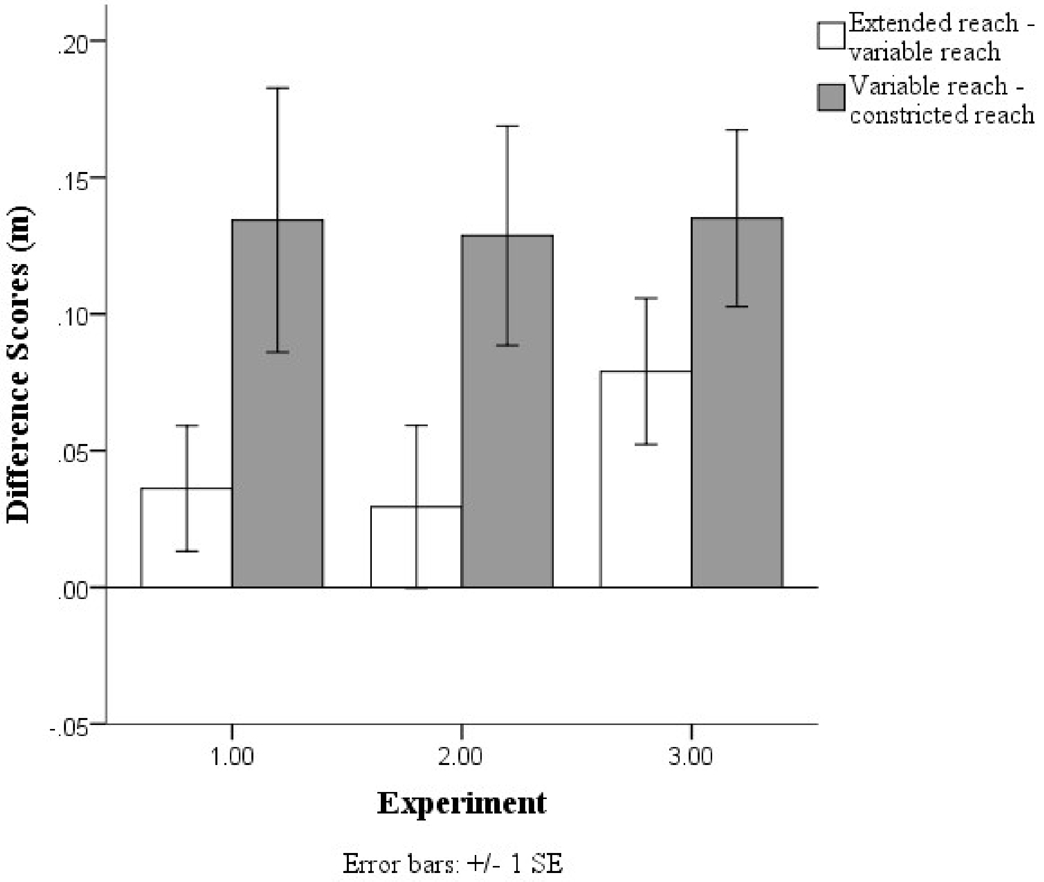

Figure 10. The difference FV and VN difference scores plotted per each experiment. Error bars are 1± SE calculated as within-subject with the method provided by Loftus and Masson (1994).

Using the collapsed difference scores, we also assessed whether the extended reach and constricted reach conditions significantly differed from the variable reach condition. If so, then both FV and VN should be significantly greater than zero. To assess this contention, we performed one-sample t-tests on both the FV and VN scores. We found that the both the FV scores ($M$ = .05, $SE$ =.02, $t(67)$ = -3.26 , $p$ =.002, 1, $B_{H(0, 0.10)}$ = 54.45, $RR$[.006, 2.06] ) and VN scores ($M$ =.13, $SE$ =.02, $t(67)$ = 5.87, $p$ <.001, $B_{H(0, 0.10)}$ = 5.72 x $10^6$, $RR$[.005, 46.38]) were greater than zero, see Figure 11. However, as shown in the analysis above, the difference between the extended reach and variable reach conditions was smaller than the difference between the variable reach and constricted reach conditions. Overall, these findings suggest that individuals took a more liberal approach when estimating their action boundaries following perceptual motor variability.

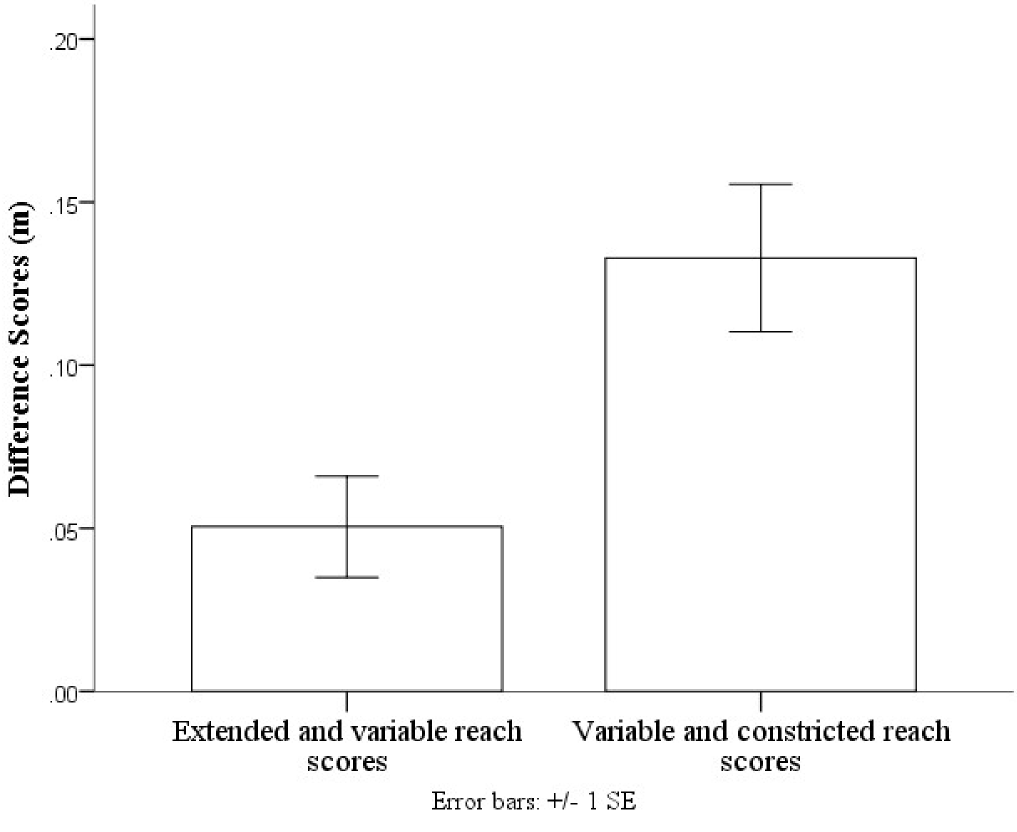

Figure 11. The difference FV and VN difference scores collapsed across all 3 Experiments. Error bars are 1± SE calculated as within-subject with the method provided by Loftus and Masson (1994).

# Discussion

Although individuals' astonishing levels of accuracy in affordance judgements and their ability to flexibly recalibrate to changes in the size of action boundaries have been well documented, we report the first sets of studies to demonstrate how the perceptual system accounts for variability in motor performance when determining action boundaries for reaching. In a series of studies, we examined the effect of different forms of perceptual-motor variability on the perception of action boundaries. Participants were asked to estimate the maximum extent of their reaching ability after being calibrated with a long virtual arm, a short virtual arm and a virtual arm that varied in size. Experiment 1 examined how individuals select their action boundaries when all reaches were experienced with equal probability, Experiment 2 examined how individuals select their action boundaries when reaching distances were greatly weighted towards the extended reach, and Experiment 3 examined how individuals select their action boundaries when reaching distances were greatly weighted towards the constricted reach.

Firstly, we found that individuals were able to calibrate to changes in their action capabilities for reaching in virtual reality even with relatively little experience. Participants consistently estimated their reach to be roughly 17cm larger in the extended reach condition than in the constricted reach condition after 54 calibration trials of reaching in all 3 experiments. This finding was consistent across all three studies, and provides evidence that individuals are capable of adapting to their avatar's abilities in virtual environments. Other studies have found similar evidence for perceptual motor calibration in virtual environments for aperture passing and grasping (Linkenauger, Leyrer, Bülthoff & Mohler, 2013; Linkenauger et al., 2014; Piryankova et al., 2014; Fajen & Matthis, 2011). Hence, these findings provide evidence that virtual reality can be a useful tool for investigating perceptual motor calibration due to the ability to easily manipulate the perceptual motor feedback associated with motor learning.

However, our key interest was how people determined their action capabilities in situations in which they experienced perceptual motor variability. Across all three experiments, people estimated their reach in the variable conditions as greater than in the constricted reach conditions. Across all 3 experiments, we found a general bias towards liberal estimates in the variable conditions, but this bias could be reduced slightly with more extensive experience with the constricted arm's reach as shown in Experiment 3. Collapsing across the three experiments to increase power and showing that the difference between the extended and variable conditions was substantially smaller than the difference between constricted and variable conditions provided support for this conclusion. Had participants used a weighted average, we should have expected the difference between extended and variable to be the same as the difference in constricted and variable (collapsing across experiments essentially created a situation in which the variable condition was random as Experiments 2 and 3 were the opposite in their systematic variability). Hence, this analysis provides further evidence for the perceptual system employing a liberal tactic rather than a weighted average.

These results coincide with prior studies which have shown that individuals constantly over-estimate their reaching ability (Rochat & Wraga, 1997; Fischer, 2000; Linkenauger et al., 2009a; Linkenauger 2009b). Although some of this overestimation can be contributed to the limited degrees of freedom required due to methodological constraints, one could also interpret this overestimation as individuals showing a general tendency towards a liberal estimate of action boundaries. Using the most liberal reach experience as action boundary would be beneficial as it would generate the highest number of successful attempts (although also the largest number of errors). Taken together, these findings not only demonstrate that alternations of arm's reach in virtual reality influence the perceived size of action boundaries, but also serve as a rough indicator for the way in which the perceptual system determines action boundaries for reaching in the event of perceptual motor variability, which would be useful in training and/or rehabilitation scenarios in which the motivation is to encourage or repress various behaviours.

Remarkably, the pattern of results was similar regardless of whether participants experienced all reaches with equal probability or whether their perceptual motor experience in the variable condition was systematically weighted towards the constricted or extended reach. Participants estimated their reach to be more similar to the extended reach than the constricted reach, suggesting a liberal approach in estimating action boundaries. However, these results may be a result of the context in which the actions were learned and/or the specific action being performed. With respect to context, in the current set of studies, failing to reach the target did not result in any negative consequences. Hence, by selecting the liberal action boundary, participants were likely maximising their probability of success while ignoring their probability of failure. However, in different contexts where the penalties for selecting the inappropriate action boundary are severe (e.g., deciding whether to jump across a crevasse when the perceiver's ability to jump is constantly fluctuating and the penalty for failure is falling), individuals would likely be more conservative. For instance, younger adults, older adults and infants have been shown to make more conservative motor decisions when navigating through doorways when the penalty associated with motor decision errors was falling in comparison to when the penalty for error was getting stuck (Franchak & Adolph, 2012; Comalli et al., 2013). Therefore, we suspect that the context in which the action occurs, and the resulting consequences associated with failing to perform the action, would influence how individuals account for perceptual-motor variability when assessing their action capabilities.

Similarly, the way in which the perceptual system determines action boundaries following perceptual-motor variability may also vary depending on the action. For instance, reaching horizontally is different from reaching vertically as the actor's overall postural configuration is different, and they must also maintain their postural balance while reaching. Therefore, selecting the action boundary using the most liberal reaching experience may not be the best strategy as it may jeopardise the actor's ability to balance. In other words, the current findings could only reflect the ways in which the perceptual system accounts for perceptual-motor variability when determining action boundaries for horizontal reaching, and it may or may not be generalisable to other actions. Future research could explore these factors further by examining whether different strategies are employed for different actions, as well as in different contexts.

The age of the participants may be another factor that might modulate these findings. Individuals' action capabilities change across lifespan; action capabilities improve from childhood to young adulthood, and decline from adulthood to old age (Leversen, Haga & Sigmundsson, 2012). Therefore, it is possible that individuals from different age groups would differ in their selection of action boundary when facing with variability in their action capabilities.

Individuals across the lifespan are excellent at determining their action capabilities. Even Infants as young as 5 months-old are able to accurately judge whether they could reach an object, as they attempt to reach objects that are within their action capacity and refuse those that are not (Yonas & Hartman,1993). However, infants and young children often attempt actions that are beyond their action capabilities, such as squeezing their bodies into doorways that are impassable for them (Brownell, Zerwas & Ramani, 2007); or fitting their hands into apertures that are too small (Ishak, Franchak & Adolph, 2014). Attempting actions that are beyond their action capabilities may represent an evolutionary adaptive motivational force that facilitates perceptual learning and discovery of novel action possibilities. Therefore, these factors may contribute to infants and young children making more liberal motor decisions. This pattern of behaviour in infants and young children may be generalisable to their selection of action boundaries in that they favour more liberal action boundaries.

On the contrary, older adults may do the opposite and select the most conservative action boundary when the information that specify their action capabilities is inconsistent. After young adulthood, the range of action possibilities decreases due to decline in perceptual-motor functions associated with increasing age (Welford, 1977; Larsson, Grimby, & Karlsson, 1979). Consequently, older adults may be more risk-aversive than their younger counterparts due to decline in perceptual-motor abilities, as well as increased risk of severe physical injuries because of erroneous motor decisions. Hence, older adults may tend towards a more conservative estimates of their action capabilities. Nevertheless, this explanation is purely speculative as the age of participant was not manipulated in the current study, and future research could examine the effect of aging on action boundary selection under conditions of perceptual-motor variability.

These results also have implication for motor learning in sports. Motor learning is characterised by the gradual reduction and minimisation of perceptual-motor variability that is associated with improvement in the quality of motor performance outcome (Willingham, 1998; Sternad, 2018). Novices have been shown to be less accurate at making action boundary/affordance judgements relevant to their skill domain for themselves and for others (Ramenzoni et al., 2008; Weast et al., 2011), and exhibit greater variability and less accuracy in their motor performance in comparison to experts (Müller & Sternad, 2004;2009). And yet, because the perceptual motor system is inherently noisy; some degree of variability is always present, even in experts. Therefore, it is possible that novices would be more conservative with their action boundary estimates, and as they progress, they would become more liberal with their action boundary estimates as a result of the reduction of variability in their movement.

Additionally, we feel it would be important to mention that in this set of studies, we used large, observable changes in arm's reach during the perceptual motor calibration phase. Because there is no precedent in the literature for this research question, we employed such a large manipulation to a) ensure that we could detect any underlying pattern in the dependent measure between the 3 conditions (especially between the extended and constricted conditions, without a difference in these two conditions, we would be unable to assess what was going on in the variable condition), and b) get an overall impression of the outcome. This type of gross manipulation is pertinent to the daily lives of patient populations or those learning/perfecting new motor skills. As a consequence, we can use this research to optimise the learning/rehabilitation plans of these individuals. Possibly, smaller and less obvious changes in arm's reach during calibration may result in different pattern of results, because this type of manipulation may not engage conscious decision-making processes. It is also possible that calibration to a new action boundary requires noticeable changes in one's perceptual motor feedback. If this is the case, then subtle, unnoticeable changes in arm's reach should not produce any differences in the perceived action boundaries across any of the 3 conditions. Regardless, this question would be very interesting to explore in the future.

Finally, these results also have implications for the perception of distances in near space. The body-based scaling perspective (also known as the action specific perspective) hypothesises that individuals use the action boundaries of their bodies as a perceptual ruler (see Proffitt & Linkenauger, 2013). Hence, a larger action boundary for reaching makes distances appear shorter; whereas, a smaller action boundary for reaching makes distances appear longer. In general, people tend to underestimate distances in near space (Linkenauger et al., 2009; Witt, Proffitt & Epstein, 2005; Witt & Proffitt, 2008). This underestimation of distance may be due to individuals opting for a liberal, larger action boundary for reaching, thus leading to underestimations of perceived distance.

In summary, the current studies demonstrate that the manipulation of perceptual-motor feedback from virtual bodies can influence the perception action boundaries in virtual environments. They also illustrate that in situations where the perceptual-motor feedback specifying an action boundary for reaching is inconsistent due to changes in the body and action capacities, the perceptual system selects a liberal action boundary. However, other factors such as the type of variability, age and potential outcomes resulting from the action may also influence the size of the action boundary selected.

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# Chapter 3: Perceiving action boundaries for overhead reaching in a height-related situation

Findings from Chapter 2 showed that the manipulation of perceptual-motor feedback from virtual bodies can influence the perception action boundaries in virtual environments, and that in situations where the perceptual motor feedback that specify one's action boundary is inconsistent, the perceptual system selects a liberal action boundary regardless of whether participants experienced all reaches with equal probability or whether the perceptual-motor experience was systematically biased towards the long or short reach. However, these results may be due to the specific action being performed and the context in which the action is performed. With respect to context, failing to reach the target did not result in any negative consequences. Hence, by selecting the liberal action boundary, participants were likely trying to maximise their probability of success while ignoring their probability of failure. Similarly, the way in which the perceptual system determines action boundaries following perceptual-motor variability may also vary depending on the action itself. Reaching horizontally while seated has little postural demand and selecting the action boundary using the most liberal reaching experience would be an appropriate strategy to maximise successful attempts. However, the ways in which action boundaries are determined following perceptual-motor variability could also vary depending on the environmental context as well as the consequence associated to a failed action. Thus, this chapter presents a series of experiments that investigated the effect of action consequences in two dimensions, a) consequences incurred from the *environmental context* in which the action occurs, and b) consequences associated with failing the particular *action*.

# Abstract

To successfully interact within our environment, individuals need to learn the maximum extent (or minimum) over which they can perform actions, popularly referred to as action boundaries. Because people learn such boundaries over time from perceptual motor feedback across different contexts, both environmental and physiological, the information upon which action boundaries are based must inherently be characterised by variability. With respect to reaching, recent work suggests that regardless of the type of variability present in their perceptual-motor experience, individuals favoured a liberal action boundary for horizontal reaching. However, the ways in which action boundaries are determined following perceptual-motor variability could also vary depending on the environmental context as well as the type of reach employed. The present research aimed to establish whether the perceptual system utilises the same strategy for all types of reaches over different contexts. Participants estimated their overhead reachability following experience reaching with either a long or short virtual arm, or a virtual arm that varied in length – while standing on the edge of a rooftop or standing on the ground. Results indicated that while similar strategies were used to determine action boundaries in both height and non-height related context, participants were significantly more conservative with their reachability estimates in the height-related context. Participants were sensitive to the probabilistic information associated with different arm's reach they experienced during the calibration phase and used a weighted average of reaching experience to determine their action boundary under conditions of uncertainty.

***Keywords***: Perception, action boundaries, perceptual-motor calibration

### Perceiving action boundaries for overhead reaching in a height-related situation.

To select and modify movement plans adaptively, the perceiver needs to be sensitive to their action boundaries. Action boundary is the critical point or limit that separates possible actions from impossible actions, and actions are only possible when they are within one's action boundary (Fajen, 2005). Consequently, action boundaries vary depending on the individual, e.g., an object that affords reaching for an adult may not afford the same for a child, due to the differences in their body morphology and motor abilities.

People have been shown to be highly sensitive to the boundaries of their action capabilities (Warren, 1984; Warren & Whang, 1987; Ishak, Franchak & Adolph, 2014; Carello, Grosofsky, Reichel, Solomon & Turvey, 1989). Additionally, people could rapidly recalibrate to a new action boundary and modify their affordance judgements following changes in their body dimensions and action capabilities. Such examples include updating their judgements of passability when fitting one's hand through an opening when their hand width has been enlarged by a prosthesis attached to their hand (Ishak, Adoph & Lin, 2008) and passing through doorways while wearing a different sized artificial belly (Franchak & Adolph, 2014). Individuals also adjust their maximum sitting or stepping height judgement while wearing platform shoes/blocks under their feet (Hirose & Nishio, 2001; Mark, 1987) and decrease their jumping ability judgements when wearing ankle weights (Lessard, Linkenauger, & Proffitt, 2009).

Action boundaries change over the course of lifetime due to variations in one's action capabilities caused by physical or physiological changes in one's body associated with natural processes. However, much like our environments, our bodies and our action capabilities are not stagnant. Variability is always present when we navigate our surroundings, and studies have shown that individuals account for their own movement variability when making action boundary judgements. For instance, children and older adults have been shown to leave greater margin of safety when judging whether an aperture affords passing, and they also rotate their shoulders to a greater extent for a given aperture size compared to younger adults (Wilmut & Barnett, 2010;2011; Hackney & Cinelli, 2011). These group differences suggest that individuals take into account their action capabilities and movement variability by making more conservative action boundary judgements. Additionally, factors such as injuries, flexibility, anxiety or fatigue, can also lead to changes in body, and in turn fluctuations in action capabilities (Franchak & Adolph, 2014; Pijpers, Oudejans, Bakker & Beek 2006; Pijpers, Oudejans & Bakker, 2007; Konczak et al., 1992). Hence, regardless of how consistent an action's outcome may seem, the perceptual motor information specifying action boundaries is always characterised by some amount of variability. As a result, the perceptual system must select an action boundary from a variety of perceptual motor experiences which conflict in terms of their indication of the perceiver's maximum reachability.

One such solution that the perceptual system could employ would be to select action boundary size using something akin to a weighted average, in which prior perceptual motor experiences are combined on the basis of their relative likelihood to identify the most statistically likely outcome (Kording & Wolpert, 2006; Deneve & Pouget, 2004). To determine the appropriate action boundary from the most likely outcome when considering all similar perceptual motor experiences, one could assign weighting to action boundaries based on the probabilistic information associated with each action boundary they have experienced during reaching experience. For instance, consider, an individual who has experienced two different action boundary sizes (large and small) during their reaching experience, in which they experienced the large action boundary half of the time and the small action boundary half of the time. Given that they have experienced both action boundaries with equal probability, they could then take the average of the action boundary experienced – which would be similar to the mean. Alternatively, if they have experienced the large action boundary 75% of the time, and 25% of the time they experienced the small action boundary, then more weight would be assigned to the large action boundary as it was encountered more often than the other action boundaries. The selected action boundary would be closer to the large action boundary (but not as large) they have experienced during reaching experience, because it is more statistically likely than a smaller one. Hence, by incorporating probabilistic information in the selection of action boundaries, we would expect individuals' action boundary estimates to reflect a systematic shift in size depending on the weighing attributed to each action boundary experienced.

While this method may allow for an optimising approach to determining action boundaries, it does not come without a cost. Such information processing, i.e., taking into account all experiences and weighting them with respect to their reliability, incurs considerable temporal and energetic costs, and the brain is the most energy consuming organ in the human body (Niven & Laughlin, 2008; Clarke & Sokoloff, 1999). Evolutionary approaches have characterised the optimising processes underlying such computations as inefficient given that human cognitive capacities are necessarily limited, and some have argued that perceptual system functions to satisfice and produce adaptive behaviours rather than to optimise (Hoffman, Singh & Prakash, 2015). Heuristics provide satisfying solutions that are time and effort efficient (i.e., require less computation), and heuristics produce comparable, and more energetically adaptive solutions than more complex computations in real world situations (Gigerenzer & Gaissmaier, 2011; Martignon, 2001). Nevertheless, this may also depend on the situation, and it is possible that more deliberated computation may be required in situations where the stakes are high.

Hence, the perceptual system could use heuristics for a fast and efficient evaluation, by examining fewer alternatives and adopting a single action boundary that doesn't vary drastically regardless of the probabilistic information associated with each possible action boundary, and nonetheless achieve satisfactory performance. One possible heuristic that the perceptual system could employ would be to select the action boundary using the most liberal sized action boundary experienced. This method is akin to signal detection theory; in a situation that requires you to reach a target, if you think that you could possibly reach the target, then you would always attempt (e.g. Green & Swets, 1966;Swets, Tanner & Birdsall, 1961). Consequently, in the event that the action capabilities of an individual fluctuate constantly, attempting the action using the most liberal sized action boundary experienced, would result in the highest number of successful attempts. However, this option would only be beneficial to the individual in the absence of consequences associated with a failed action because it would lead them to fail more often as well. Alternatively, individuals could use the most conservative sized action boundary experienced regardless of the variability. This option would be in the perceiver's best interest especially when making motor decisions in situations in which motor errors are associated with negative consequences. However, this method would also result in the smallest number of successful attempts.

Recent studies have investigated participants' judgement of action boundaries for reaching following changes in their action capabilities in a virtual environment. Lin, McLatchie and Linkenauger (2020) had participants estimate their action boundary for horizontal reaching following calibration to either a long virtual arm, a short virtual arm, or a variable virtual arm that varied randomly but in equal frequency between a long, medium and short virtual arm. In the following experiments, the design was the same, except that in the variable condition, the frequency of the virtual arm lengths varied systematically in that they were greatly weighted towards the long virtual arm or the short virtual arm. Across three experiments, participants have recalibrated to a new action boundary that was consistent with their reaching experience and estimated their reachability to be farther in the consistent long virtual arm conditions than in the consistent short virtual arm conditions. Interestingly, findings demonstrated that the pattern of results was similar regardless of whether participants experienced all reaches with equal probability or whether their perceptual motor experience in the variable conditions was systematically weighted towards the long virtual arm or short virtual arm. Participants estimated their reachability in the variable condition more similarly to when they were calibrated only with a long virtual arm's reach. This finding suggests that individuals may have selected action boundaries using heuristics and employed a liberal approach when estimating action boundaries in the event of perceptual motor variability.

However, Lin, McLatchie and Linkenauger's (2020) results may be due to the specific action being performed and the context in which the action is performed. Consider overhead reaching, in contrast to horizontal reaching. Reaching vertically is kinematically different from reaching horizontally, not only is the actor's overall postural configuration different, the perceiver must also maintain their balance while executing the reach. Hence, selecting the action boundary using the most liberal reach experienced may not be the most appropriate strategy, as a failed liberal reach may impair their ability to maintain balance and result in falling. Previous research has shown that individuals tend to overestimate their reachability, and they perceive targets that are out of reach to be reachable (Fischer, 2000; Rochat & Wraga, 1997). However, individuals were found to be more conservative with their estimates or even underestimate their reachability when executing reaches that would shift their centre of mass beyond the base of support of their feet, such as reaching for high objects while standing or reaching while bending at the hip (Carello, Grosofsky, Reichel, Solomon & Turvey, 1989; Robinovitch, 1998). Hence, perceived action consequences associated with postural stability may lead to more conservative action boundary estimation. The perceptual system could change the strategy it employs to determine action boundaries depending on the consequences of failing. If this is the case, then individuals would be more conservative with their action boundary when the reaching task requires greater postural stability demands.

Similarly, with respect to context, in Lin, McLatchie & Linkenauger (2020), failed action was not associated with any negative consequences. Hence, by selecting the liberal action boundary, participants were likely trying to maximise their probability of success while disregarding their probability of failure. However, in context where there are penalties for selecting the inappropriate action boundary, individuals may be more conservative with their judgements. For instance, younger adults, older adults and infants have been shown to make more conservative motor decisions when navigating through doorways when the penalty associated with motor decision errors was falling in comparison to when the penalty for error was to become wedged (Franchak & Adolph, 2012; Comalli, Franchak, Char, & Adolph ., 2013). Therefore, we suspect that the context in which the action occurs, and the resulting consequences associated with failed action would influence how individuals account for perceptual-motor variability when determining their action boundaries.

Nevertheless, these attributes may be difficult to investigate in the real world, due to the consistency of individuals' bodies and action capabilities, as well as the possibility of incurring risks or injuries to participants. However, by using virtual reality and motion capture technology, we would be able to investigate these attributes in a safe yet realistic manner. Studies using virtual reality have found that individuals react to and interact with the virtual environment as if they were real and exhibit behavioural and physiological responses that are comparable to those occurring in the real world (Slater et al., 2006). In this set of studies, we have opted to use virtual height-related situations as a potential risk or negative consequence associated with failed action. Fear of heights is one of the most common types of fears, and one of the earliest acquired ones (De Jongh, Oosterink, Kieffer, Hoogstraten & Aartman, 2011). After a few weeks of self-generated motor experiences, 6 months old infants show wariness of heights and avoid the deep side of the visual cliff (Gibson & Walk, 1960; Bertenthal, Campos, & Barrett, 1984). Furthermore, height fear has been shown to influence visual perception, in which individuals with greater levels of acrophobia perceive vertical extents to be higher (Teachman, Stefanucci, Clerkin, Cody & Proffitt, 2008; Stefanucci & Proffitt, 2009). Virtual reality has also been used as a medium for exposure treatment for various types of phobias, including fear of heights. Individuals have reported physical symptoms of anxiety when exposed to virtual height situations, and their fear of heights was reduced successfully after several sessions of virtual reality exposure (Rothbaum et al., 1995; Regenbrecht, Schubert & Friedmann, 1998). Taken together, we believe that a virtual heights situation would allow us to examine whether individuals could associate negative action consequences with their selection of action boundaries under conditions of perceptual motor variability.

In a series of studies, we examined the effect of environmental context and the type of perceptual-motor variability in reaching experience on the perception of action boundaries for overhead reaching using virtual reality. Participants engaged in a calibration phase where they executed a series of reaches to targets of various heights with either a long virtual arm, a short virtual arm, or a virtual arm that varied in size randomly or systematically across reaching trials. Participants performed this calibration while standing on the edge of a tall building or standing on a horizontal ground plane. After the calibration phase, participants estimated their maximum reaching ability. We expected individuals to employ different strategies when determining their action boundaries in different environment contexts. It is possible that individuals would be more deliberate/conservative in the height-related situation and incorporate probabilistic information associated with the reach lengths they have experienced during the calibration phase into their action boundary judgement as a result of negative consequences. If so, their reachability estimates would likely reflect a systematic shift in size depending on the weighting attributed to each arm's reach experienced, in that they would favour a more liberal size action boundary if they have experienced a long virtual arm's reach more often than other reaches. Whereas in the non-height related situation where failed action is not associated with negative consequences, individuals would adopt an action boundary size that does not vary drastically regardless of the probabilistic information associated with each possible action boundary.

# Experiment 1

In this experiment, we investigated the effect of random variability on the perception of action boundaries in a high-risk situation. In a virtual environment, participants estimated their maximum reachability after being calibrated with either a long virtual arm, a short virtual arm, or a virtual arm that varied in size randomly.

## Method

### Participants

G*Power software application (Faul, Erdfelder,Buchner & Lang, 2009) was used to perform an a priori power analysis to estimate sample sizes required to achieve adequate power. The required power was set at $1- \beta = .85$, and the level of significance was kept at $\alpha = .05$. We expected a medium effect size of .25 due to the novelty of the paradigm. Power analysis indicated that a sample of $N = 15$ would be sufficient to achieve a power of .85 and an alpha of .05. We have increased our sample size to a minimum of 20 participants for all 4 experiments due to the possibility of technical failure with this type of equipment.

Twenty-one participants (15 Females) between 18 to 29 years of age ($M_{age} = 21.05$ years, $SD_{age} = 2.64$ years) were recruited from Lancaster University through opportunity sampling. All participants but two were right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experiment was conducted in front of a table, and a chair was placed in front of it. The chair was placed against the table and in front of the participants to minimise the risk of participants losing their balance, participants stood roughly 40 cm from the table. Participants wore an Oculus Rift CV1 head-mounted display (HMD) that displayed a stereoscopic image of the virtual environment with a resolution of 2160 x 1200 pixel and a frame rate of 90Hz. The position of the participants' arms and hands was tracked using a Leap Motion hand tracking sensor mounted on the front of the Oculus HMD. The leap motion fully animates the arm and individual finger movements in real time based on the movements of the user.

The experimental program and environment were created using Unity 3D© Gaming Engine with the Leap Motion plugin. For the virtual environment, a 3D model of a city with skyscrapers was used. The virtual avatar was placed on the edge of a skyscraper's rooftop; a

Figure 1. Left panel: Screenshot of the virtual environment showing the complete scene. Right panel: Image of what the participant would see from their perspective during the calibration trial.

3D model of a transport chopper was placed above the avatar, with a ladder that extended from the bottom of the chopper.

The 3D camera was placed at eye-level, enabling the participant to perceive the virtual environment in a first-person perspective, and the position of the 3D camera was consistent with the participant's physical eye-height. They were positioned in the virtual environment so that they were standing under the chopper and in front of the ladder, see Figure 1. The movement of the participant's head was tracked, and graphics were updated as the participant looked around in the virtual environment by moving their head. The movement and position of the participant's tracked hands were mapped onto the virtual arms and hands, so that the movement of the virtual hands was congruent with the movement of the participant's actual hands. The avatar hands that we used were taken from the realistic human hand models provided by the Leap Motion V2 SDK. Three different virtual arm sizes were used: the original arm model was used for the normal arm's reach; the length of the original arm model was mapped onto the physical model derived from the actual arm length of each participant. For the extended arm's reach, the virtual arm was scaled as 50% longer than the original arm model, and for the constricted arm's reach, the virtual arm was scaled as 50% shorter than the original arm model.

## Procedure

After providing their informed consent, participants were asked to stand facing the table. They were given instructions for both the calibration and estimation phases of the experiment. After donning the Oculus HMD, participants completed all three experimental conditions, and participants were randomly assigned to different orders of conditions. In the extended reach condition, the virtual arm was 50% longer than the participant's normal arm and was made to reach 50% farther than their physical reach. In the constricted reach condition, the virtual arm was limited to 50% of the participant's physical reach with the arm being 50% shorter than the participant's normal arm. In the variable reach condition, the virtual arm varied between the extended arm's reach, the constricted arm's reach and the normal arm's reach; and participants experienced all reaches with equal probability (i.e., equal number of trials).

Each condition consisted of two parts: calibration and estimation. The calibration phase consisted of 48 trials in which a pink-coloured ladder rung was presented in front of the participant at various vertical heights. Participants were instructed to reach and grab the pink-coloured bar with their virtual hands. If the bar was too far or high for the participant to reach, they were instructed to point towards it instead, see Figure 2. After they reached out and touched/pointed at the bar, the bar disappeared and another pink-coloured bar at a different location appeared. The bars were presented at one of the six vertical distances from the rooftop to which the participant was standing on (140, 160, 180, 200, 220, 240cm), for a total of six possible locations each presented eight times for a total of 48 trials with the bar location being presented in randomised order.

Participants engaged in an estimation phase following each calibration phase. Prior to beginning the estimation phase, participants were told to estimate their reaching ability in the virtual environment. To prevent participants from counting and memorising the number of times they have pressed the arrow keys, the experimenter would adjust the estimation bar for participants while looking away from the monitor as each trial began. The estimation phase consisted of 12 trials, the experimenter used the arrow keys to move the position of an orange-coloured bar (estimation bar), and participants were instructed to inform the experimenter when to stop so that the bar was just within their reach. The up arrow key moved the estimation bar upwards and the down arrow key moved the bar downwards. Each button press moved the bar 5 cm upwards or downwards. During the estimation phase, the virtual hands were removed from the scene so that participants had no visual feedback about their arm length. For half of the trials, the estimation bar originated from 100cm above the rooftop. In order to control for hysteresis- the phenomenon in which the individuals' estimates are typically longer if the stimulus starts away from the perceiver and is moved towards the perceiver relative to when the stimulus starts close to the perceiver and is moved away. Hence, for the other half of the trials, the estimation bar's starting position was 280 cm above the rooftop. Hence, the bars either started below or above the participants, for a total of two locations each presented six times for a total of 12 trials. Participants were reminded that there was no right or wrong answer, and they could make as many fine adjustments as they needed until they were satisfied with their estimate of their reaching ability. Once they were satisfied with their estimate, the bar disappeared and the next trial began. To sum up, each participant completed three reaching conditions (extended, constricted, variable) in randomised order, and in each condition, they completed a calibration phase consisting of 48 trials followed by an estimation phase consisting of 12 trials.

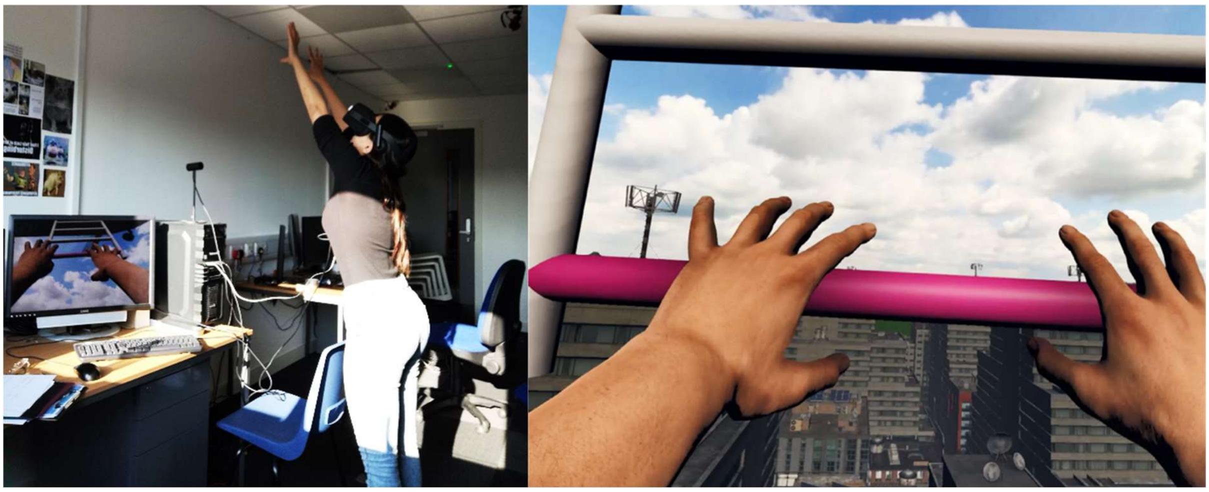

Figure 2. Left panel: Illustration of a participant completing a calibration trial. Right panel: Image of what the participant would see while completing the calibration phase.

## Results

To account for the height of the building rooftop the participants were standing on, we have subtracted 64.228 from the raw reaching estimates. To analyse the influence of reaching condition on reachability estimates, where reachability was defined as the farthest extent to which participants estimated they could reach vertically, we employed a repeated measures ANOVA with reaching condition (extended/ constricted/variable) as within-subjects variable and the estimated reachability as the dependent variable.

As predicted, analysis showed effects of reaching condition on estimated reachability, $F(2,40) = 14.96$, $p = .001$, $\eta_p^2 = .43$. Bonferroni post-hoc analysis showed that participants estimated the extent of their reach as being farther in the extended reach condition ($M = 2.39$m, $SE = .04$m) than in the constricted reach condition ($M = 2.24$m, $SE = .04$m, $p < .001$). They also estimated their reachability to be farther in the variable condition ($M = 2.32$m, $SE = .04$m, $p = .04$) than in the constricted reach condition. Furthermore, they have estimated their reachability to be farther in the extended reach condition than in the variable reach condition ($p = .02$), see Figure 3.

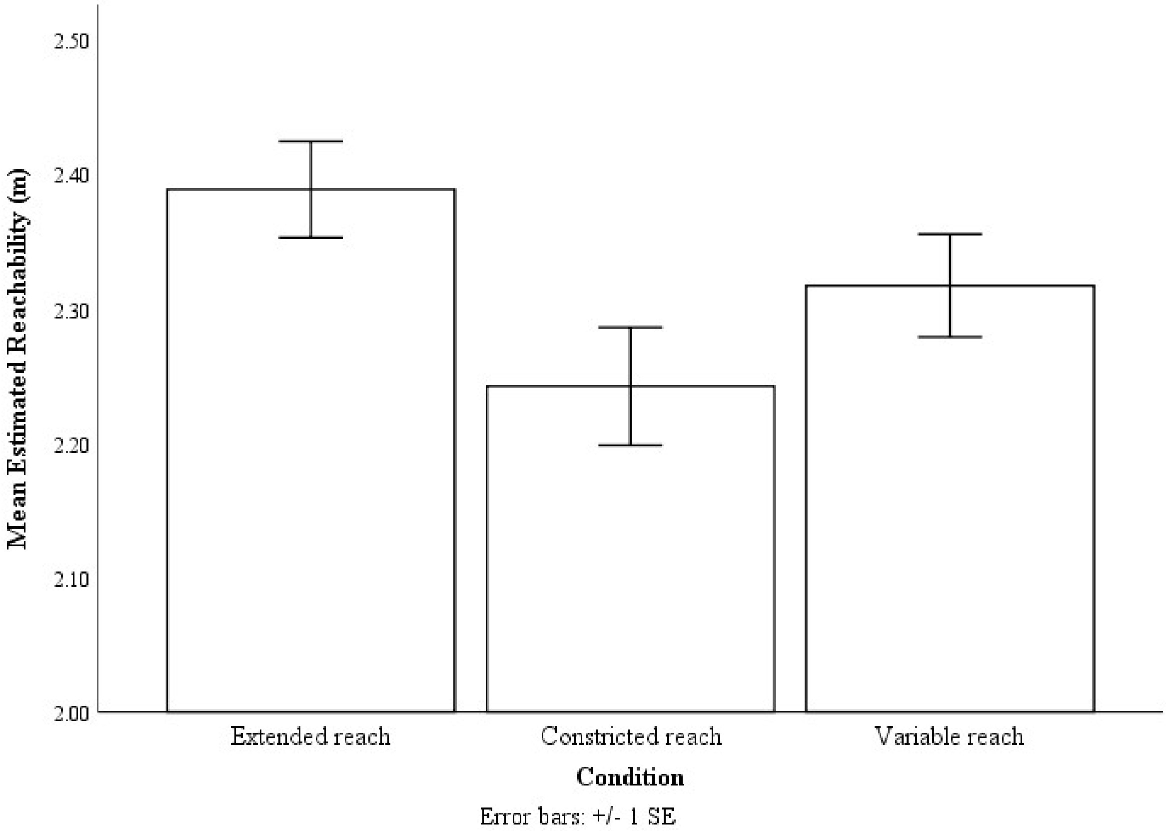

*Figure 3.* The mean estimated reachability of the three reaching conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

These results indicate that there was evidence for a difference between the variable and both the extended and constricted reach conditions, suggest that participants have selected a moderate sized action boundary that was smaller than the one selected in the extended reach condition but larger than the one selected in the constricted reach condition. Had they used heuristics to determine action boundary and employ a liberal tactic, we would expect their reachability estimates to be similar to their reachability estimates in the extended reach condition. Alternatively, had participants employed a conservative tactic as a heuristic strategy, we would expect their reachability estimates to be similar to those in the constricted reach condition. Instead, we found that participants have opted for a moderate sized action boundary after experiencing the three different reaches with equal probability (i.e., equal number of trials), and this strategy is consistent with what would be expected if participants had used an average of their reaching experience to determine action boundary.

# Experiment 2

Findings from Experiment 1 demonstrated that when the perceptual-motor experience was completely random in that individuals experienced all three reaches with equal probability, individuals selected an averaged size action boundary size that was smaller than the one selected in the extended reach condition but larger than the one selected in the constricted reach condition. Findings from Experiment 1 were consistent with what would be expected if individuals were using a weighted average of their reaching experience to determine their action boundary for reaching. In Experiment 2, we sought to investigate how individuals select their action boundary when the perceptual-motor experience is systematically weighted towards the extended arm's reach and that they experienced the farther reach twice as often. If individuals were using a weighted average of their experience, we would expect them to favour a larger action boundary as more weight would be assigned to the larger action boundary.

## Method

### Participants

Twenty-four participants (19 Females) between 18 to 49 years of age ($M_{age}$ = 23.67 years, $SD_{age}$ = 7.24 years) were recruited from Lancaster University through opportunity sampling. All participants but two were right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experimental set-up was the same as in Experiment 1. Participants estimated their maximum reachability after being calibrated with either a long virtual arm, a short virtual arm, or a virtual arm that varied in size systematically.

### Procedure

The procedure was the same as in Experiment 1. In the variable reach condition of this experiment, 50% of their reaches had the extended arm's reach, 25% of the reaches had the constricted arm's reach, and 25% of their reaches had the normal arm's reach. All reaches were experienced in randomised order.

## Results

To account for the height of the building rooftop that the participants were standing on, we have subtracted 64.228 from the raw reaching estimates. A repeated measures ANOVA was conducted with reaching condition (extended/ constricted/variable) as within-subjects variable and the estimated reachability as the dependent variable.

There was a main effect of reaching condition on estimated reachability, $F(2, 46) = 13.44, p < .001, \eta p^2 = .37$. Participants estimated their reachability to be farther in the extended reach condition ($M = 2.16$m, $SE = .04$m) than in the constricted reach condition ($M = 2.05$m, $SE = .04$m, $p = .001$). They also estimated their reachability to be farther in the variable condition ($M = 2.13$m, $SE = .03$m, $p = .01$), than in the constricted reach condition, see Figure

4. Furthermore, we found no evidence for a difference between the extended and variable reach conditions (*p* = .26).

These results demonstrated that the perceived reachability was affected by the type of perceptual motor variability present. Specifically, when the perceptual motor experience was systematically weighted in that participants have experienced the farther reach substantially more often than other reaches, participants were more liberal with their reachability estimates than when all reaches were experienced with equal probability. Taken together with Experiment 1, these results provide further evidence that participants were sensitive to the probabilistic information associated with each arm's reach they have experienced, and a weighted average of reaching experience was used to determine action boundaries under conditions of uncertainty.

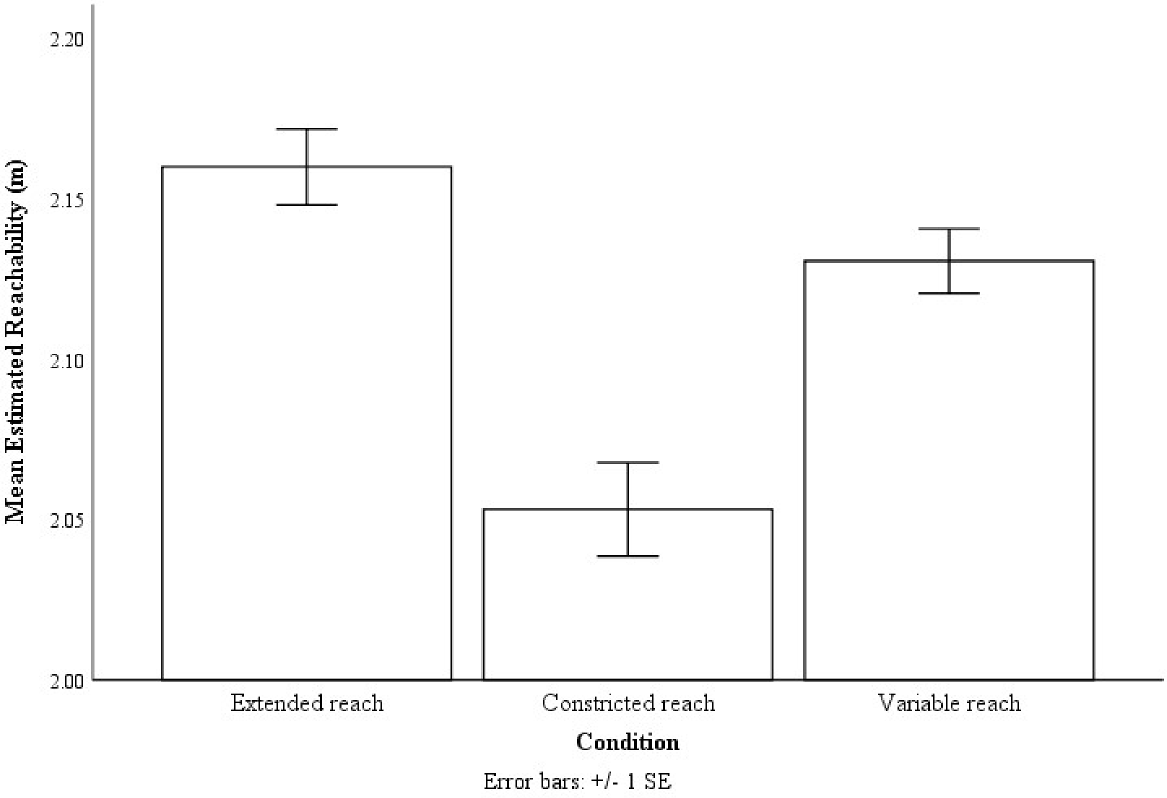

*Figure 4*. The mean estimated reachability of the three reaching conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

# Experiment 3

Findings from Experiment 1 and 2 showed that individuals were sensitive to the type of perceptual-motor variability present and have used a weighted average of reaching experience to determine action boundaries. However, a question remains as to whether the perceptual system takes into account the environmental context in which the action occurs and employs different strategies to determine action boundaries. Findings from Experiment 1 and 2 can be interpreted as participants recognised the costs associated with failed actions in the height related situation and were therefore more cautious with the selection of action boundaries. It is possible that in the absence of cost to making errors, individuals would opt for a more time efficient and less deliberate method to determine action boundaries. They may adopt a single action boundary regardless of changes in probabilistic information associated with each action boundary experienced, similar to those reported in Lin, McLatchie and Linkenauger (2020). Hence, in Experiment 3, we sought to investigate how individuals select their action boundaries for overhead reaching in a low-risk (non-height-related) situation.

## Method

### Participants

Twenty participants (15 Females) between 18 to 22 years of age ($M_{age}$ = 19.15 years, $SD_{age}$ = 1.39 years) were recruited from Lancaster University through opportunity sampling. All participants were right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experimental setup was similar to Experiment 1 and 2. The experimental program and environment were created using Unity 3D© Gaming Engine with the Leap Motion plugin. For the virtual environment, a 3D model of a city with skyscrapers was used. The virtual avatar was placed in a city square/ plaza surrounded by trees and buildings; a 3D model of a transport chopper was placed above the avatar, with a ladder that extended from the bottom of the chopper, see figure 5.

*Figure 5*. Left panel: Screenshot of the virtual environment showing the complete scene. Right panel: Image of what the participant would see from their perspective during the calibration trial.

### Procedure

The procedure was the same as Experiment 1 and 2, but instead of rooftop, participants performed the calibration and estimation phase while standing on a horizontal ground plane. Participants estimated their maximum reachability after being calibrated with either a long virtual arm, a short virtual arm, or a virtual arm that varies in size randomly. In the variable reach condition of this study, participants experienced all three reaches with equal probability.

# Results

A repeated measures ANOVA was conducted with reaching condition (extended/ constricted/variable) as within-subjects variable and the estimated reachability as the dependent variable. Analysis showed effects of reaching condition on estimated reachability, $F(2,38) = 20.55$, $p < .001$, $\eta_p^2 = .52$. Bonferroni post-hoc analysis showed that participants estimated the extent of their reachability as being farther in the extended reach condition ($M$ = 2.64m, $SE$ = .04m) than in the constricted reach condition ($M$ = 2.45m, $SE$ = .04m, $p < .001$). They estimated their reachability to be farther in the variable condition ($M$ = 2.57m, $SE$ = .04m, $p = .003$) than in the constricted reach condition. Furthermore, they have estimated their reachability to be farther in the extended reach condition than in the variable reach condition ($p = .02$), see Figure 6.

These results indicate that the estimates in the variable condition significantly differed from both the estimates in the extended and constricted condition, suggest that participants have selected a moderate sized action boundary after experiencing all three reaches with equal probability. Based on these findings, it is reasonable to postulate that participants have selected their action boundary using a weighted average of their reaching experience. However, it is also possible that the perceptual system was merely adopting a moderate sized action boundary without taking the probabilistic information into account, as failed action in this environmental context was not associated with dangerous consequences. Hence, in order to provide more clarity, in the next experiment, we investigated whether perceived reachability was altered by more extensive experience with the farther reach.

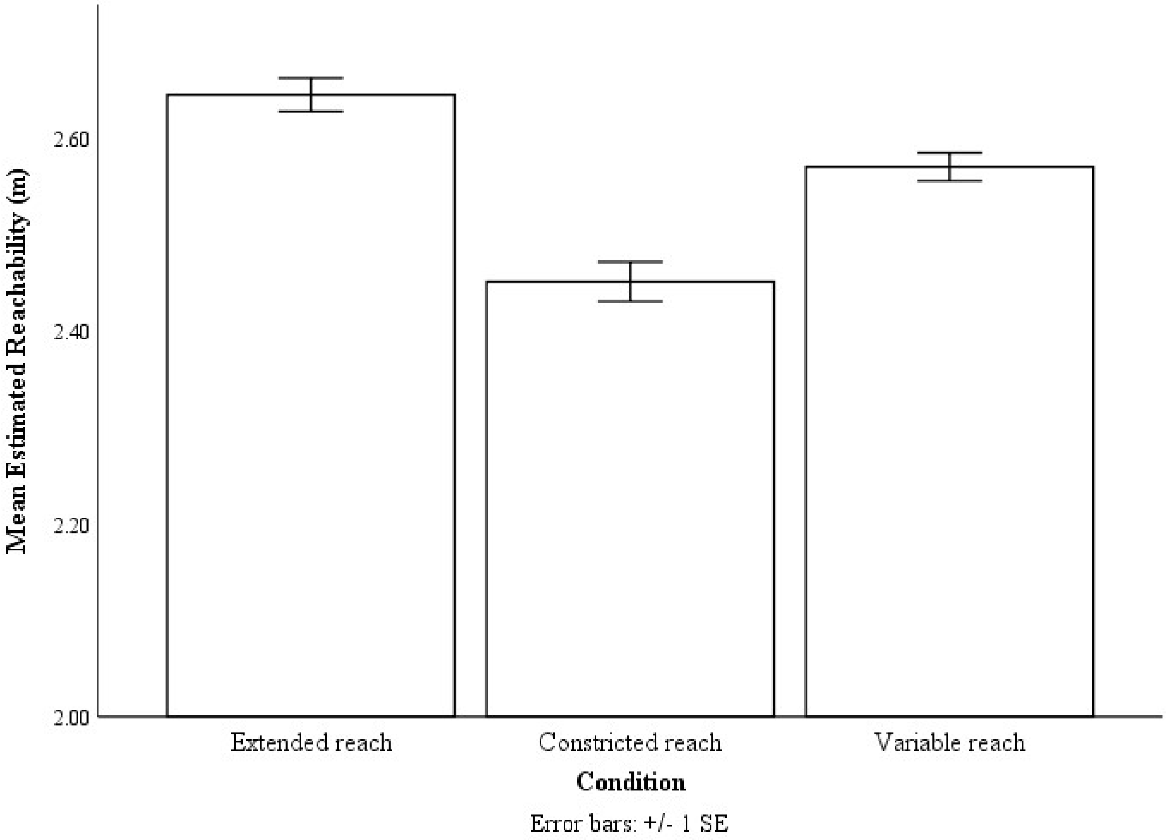

*Figure 6.* The mean estimated reachability of the three reaching conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

# Experiment 4

Findings from Experiment 3 demonstrated that when the perceptual-motor experience is completely random in that individuals experienced all three reaches with equal probability, individuals selected an averaged size action boundary size that was smaller than the one selected in the extended reach condition, but larger than the one selected in the constricted reach condition. However, it remained unclear as to whether the perceptual system took into account the probabilistic information associated with each action boundary experienced, or was merely selecting a moderate sized action boundary as an effort-reduction strategy. Thus, in Experiment 4 we investigated the effect of systematic variability on the perception of action boundaries in a non-height-related situation. If individuals were not taking probabilistic information into account, then given the absence of costs to making errors, we would not expect to see an increase in action boundary size despite having more experience with the extended arm's reach, and action boundary selected would be similar to the action boundary selected in Experiment 3. However, if individuals were taking the probabilistic information into account and used a weighted average of reaching experience to determine action boundary, then we would expect participants to estimate their reachability liberally.

## Method

### Participants

Twenty participants (16 Females) between 18 to 28 years of age ($M_{age}$ = 21.65 years, $SD_{age}$ = 3.05 years) were recruited from Lancaster University through opportunity sampling. All participants but two were right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

### Stimuli and Apparatus

The experimental set-up was the same as in Experiment 3. Participants estimated their maximum reachability after being calibrated with either a long virtual arm, short virtual arm, or a virtual arm that varies in size systematically.

### Procedure

The procedure was the same as Experiment 3. In the variable condition of this experiment, 50% of their reaches had the extended arm's reach, 25% of the reaches had the constricted arm's reach, and 25% of their reaches had the normal arm's reach. All reaches were experienced in randomised order.

## Results

A repeated measures ANOVA was conducted with reaching condition (extended/ constricted/variable) as within-subjects variable and the estimated reachability as the dependent variable.

The analysis provided Greenhouse-Geisser corrected degrees of freedom to account for possible violations of sphericity, therefore the degrees of freedom were not always integers. As predicted, analysis showed effects of reaching condition on estimated reachability, $F(1.50, 28.52) = 10.50$, $p < .001$, $\eta_p^2 = .36$. Bonferroni post-hoc analysis showed that participants estimated the extent of their reach as being farther in the extended reach condition ($M = 2.97$m, $SE = .04$m) than in the constricted reach condition ($M = 2.85$m, $SE = .05$m, $p = .01$). They also estimated their reachability to be farther in the variable condition ($M = 2.93$m, $SE = .04$m, $p = .01$) than in the constricted reach condition. However, no difference was found between the variable and extended reach condition ($p = .20$), see Figure 7.

These results demonstrated that perceived reachability was influenced by the type of variability present, and more extensive experience with the farther reach has led participants to increase their reachability estimates to a more liberal size. Additionally, these findings showed that our findings from the previous experiment was not the result of the perceptual system adopting a moderate sized action boundary as a heuristic strategy, instead, the perceptual system was taking the probabilistic information associated with each action boundary experienced into account and used a weighted average to determine action boundary.

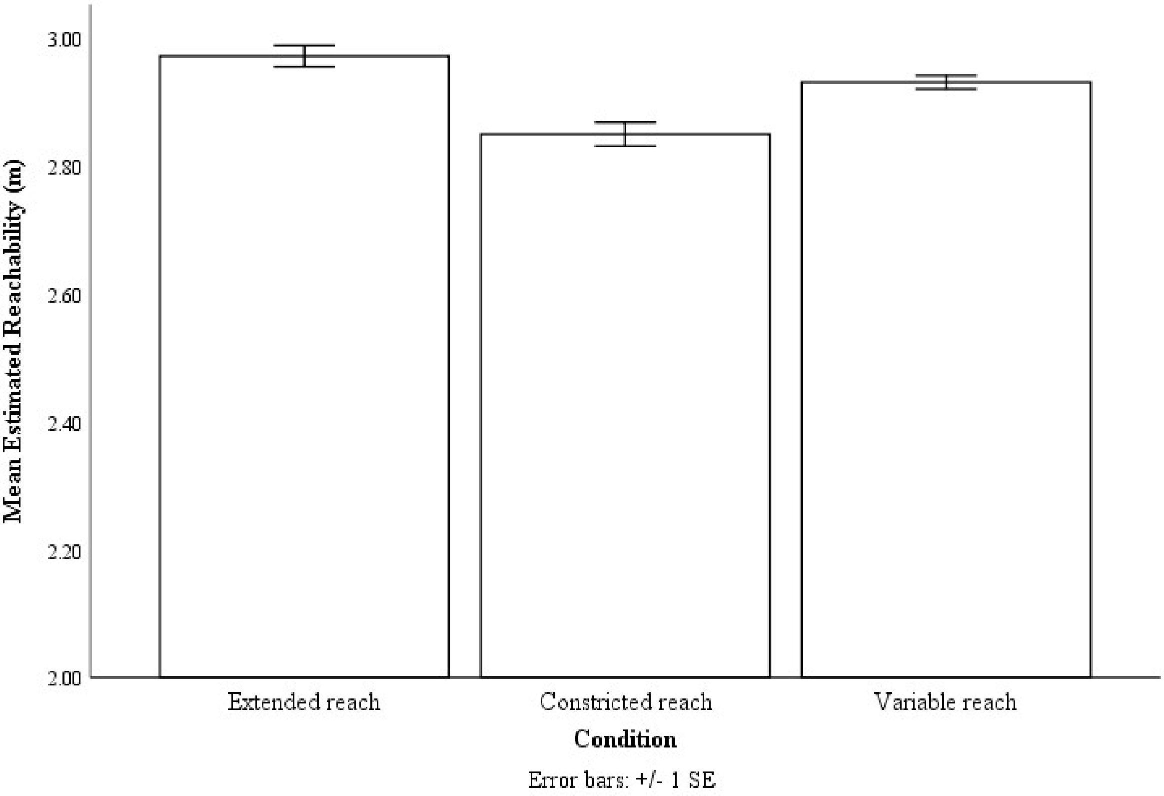

*Figure 7.* The mean estimated reachability of the three reaching conditions. Error bars are *1±SE* calculated within-subject with the method provided by Loftus and Masson (1994).

## Across 4 experiments

Findings across 4 experiments revealed that similar strategies were used in both height and non-height-related contexts to determine action boundaries following the experience of perceptual motor variability. Regardless of environmental contexts, following experience reaching where their reaching length varied drastically, participants have selected action boundary using a weighted average. Although environmental context did not appear to influence the *strategy* by which action boundaries were determined as a result of high versus low perceptual motor experience, it is possible that it has an additive effect on action boundary selection, with participants being more conservative *overall* (in both high and low variability conditions) with their reachability estimates in the height-related context. In order to assess the influence of environmental context on estimated reaching ability, we have collapsed across experiment 1 and 3 (random variability), and experiment 2 and 4 (systematic variability), and analysed the combined data to get a better idea of the relationship between environmental context and perceived action boundaries.

## Across Experiment 1 and 3

We have conducted a repeated measure ANOVA with mean estimated reachability (Extended/ Constricted/ Variable) as within-subjects variable and the environmental context (Height-related/ Non-height-related) as between subject variable. We found an effect of reaching condition $F(2,78) = 35.57$, $p < .001$, $\eta_p^2 = .48$, with the mean extended reach ($M$ = 2.52m , $SE$ = .03m) being larger than the mean constricted reach ($M$ = 2.35m, $SE$ = .03m, $p$ <.001) and the mean variable reach ($M$ = 2.44m, $SE$ = .03m, $p < .001$). Furthermore, the mean variable reach was also larger than the mean constricted reach ($p < .001$). Analysis showed effects of environmental contexts on estimated reachability, $F(1,39) = 22.60$, $p < .001$, $\eta_p^2 = .37$, with reachability estimates in the non-height-related conditions ($M$ = 2.55m, $SE$ = .04m) being significantly larger than those in the height-related conditions ($M$ = 2.32m, $SE$ = .04m, $p < .001$), see figure 8. The interaction between reaching condition and environmental context was not significant, $F(2,78) = .85$, $p = .43$, $\eta_p^2 = .02$). These results suggest that overall Experiment 1 and 3, participants' reachability estimates were more conservative in the height-related conditions than non-height-related conditions.

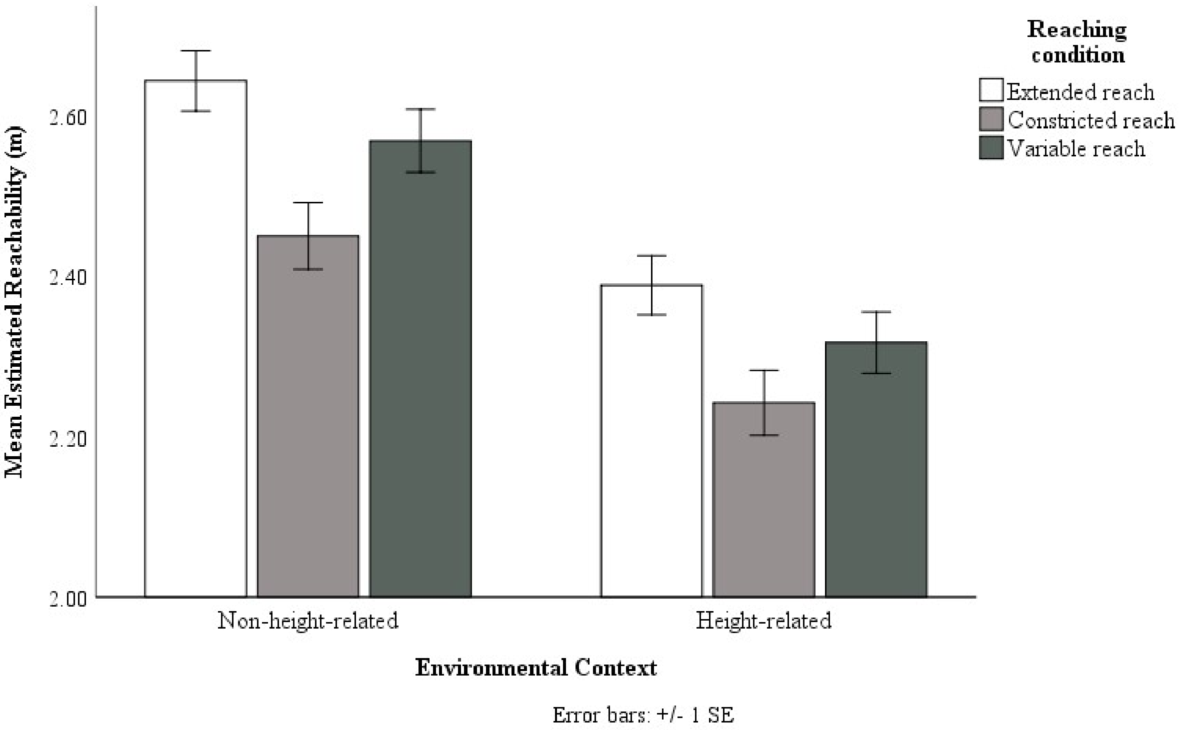

*Figure 8*. The mean estimated reachability of the three reaching conditions across the two environmental contexts. Error bars represent 1±SE of the mean.

To get a better idea of the relationships between the three reaching condition, using the collapsed data, we created two difference scores for each participant. We created one difference score by subtracting the mean variable reach estimate from the mean extended reach estimate (EV) and the other by subtracting the mean constricted reach estimate from the mean variable reach estimate (VC). If participants have used a weighted average to determine their action boundary in the random variability conditions, we should expect no difference between the EV and VC scores. A paired-sample t-test was conducted to compare the difference between the EV and VC scores. The t-test found no evidence for a difference between the EV scores (*M* = .07m, *SD* = .11m) and the VC scores (*M* = .07m, *SD* = .13m); *t*(20) = -.07, *p* = .94, see Figure 9. These findings indicate that in the random variable reach conditions participants have likely used a weighted average to determine action boundary, and the action boundary size selected was in between the extended reach condition and the constricted reach condition.

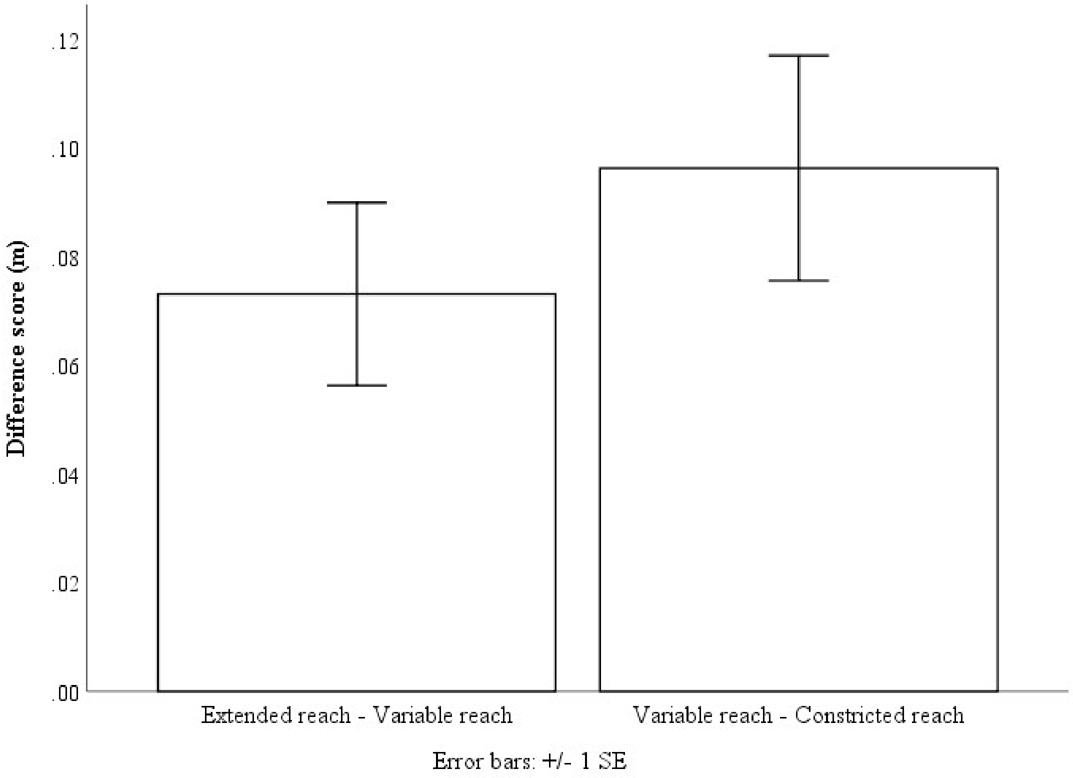

*Figure 9.* The EV and VC difference scores. Error bars represent 1±SE of the mean.

## Across Experiment 2 and 4

We have conducted a repeated measure ANOVA with mean estimated reachability (Extended/ Constricted/ Variable) as within-subjects variable and the environmental context (Height-related/ Non-height-related) as between-subjects variable. We found an effect of reaching condition $F(1.60,67.35) = 23.79$, $p < .001$, $\eta_p^2 = .36$, with the mean extended reach ($M = 2.57$m , $SE = .03$m) being larger than the mean constricted reach ($M = 2.45$m, $SE = .03$m, $p <.001$) and the mean variable reach ($M = 2.53$m, $SE = .02$m, $p = .03$). Furthermore, the mean variable reach was larger than the mean constricted reach ($p < .001$). Analysis showed effects of environmental contexts on estimated reachability, $F(1,42) = 254.208$, $p < .001$, $\eta_p^2 = .86$, with reachability estimates in the non-height-related conditions ($M = 2.92$m, $SE = .04$m) being significantly larger than those in the height-related conditions ($M = 2.12$m, $SE = .03$m, $p < .001$), see figure 10. The interaction between reaching condition and environmental context was not significant, $F(2,84) = .11$, $p = .90$, $\eta_p^2 = .003$). These results suggest that in Experiment 2 and 4, participants' reachability estimates were more conservative in the height-related conditions than non-height-related conditions.

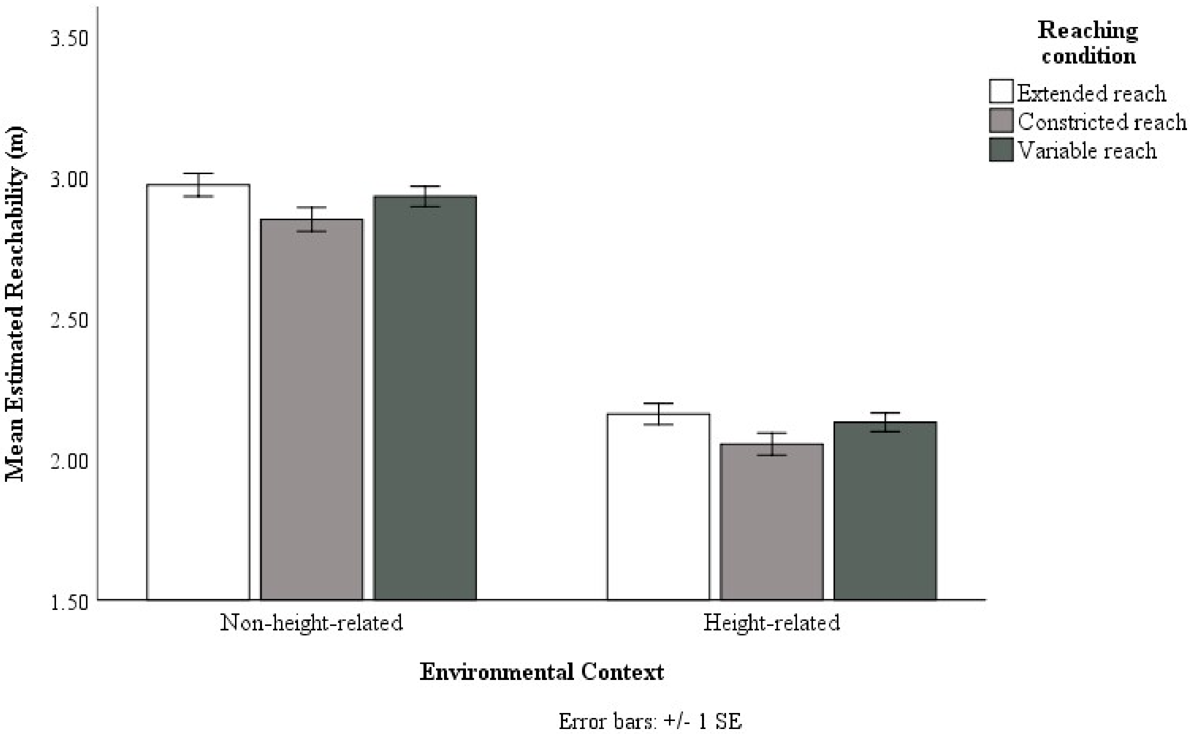

*Figure 10.* The mean estimated reachability of the three reaching conditions across the two environmental contexts. Error bars represent 1±SE of the mean.

Using the collapsed data from Experiment 2 and 4, we created one difference score by subtracting the mean variable reach estimate from the mean extended reach estimate (EV) and the other by subtracting the mean constricted reach estimate from the mean variable reach estimate (VC). If participants have used a weighted average to determine their action boundary in the systematic variability conditions, we should expect a difference between the EV and VC scores. A paired-sample t-test was conducted to compare the difference between the EV and VC scores. We found an effect of difference scores with the EV scores (*M* = .03, *SD* = .09) being smaller than the VC (*M* = .08, *SD* = .11); *t*(43) = -2.08, *p* = .04, indicating that estimates in the systematic variable conditions were closer to the extended reach estimates than the constricted reach estimates, see figure 11. Participants have used a weighted average to determine their action boundaries and were estimating liberally in the systematic variable reach conditions.

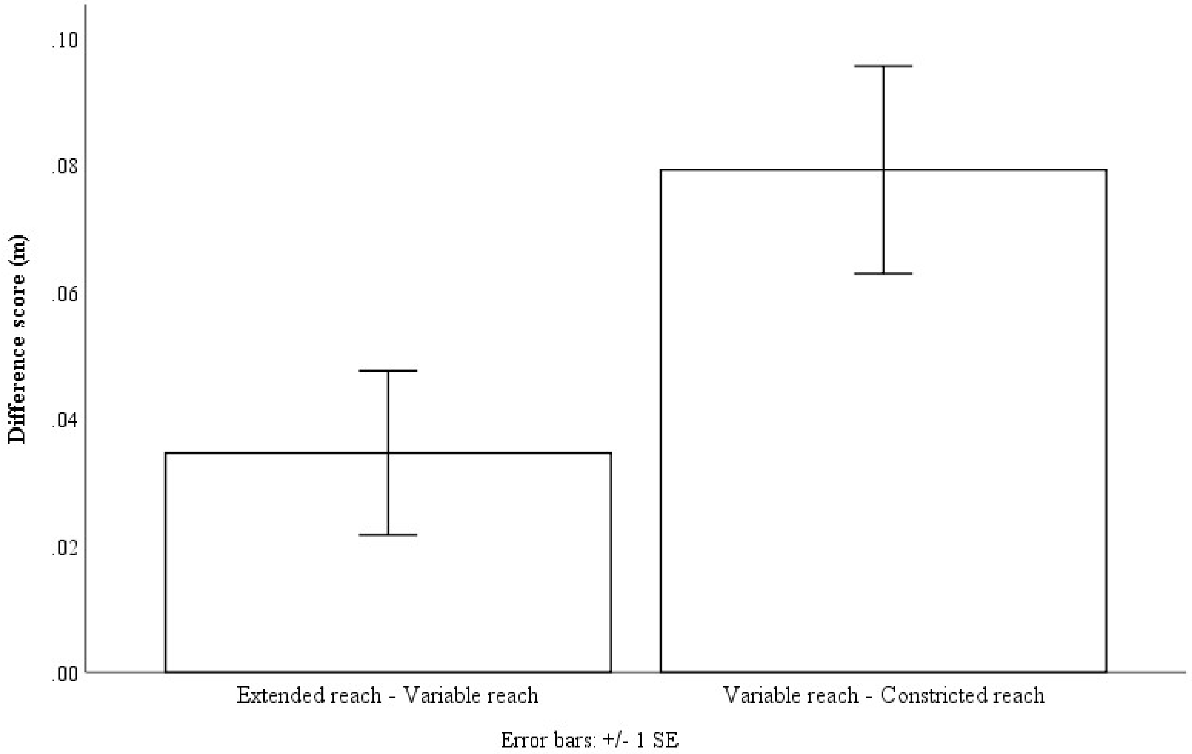

*Figure 11*. The EV and VC difference scores. Error bars represent 1±SE of the mean.

Taken together, these findings suggest that while the similar strategies were used in both height and non-height-related contexts to determine action boundary, participants were significantly more conservative with their reachability estimates in the height-related context than they were in the non-height-related context.

# Discussion

Recent studies using a similar paradigm have investigated the influence of perceptual-motor variability on the perception of action boundaries for horizontal reaching and found that individuals tended towards liberal estimates of their reachability in the event of perceptual motor variability. However, from these results, one could not determine whether the perceptual system utilises the same strategy to determine action boundaries for all types of reaches and different environmental contexts. Hence, in this set of studies, we examined the effect of different types of perceptual-motor variability and environmental contexts on the perception of action boundaries for overhead reaching. Participants were asked to estimate the maximum vertical reachability following calibration to either a long virtual arm, a short virtual arm or a virtual arm that varied in size either randomly, or systematically weighted in that the long virtual arm was experienced twice as often. We also contrasted participants' recalibration of action boundaries following changes in their action capabilities in two situations: a height-related situation (Exp 1 and 2) and a non-height-related situation (Exp 3 and 4). The perceived penalty for error was presumably more severe in the height-related situation, which enabled us to examine whether participants take into account the context in which the action occurs with the selection of action boundaries in the event of perceptual-motor variability.

We replicated the effect of perceptual motor experience on perceived reachability reported by Lin, McLatchie and Linkenauger (2020). Our findings demonstrated that participants were sensitive to changes in their action capabilities, and their reachability judgements were consistent with their reaching experience during calibration phases. In all four experiments, participants have consistently estimated their reachability in the extended reach condition to be farther than in the constricted arm's reach. This finding provides further evidence that manipulation of perceptual motor feedback could influence perceived action boundaries, and perceptual motor recalibration could occur after a brief exposure in virtual environments.

Experiment 1 and 3 demonstrated that when faced with random variability in their reaching experience and participants have experienced all three reaches with equal probability, participants subsequently reported their reachability to resemble the mean. Experiment 2 and 4 indicated that when reaching experiences were greatly weighted towards the extended arm's reach, participants have opted for a more liberal, larger action boundary for reaching. Taken together, results from the four experiments indicated that participants were sensitive to the probabilistic information associated with different arms' reach they have experienced during the calibration phase, and used a weighted average of reaching experience to determine their action boundary under conditions of uncertainty.

Interestingly, our findings reveal that similar strategies were used to determine action boundaries following perceptual motor variability in both environmental contexts. Had participants employ different strategies depending on the environmental context in which the action occurred, given the absence of perceived penalty/negative consequences associated with a failed action in the non-height related situation, we would expect participants to be less deliberate in their reachability estimates. Instead, participants have used a weighted average to determine action boundary following variability experience in both contexts, and participants have incorporated probabilistic information associated with the reach lengths they have experienced during the calibration phases into their subsequent action boundary judgements.

It was possible that participants did not perceive any negative consequences associated with failed reaching in the virtual environment, which could account for the similar pattern of results observed in both environmental contexts. In order to conclude that environmental context had no influence on the strategy by which action boundaries are determined, we have collapsed across experiment 1 and 3, as well as 2 and 4. Results from the cross-experiment analyses showed that participants were more conservative with their reachability estimates overall in the height-related context. These findings suggest that while similar strategies were used to determine action boundaries relative to perceptual motor variability in both contexts; environmental context had an additive effect on participants' action boundary selection, with participants being more conservative with their reachability estimates across all reaching conditions in the height-related context.

Our findings here differ from those in Lin, McNatchie and Linkenauger (2020) in that they showed that individuals were quite liberal in their approximations of their action boundaries; whereas here we found that individuals have chosen the medium action boundary. Hence, we can reasonably postulate that the strategy in which the perceptual system employ to determine action boundary in the event of perceptual motor variability is action specific (i.e., type of reach) rather than context specific. This presumption may seem counterintuitive, however, if action boundary determination is context specific, then the strategy by which the action boundary for overhead reaching is determined would be generalised to all actions performed in the same situation (e.g., similar strategy would be employed to determine action boundary for horizontal reaching and jumping in the same situation). While this could be a more efficient approach, it is also less behaviourally adaptive, because different actions have different associated consequences and their respective costs and benefits. Employing a context-specific blanket approach to determine action boundary would not be flexible enough to account for all possible actions and their associated consequences. Although our results showed that environmental context has an additive effect on participants' action boundary selection, we found no evidence for a context-specific effect on the *strategy* used by the perceptual system to determine action boundary. We are aware that we only assessed two different contexts (even though they were specifically chosen because we expected a context effect for these different contexts). It would be premature to conclude that context has no influence on the strategy in which action boundaries are determined under conditions of perceptual-motor variability. It is possible that in addition to the consequence and costs-benefits ratio of a particular action, the perceptual system may employ different strategies to determine action boundary to meet the demands of the specific situation for various other actions. Future research could expand on this further and examine the influence of different environmental contexts as well as actions on action boundary selection.

One possible interpretation for our current findings in the context of previous findings is that not all actions are important enough to warrant spending the time and effort to integrate probabilistic information and/or to generate optimal solutions. However, for some actions, it is worth the time and effort to determine the optimal solution, especially when an erroneous motor decision (or selection of inappropriate action boundary) could lead to negative consequences. In the case of overhead reaching, selecting an inappropriate may result in loss of balance and falling. Hence, a better strategy would be to forgo short-term gains in efficiency for more deliberate and careful evaluation (Beach & Mitchell, 1978; Glöckner, 2008). Thus, the perceptual system would possibly behave in ways that mimic a weighted average for more than just ‘good enough’ solutions in situations where a failed attempt at an action could result in harm. Although heuristics generally provide sufficient solutions for certain actions’ boundaries, other more dangerous actions’ boundaries situations may exist in which it would be a non-adaptive strategy for human ancestors to disregard uncertainties and/ or probabilistic information. By using different approaches for different actions on an ad hoc basis to determine action boundaries, the perceptual system could maximise the efficiency of information processing in the event of perceptual motor uncertainties, while minimising the exposure to potentially dangerous situations and aversive consequences.

Similarly, our findings indicate that participants have favoured a more conservative sized action boundary for overhead reaching than for horizontal reaching as reported in Lin, McLatchie & Linkenauger (2020); in which participants have demonstrated a tendency for a liberal estimates of their horizontal reachability regardless of whether they have experienced all three arms' reach with equal probability, or whether their reaching experience was greatly weighted towards the constricted or the extended arm's reach. This difference could also be attributed to the increased postural demand required by the reaching task in the present study. In Lin, McLatchie & Linkenauger (2020), participants were asked to estimate their reachability of one arm for horizontal objects while seated. In the present study, participants had to extend both arms upwards while standing upright with both feet on the ground, which led to reduced postural control and increased postural sway. Thus, when facing with inconsistency in the perceptual motor feedback, selecting a more conservative action boundary could be an indication of the presence of a larger safety margin. Additionally, these results resonate with findings reported in the literature suggest that there is a reduction in the magnitude of overestimation or even underestimation in perceived reachability for reaching tasks that required greater postural stability demands (Carello et al.,1989; Robinovitch, 1998; Gabbard, Cordova & Lee, 2007). Hence, selecting action boundary using a weighted average for overhead reaching would prevent individuals from executing reaches that would jeopardise their balance and reduce the exposure to potentially adverse consequences.

In summary, the present studies extended findings from previous studies that examined the effect of perceptual motor variability on perceived action boundaries for reaching. Our findings demonstrate that the perceptual systems utilised similar strategies to determine action boundaries in both height and non-height related contexts, and participants have used a weighted average of their reaching experience to determine action boundaries for overhead reaching under conditions of perceptual-motor variability.

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# Chapter 4: Jumping and leaping estimations using optic flow, and the influence of perceptual motor variability in optic flow on the perception of jumping ability

Findings from previous chapters suggested that the point on the distribution that acts as the judged action boundary may have varied as a function of task. Specifically, the strategy in which the perceptual system employs to determine action boundary in the event of perceptual motor variability is specific to the action but not the context. It has been found that actions that have little to no consequences following a failed execution result in a more liberal action boundaries judgement (chapter 2), whereas actions where an erroneous decision could lead to potentially negative consequences, then probabilistic information is taken into account and a strategy akin to a weighted average was used to determining action boundaries under conditions of perceptual motor uncertainties (chapter 3). Thus, it is possible that the perceptual system may employ different strategies to determine action boundary to accommodate demands arisen from the consequences and costs-benefits ratios of a particular action. To explore this further, in this chapter present a series of experiments that focused on jumping, a full-bodied ballistic action that allows little online movement correction, and an action that is also associated with more severe consequences if one failed to perform the action, in comparison to the other actions we have examined in previous chapters. The first half of the chapter investigated the effect of optic flow and walking speed calibration on the perception of leaping and jumping ability, in order to determine whether optic flow could specify an action boundary when calibrated or scaled to actions such as leaping and jumping. The second half of the chapter assessed how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping.

# Abstract

Optic flow provides information on movement direction and speed during locomotion. Changing the relationship between optic flow and walking speed via training has been shown to influence subsequent distance and hill steepness estimations. Experience with slow optic flow at a given walking speed was associated with increased effort and distance overestimation in comparison to experience with fast optic flow at the same walking speed. We expected that the manipulation of the relationship between optic flow rate and walking influences anticipated effort, which in turn influences individuals' perception of the extent over which an action can be performed. The current study investigated the effect of optic flow and walking speed calibration on the perception of leaping and jumping ability. Participants were asked to estimate their maximum leaping or jumping ability following exposure with either fast optic flow or slow optic flow at the same walking speed. We found that individuals estimated their leaping and jumping ability to be farther when they were calibrated to fast optic flow compared to when they were calibrated to slow optic flow. Findings suggest that recalibration between optic flow and walking speed may specify an action boundary when calibrated or scaled to actions such as leaping, and manipulating optic flow speed and associated anticipated effort for walking a prescribed distance could influence one's perceived action capabilities for jumping and leaping.

***Keywords***: Perception and action, optic flow, perceptual-motor calibration

Visual perception is an active and continuous process, whereby we use the changes in optical information over time to specify potential opportunities for actions available and to aid navigation in the environment. To perform actions adaptively and avoid performance errors, the perceiver must be able to perceive those behaviourally relevant properties in the environment with respect to their action capabilities (Gibson, 1979; Chemero, 2003). Warren (1984) assessed individuals' ability to perceive the optimal and maximum height of the surface that affords bipedal climbing and found that independent of body height, tall and short individuals perceived the maximum step height that affords bipedal climbing to be approximately 0.88 of their leg lengths. This finding demonstrated that individuals are calibrated to their action capabilities and use the task-relevant part of their bodies, that is, their leg length in this case to scale possibilities for action and to distinguish between possible and impossible actions.

However, one's action capabilities are not completely stagnant, and humans have to make motor decisions under changing and at times unpredictable environmental conditions, rendering it necessary for the scaling between perceptual information and action to be recalibrated for actions to be executed adaptively and to avoid motor errors (Brand & de Oliveira, 2017; van Andel, Cole & Pepping, 2017). For example, Mark (1987) had participants make judgments about their bipedal stair climbing capabilities while standing on blocks. Information about the climb-on-ability of steps is scaled to one's body dimensions such as leg length and standing eye height (Warren, 1984). By standing on the blocks, participants' eye height information for stair height scaling was increased and the same stair was of a smaller proportion of their new standing eye height, and this information has to be recalibrated to allow the accurate perception of action possibilities. Results demonstrated that participants' subsequent affordance judgements were consistent with the changes in their body dimensions (i.e., eye height), which suggested that individuals could rapidly re-learn their action capabilities after a small amount of practice and recalibrated to changes in their eye height. Hence, the recalibration between perceptual information and action is fundamental to the successful performance of visually guided actions.

For actions such as walking, idiothetic information which consists of muscular and joint proprioception, motor efference and vestibular information contributed to human perception of self-motion, this internal sense of self-motion covaried with the visual information specifying the displacement in the environment resulting from the movement of the perceiver, known as global optic flow (Gibson, 1950; Rieser et al., 1995). Optic flow can be defined as the transformation in the pattern of the visual array resulting from the movement of the perceiver. Global optic flow is generated as the perceiver moves through the environment, and over time through action, the rate of optic flow is calibrated with idiothetic information about the locomotor distance travelled by gait, and the resulting visual locomotor coupling thus allows perceivers to guide their actions, regulate their gait transition, to determine speed and heading. (Gibson, 1950; Warren, Kay, Zosh, Duchon & Sahuc, 2001; Mohler et al., 2007; Warren & Hannon, 1990). Additionally, calibration between movement and optic flow allows the perceiver to determine the locomotor distance traversed by integrating the rate of optic flow relative to their gait, such that they can determine the locomotor distance travelled from optic flow by knowing one's gait, to estimate travel distance from optic flow given that appropriate scaling information is provided (e.g. Redlick, Jenkins & Harris, 2001; Frenz & Lappe, 2005; Frenz, Bremmer & Lappe, 2003), as well as to accurately estimate the amount of walking required to traverse a given extent, even in the absence of continuous visual information (e.g., Rieser, Ashmead, Talor & Youngquist, 1990).

Optic flow calibration is fundamental to visually controlled locomotion, and several recalibration studies have found evidence that humans can quickly and flexibly adapt to perturbations in this learned relationship between gait and optic flow rate. In their seminal study, Rieser, Pick, Ashmead and Garing (1995) introduced a discrepancy between forward walking and optic flow by having participants walk on a treadmill that was being pulled by a tractor moving at a speed that was different from the participants' walking speed. After experiencing optic flow speed that was slower than their walking speed, participants overshoot the target when asked to walk blindly towards a previously seen location. Conversely, after experiencing optic flow speed that was faster than their walking speed, participants tended to undershoot the target. These results demonstrated that the perception of the amount of walking required to traverse a prescribed distance can be altered by the recalibration of optic flow relative to gaits, thus influencing participants' subsequent blind walking judgments. Interestingly, this recalibration of optic flow relative to gait could be generalised to subsequent blind walking and blind side-stepping but failed to generalise to blind throwing or turning in place. These findings led Rieser et al., (1995) to postulate that the calibration of locomotion is functionally organised and that calibration of one action can be transferred to other actions that execute the same function goal. Similarly, Withagen and Michaels (2002) found generalisation of optic flow calibration from walking to crawling, and Kunz, Creem-Regehr and Thompson (2009) found generalisation from walking to imagining walking. In line with this, recent studies using various forms of immersive displays (e.g., CAVEs, VR head-mounted displays) have reported similar generalisation of optic flow calibration to subsequent walking (Adams et al., 2018; Mohler et al., 2004; 2007; Ziemer et al., 2013; Solini, Bhargava & Pagano, 2019; 2021; Waller & Richardson, 2008).

Nevertheless, what is less clear is how optic flow recalibration relative to gait affects other types of locomotor actions that involve the same limbs and have a similar functional goal but are more dynamic and ballistic in nature, such as leaping. For example, when viewing an extent over which one intends to leap across, what is the optical information used by the perceptual system to determine whether the action can be accomplished? Would it be possible that like walking, the perceiver would utilise the learned relation between rate of walking and optic flow rate to anticipate the amount of optic flow that they should experience as a consequence of launching oneself across the given extent? Previous research has shown that individuals are capable of adequately making judgements about their jumping ability, as well as adjusting these judgements following changes in their action capabilities. For instance, Lessard, Linkenauger and Proffitt (2009) manipulated participants' jumping ability by attaching weights to their ankles, and participants estimated their jumping ability to be farther when they were not wearing ankle weights compared to when they were wearing ankle weights. Presumably, it would take more effort to launch oneself off the ground with a forward momentum if you have a higher body mass or have been weighed down. It follows that if the anticipated effort to act could influence one's perceived jumping ability, then it is possible that the manipulation of anticipated effort via optic flow recalibration could influence one's perceived action capability for launching actions such as leaping.

With regards to manipulating anticipated effort by changing the optic flow rate during walking, it has been shown that the manipulation of optic flow relative to gait could influence perceived travelled distance when a discrepancy was introduced between anticipated patterns of optic flow and walking effort. Proffitt et al. (2003) had participants walk on a treadmill while wearing an HMD that provided them with no optic flow, and during calibration, participants learned from the locomotor experience that it took more effort to remain "optically" stationary. Following calibration, when asked to walk blindly to a target, participants consistently demonstrated an overestimation of distance to the target. Similarly, a recent study manipulating optic flow speed and walking effort has been shown to influence the perceived steepness of hills. Linkenauger and Readman (2020) had participants walk on a treadmill in which forward walking effort was paired with optic flow that was either faster or slower than the walking speed. In the fast optic flow condition, participants learned that it took little effort to traverse a great distance; whereas, in the slow optic flow condition, participants learned that despite exerting a great deal of effort they were unable to traverse very far. The findings demonstrated that after experiencing slower optic flow relative to gait, participants estimated hills to be steeper than when they experienced the faster optic flow. Taken together, these findings indicate that the manipulation of optic flow relative to gait could influence the anticipated effort to perform a given action, which in turns influence an individual's perception of spatial properties.

So if one adapted to a change in the optical distance that followed each step, does this learning translate to launching actions such as leaping and jumping? A number of studies have found support for the notion that the recalibration of optic flow relative to gait can be generalised to actions that serves the same locomotor function as walking, which is, to transport oneself from one place to another. While others have shown that recalibration of an action to be anatomically specific, in which recalibration did not generalised to other locomotor actions performed by a different limb (Durgin, Fox & Kim, 2003), or only weakly transfer to actions that have similar function but are generally less well practice (e.g., Rieser et al., 1995; Durgin et al., 2004; Kunz, Creem-Regehr & Thompson, 2013). For example, Kunz, Creem-Regehr and Thompson (2013) found that optic flow calibration relative to walking only weakly influence subsequent wheelchair-wheeling in novice wheelchair users. Hence, it is reasonable to postulate that the recalibration of optic flow relative to gait could influence one's perceived ability to perform a certain type of launching actions, but not the others.

Here, we examined the effect of optic flow calibration relative to gait on perceived jumping ability and leaping ability. We have opted to examine two different types of gaits, leaping, which is a highly familiar action and physically similar to walking in terms of leg oscillation, and two-footed jumping, which has different coordinative movement pattern to walking and the performance outcomes for such action tend to be more variable. Furthermore, it is not a common action in everyday lives, and previous studies have shown that optic flow recalibration to walking would result in no or weak generalisation to functionally similar actions that are not as well practiced (e.g., Kunz, Creem-Regehr & Thompson,2013).

We manipulated perceptual-motor coupling between forward walking and optic flow by having participants walk on the treadmill at the same speed while experiencing optic flow that was either fast or slow optic flow. Presumably, in the fast optic flow condition, participants would learn from their experience that it took a little effort to traverse a great distance; whereas, in the slow optic flow condition, participants would learn that it took a lot of effort to travel a short distance. We expected that following calibration to either fast or slow optic flow relative to gait, the expectation of greater or lesser effort to traverse a prescribed distance should influence participants' judgments of their leaping ability but would not or only weakly influenced their two-footed jumping ability. Surprisingly, we found that individuals have estimated their leaping and two-footed jumping ability to be significantly farther when they experienced the fast optic flow than when they experienced the slow optic flow. These findings suggest that optic flow calibration relative to walking could influence one’s ability to perform full body and launching actions such as jumping and leaping.

# Experiment 1

In this experiment, we investigated the effect of optic flow speed on the perception of action boundary for leaping. Participants walked on the treadmill while wearing a head-mounted display that provided them with either fast or slow optic flow. Following calibration in the virtual environment, participants estimated their maximum leaping ability in a real-world environment.

## Method

### Participants

GPower software application (Faul, Erdfelder, Lang, & Buchner, 2007) was used to perform an a priori power analysis to estimate sample sizes required to achieve adequate power. The required power was set at 1- β = .85, and the level of significance was kept at α = .05. We expected a large effect size of f = .4, we based this on Linkenauger & Readman (2020), in which a similar virtual reality programme was used to investigate the influence of optic flow speed on perceived hill steepness. In this study, an f value of .72 was obtained using a sample size of N = 15. Power analysis indicated that a sample size of N = 6 would be sufficient to achieve a power of .85 and an alpha of .05. However, due to the slight difference in methodology between the current study and that of Linkenauger and Readman (2020), we have doubled the number of participants and increased our sample to 30 for both experiments to ensure we have sufficient power and due to the possibility of technical failure with this type of equipment.

Thirty participants (5 Males) between 18 and 22 years of age (*M* = 20.21 years, *SD* = 1.03 years) were recruited from Lancaster University through opportunity sampling. One participant was excluded from the analysis as the participant was unable to complete all experimental tasks due to being heavily pregnant at the time of participation. All participants had normal or corrected- to normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

## Stimuli and Apparatus

For the optic flow calibration phase, participants walked on a treadmill set to a speed of 2.2km/h (approximately 0.61m/s). This treadmill speed was selected as it was reported by participants in our pilot study to be a comfortable speed for one to walk for a prolong period of time without feeling fatigue. Participants wore an Oculus Rift CV1 head-mounted display (HMD) that displayed a stereoscopic image of the virtual environment with a resolution of 2160 x 1200 pixels and a frame rate of 90Hz. The experimental programme and environment were created using Unity 3D© Gaming Engine, the virtual environment consisted of a horizontal ground plane with grass texture and a brick lane; several 3D models of trees and rock were placed along the path. The 3D camera was placed at eye-level enabling the participant to perceive the virtual environment in a first-person perspective, and that the position of the 3D camera was consistent with the participant's physical eye height. They were positioned in the virtual environment so that they were standing on the brick lane. The movement of the participant's head was tracked, and graphics were updated as the participant looked around in the virtual environment by moving their head. During the fast optic flow calibration phase, the virtual environment moved past participants at a rate of 6m/s; during the slow optic flow calibration phase, the virtual environment moved past participants at a rate of 2 m/s.

For the estimation phase, the ground was covered with a sheet of fabric (150cm x 300cm). The floor was covered with a piece of white fabric to create a uniform background and minimise landmarks that could influence participants' judgements, See Figure 1. A line that served as a reference point was placed 66 cm directly in front of the white fabric and participants were told to make their estimations while standing behind the line.

## Procedure

After providing their informed consent, participants were positioned on the treadmill. At the start of the experiment, participants were randomly assigned to experience the slow optic flow or fast optic flow condition first and were given instructions for both the calibration and estimation phases of the experiment. In the optic flow calibration phase, after donning the Oculus HMD and entered the virtual environment, participants were told to hold onto the treadmill rail and were encouraged to look around to familiarise themselves with the virtual environment before the experiment began. Participants then walked on the treadmill for 10 minutes, while experiencing either the fast or slow optic flow. After walking for 10 minutes,

*Figure 2.* Left panel: Illustration of a participant completing a calibration trial. Right panel: Image of what the participant would see while completing the calibration phase.

the experimenter helped the participants remove the HMD, participants were instructed to keep their eyes closed and they were led off the treadmill and positioned behind the reference line.

The estimation phase consisted of 12 trials, in which participants reported their maximum leaping ability by instructing the experimenter to move the estimation dot (using a laser pointer) closer or farther until it was at the maximum distance the participants believe they could perform a leap from a standing position. A leap is defined as a one-footed take off from a standing position and land on the other foot. To control for hysteresis, in half of the trial, the estimation dot's starting position was directly in front of the participants' feet and at the reference line in front of them; participants moved the dot away from them. For the other half of the trials, the estimation dot's starting position was at the opposite end of the white fabric covering the floor, at approximately 400 cm away from the participant, and participants moved the dot towards them. Participants were encouraged to make as many adjustments as necessary for an accurate estimation of their leaping ability, and to move the dot beyond the area covered by the white fabric if they thought it was necessary, then close their eyes in between trials while the experimenter measured the distance between the reference line and the final location of the estimation dot. After making all 12 estimations and completed the first optic flow condition, participants were led back onto the treadmill and repeated the procedure with the second optic flow condition.

## Results

To analyse the influence of optic flow calibration on leaping ability estimates, we conducted a repeated-measures ANOVA with optic flow condition (Fast versus slow) as the within-subjects variable and the estimated leaping ability as the dependent variable. We found a significant effect of optic flow condition on estimated leaping ability, $F(1,28) = 7.56$, $p = .01$,

$\eta p^2 = .21$, and participants have estimated their leaping ability to be significantly farther in the fast optic flow condition (*M* = 154.94 cm, *SE* = 4.46 cm) than in the slow optic flow condition (*M* = 147.64 cm, *SE* = 4.04 cm, *p* = .01), see Figure 2. These results indicated that there was evidence for a difference in leaping ability esimations between the fast and slow optic flow condition, suggest that optic flow recalibration relative to gait has influence participants' subsequent estimations of their leaping ability and participants who experienced fast optic flow estimated their leaping ability more liberal than after they experienced the slow optic flow.

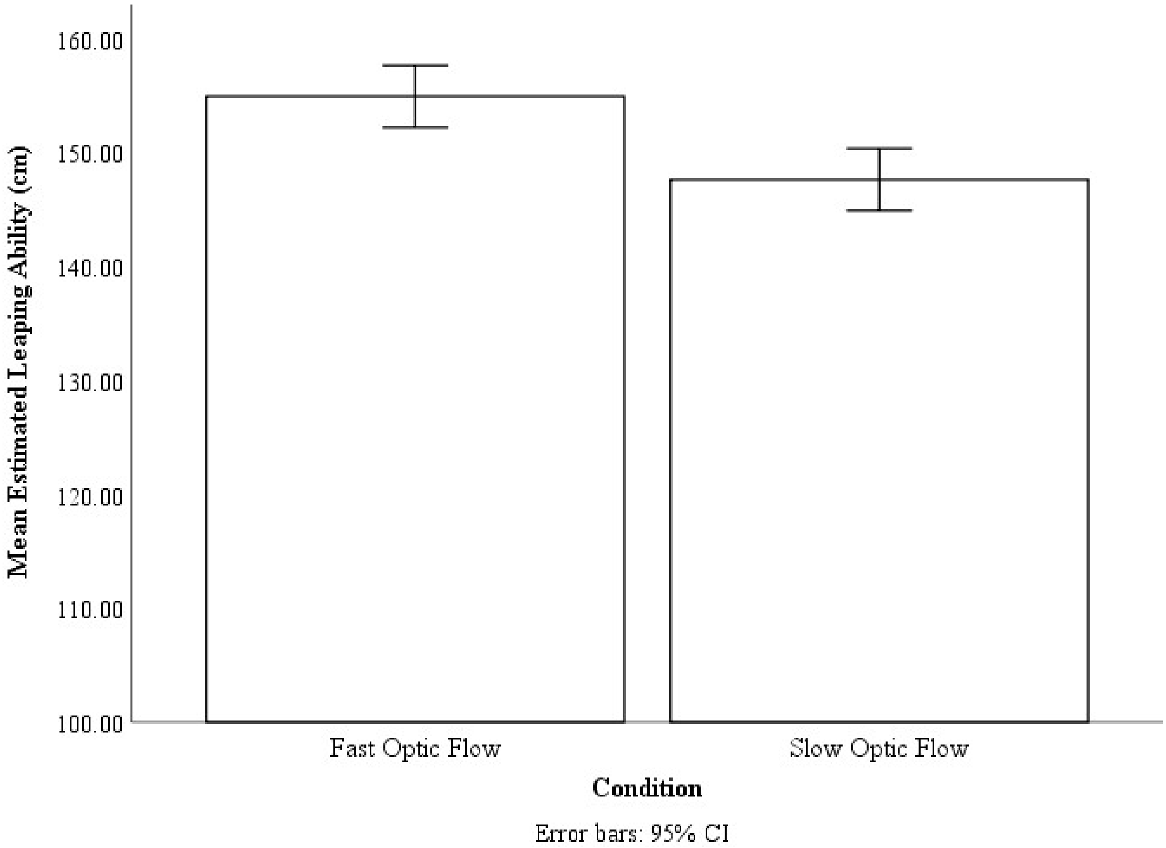

*Figure 2*. The mean estimated leaping ability of the two optic flow condition. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994).

# Experiment 2

Findings from Experiment 1 showed that experiencing different optic flow rate relative to gait influenced subsequent leaping ability judgements. Findings from Experiment 1 were consistent with what would be expected if participant's judgment of their leaping ability was influenced by the expectation of greater or lesser effort to traverse a prescribed distance, and those who experienced fast optic flow relative to gait learned from motor experience that it is less effortful to traverse a greater distance, hence judged that they could leap farther. In Experiment 2, we sought to investigate whether recalibrating the relationship between optic flow rate and walking speed could lead to corresponding shifts in judgements of the maximum distance one can jump across with two feet. We expected that the effect of optic flow recalibration to gait would have no or a lesser influence on two-footed jumping, as previous studies have shown that optic flow recalibration to walking would result in no or weak generalisation to functionally similar actions that are not as familiar and less well practiced.

### Participants

Thirty participants (8 males) between 18 to 22 years of age ($M_{age}$ = 19.25, $SD_{age}$ =.92) were recruited from Lancaster University through opportunity sampling. All participants had normal or corrected- to normal vision. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

### Materials and procedure

Everything was the same as in Experiment 1 except participants had to make estimations of their maximum jumping ability (two-footed take off and two-footed landing).

## Results

To analyse the influence of optic flow calibration on two-footed jumping ability estimates, we conducted a repeated-measures ANOVA with optic flow condition (Fast versus slow) as the within-subjects variable and the estimated jumping ability as the dependent variable. We found a significant effect of optic flow condition on estimated jumping ability,

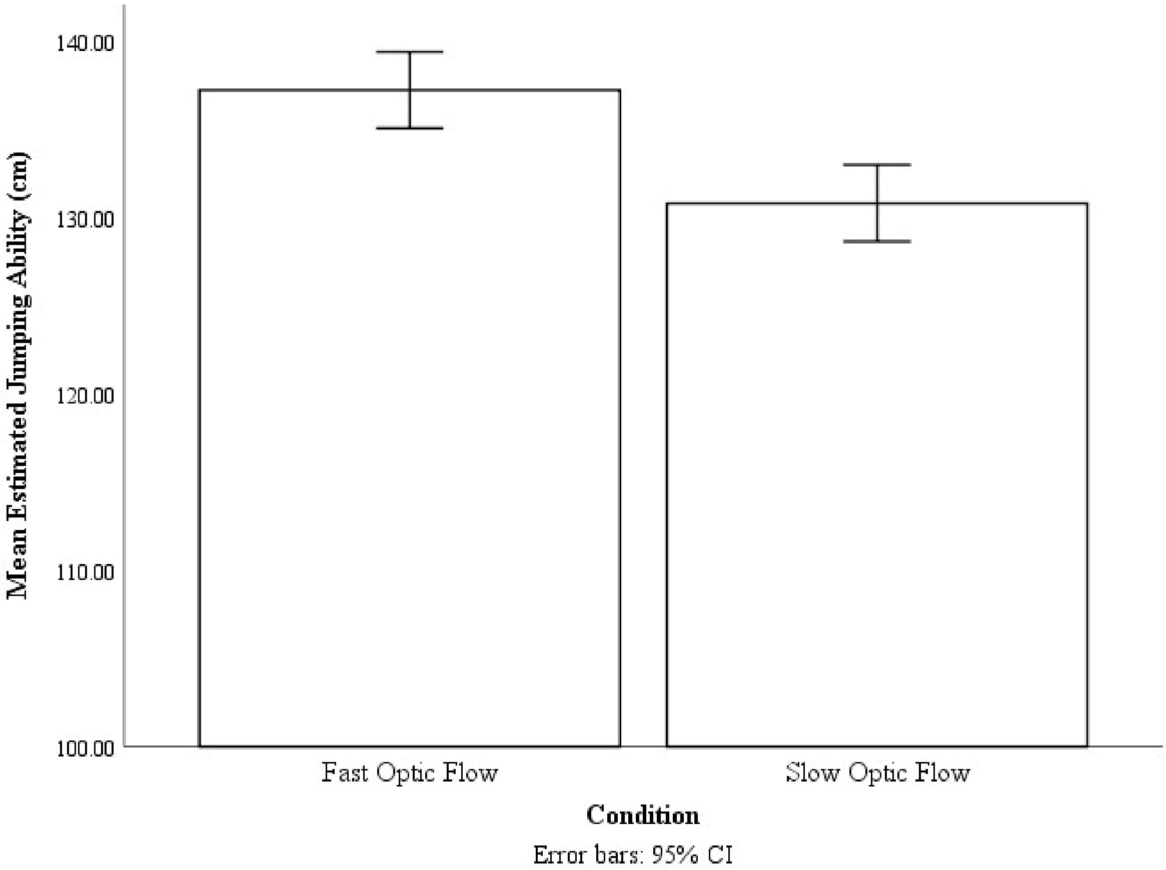

*Figure 3*. The mean estimated jumping ability of the two optic flow condition. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994).

*F*(1,29) = 9.19, *p* = .005, *ηp²* = .24, and participants have estimated their jumping ability to be significantly farther in the fast optic flow condition (*M* = 137.26cm, *SE* = 5.88cm) than in the slow optic flow condition (*M* = 130.83cm, *SE* = 5.59cm, *p* = .005), see Figure 3. These results suggested that optic flow speed has an effect on perceived two-footed jumping ability, in which participants who experienced fast optic flow while walking judged that they could jump farther than when they have experienced slow optic flow while walking. Taken together with the results from Experiment 1, these results suggested that recalibrating the relationship between optic flow rate and walking speed correspondingly shifts judgments of the maximum distance that can be leaped across (an action similar to gait). Moreover, this shift in the action boundary generalises to the maximum distance that can be jumped across (with both feet).

## Discussion

An ample body of research has demonstrated people's ability to accurately determine the locations of their action boundaries (i.e., the maximum extent over which one can perform an action) for a variety of actions across different environmental contexts. So far, however, limited work has been done to identify the information used to specify action boundary (or boundaries) for launching actions such as leaping and jumping. The current set of studies aimed to determine whether optic flow calibration relative to gait could influence launching actions such as leaping and jumping. We manipulated perceptual-motor coupling between anticipated walking effort and optic flow speed, and calibrated participants to either fast optic flow (low anticipated effort) or slow optic flow (high anticipated effort). Participants were asked to estimate the maximum extent of their jumping/leaping ability after being calibrated with the fast or slow optic flow. Experiment 1 examined how individuals select their action boundary for leaping after experiencing either fast or slow optic flow, and Experiment 2 examined how individuals select their action boundaries for jumping following calibration to either fast or slow optic flow.

We felt the need to point out that, while it is typical in the optic flow recalibration literature to utilise a pretest-calibration-posttest design, in which participants perform a motor task before and after exposure to perturbed optic flow. We have not included such a design, nor have we compared participants' perceived action capabilities with their actual action capabilities, as these comparisons would only be meaningful if we were interested in individuals' affordance judgement accuracy. This is not the main question we were addressing, as we were interested in the *relative difference* in estimated action capabilities following exposure to perturbed optic flow relative to gait.

We found that individuals recalibrated to different sized action boundaries following experience with different optic flow speeds. Participants were more liberal with their estimates and estimated their leaping ability to be significantly farther after experiencing the fast optic flow than when they were calibrated to the slow optic flow. This finding was consistent across both experiments and provides evidence that the manipulation of anticipated effort via optic flow speed does influence perception of action boundary for leaping as well as two-footed jumping . We expected a difference for only leaping because the action was similar to walking, but we still found an effect for two-footed jumping which suggests generalisation across actions that require different types of movements.

This is an interesting finding, because if this generalisation is purely driven by optic flow recalibration relative to gait, exposure to different optic flow speed relative to gait should have no or little meaningful influence on subsequent two-footed jumping estimates. Previous studies have shown that recalibration did not or only weakly generalised to other locomotor actions that are functionally similar to walking but are generally less well practiced, such as single leg hopping and wheelchair wheeling (e.g., Rieser et al., 1995; Durgin et al., 2004; Kunz, Creem-Regehr & Thompson, 2013). However, to our surprise, we found that not only did this recalibration generalise to two-footed jumping, the magnitude of difference between the two optic flow rate conditions was similar across both leaping and two-footed jumping. Hence, we suspect that the anticipated effort to perform a given action induced by optic flow recalibration may have played a larger role than just optic flow recalibration to gait alone.

Furthermore, an alternative explanation of the current findings might be that the manipulation of optic flow speed relative to gait has an effect on spaital scaling/distance perception, in which the exposure to faster or slower optic flow relative to gait has influence participants' distance perception. Suppose the visual information in optic flow for distance perception is the difference in time-to-contact (TTC) between the near and far edges of a given extent. This ΔTTC information is used to control walking, stepping, leaping and two-foot jumping. This fast optic flow condition shifts this relation, such that the same ΔTTC corresponds to a larger extent. Thus, after recalibration, the same ΔTTC is used to control crossing a larger extent, for all actions. Thus, it is possible that the common visual information that underlies the shift in the action boundary and generalises across actions. This explanation is consistent with previous studies that demonstrated the optic flow recalibration influence participants' subsequent distance perception, in that participants tended to underestimate/undershoot or overestimate distance/overshoot following exposure to visually faster or slower optic flow (e.g., Ziemer et al., 2013; Adams et al. 2018; Mohler et al., 2007). Nevertheless, this is only speculation as we did not investigate participants' distance perception, but rather their estimated ability to perform a leap or two-footed jump.

Taken together, results from the current study resonate with previous studies that have shown that manipulation of anticipated effort by accompanying walking with either fast or slow optic flow influence individuals’ perceived action capabilities. Although it is unlikely for optic flow to be the sole source of perceptual information by which jumping and leaping are scaled, it is possible that optic flow may specify an action boundary when calibrated or scaled to actions such as leaping and jumping. Previous studies have shown that some actions are determined by a combination of both geometrical properties and optical variables of the perceiver. For example, eye height has been shown to be the relevant perceptual metric for scaling distance to a given target (Cutting & Vishton, 1995). Along with leg length, eye height plays a role in judging when a step affords stepping on (Mark, 1987), and when combined with shoulder width, eye height can be used to determine the width of aperture that affords passing through (Warren & Whang, 1987). In sum, our findings provide evidence that optic flow may specify an action boundary when calibrated or scaled to actions such as leaping, and that manipulating optic flow speed and associated anticipated effort for walking a prescribed distance could influence one’s perceived action capabilities for jumping and leaping.

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**Open practices and data availability statement:**

None of the experiments was preregistered. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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# The influence of perceptual motor variability in optic flow on the perception of jumping ability

In the first half of this chapter, we have shown that optic flow recalibration relative to gait could influence participants' subsequent judgements of their maximal leaping as well as two-footed jumping ability. Which suggested that optic flow may be used to specify an action boundary when calibrated or scaled to actions such as jumping, and that manipulating optic flow speed and provided evidence that the associated anticipated effort for walking a prescribed distance could influence one's perceived action capabilities for jumping and leaping. In the second half of this chapter, we sought to investigate how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping. Previous chapters have demonstrated that actions that have little to no consequences following a failed execution result in a more *liberal* action boundaries judgement (chapter 2), and actions that have some potentially negative consequences to a failed execution, then a *weighted average* of perceptual motor experience was used to determine action boundaries (chapter 3). It is possible that for actions that carries a higher cost-benefit-ratio like jumping, the perceptual system may employ a heuristics strategy in which the most conservative sized action boundary used to determine action boundary under conditions of uncertainty.

# Abstract

One thing that distinguishes between our ecological environment and those inhibited by other animals is that our surroundings and how we experience our perceptual world are constantly changing. What would happen if one were to encounter perceptual-motor information that humans weren't evolved to process, and how does the exposure to novel perceptual-motor couplings affect our perceived action capabilities? The current study explored how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping. Participants were asked to estimate their jumping ability following experience walking with either fast, slow or variable optic flow. We found that, following experience with variable optic flow, participants tended towards conservative estimates of jumping-ability. Hence, when anticipating our jumping capability in the event of perceptual-motor variability, individuals employ a conservative approach as it would result in the smallest number of unsuccessful attempts.

***Keywords***: Perception and action, optic flow, perceptual-motor calibration

## The influence of perceptual-motor variability in optic flow on the perception of jumping ability

Gibson (1979) asserts that the primary function of our perceptual systems is to detect information which specifies the possibilities for actions to support adaptive interactions with the environment. Through our experience interacting with the environment, we learned to pair the perceptual consequences of our motor commands to discover our action capabilities and use these perceptual-motor couplings to control and guide our actions. Take walking, for example, an action that is highly practiced and one of the first forms of locomotion humans acquired. As we walk through space, the biomechanical indicators of self-motion such as proprioception and vestibular information covary with optic flow, the rate at which visual information moves across the retina as one moves through the environment (Gibson, 1966;1979). Through our extensive experience interacting with the environment, we learned to associate the rate of optic flow with the idiothetic information about the locomotor distance travelled by gait, and the resulting perceptual-motor couplings serve to guide our movements with respect to the external environment. Furthermore, these perceptual-motor couplings allow us to determine the locomotor distance travelled from optic flow by knowing one's gait, to coordinate our movements, control our gait transition as well as to determine the speed and direction at which we are travelling (e.g., Gibson, 1979; Warren, Kay, Zosh, Duchon & Sahuc, 2001; Mohler et al., 2007; Warren & Hannon, 1990). Hence, optic flow calibration is crucial to all visually controlled locomotion, and we have evolved to calibrate to its relationship with our movements. Furthermore, it has been shown that like humans, other non-human species also utilise optic flow to guide their locomotive behaviours. For instance, bees have been found to utilise optic flow to maintain the course of their flight, to control their flight speed (Baird, Srinivasan, Zhang & Cowling, 2005), to estimate the distance of objects and to distinguish between objects at different distances (Srinivasan,1992; Esch & Burns, 1995).

Nevertheless, one thing that distinguishes between our ecological environment and those inhibited by other animals is that our surroundings and experience our perceptual world are constantly altered by technological innovation. Because of the immense technological progress made by humanity, the way we experience and move about the world has changed and will undoubtedly continue to change. From walking and running bipedally across the vast stretch of landscape to travelling via boats and carriages, to travelling in modern locomotives such as airplanes and autonomous vehicles, the perceptual information we experienced via these means of conveyance was not something we have evolved to process. For some, this has manifested itself as motion-sickness like symptoms that occur when an incongruency between idiothetic cues of self-motion and visual cues of self-motion was introduced to the perceptual-motor system (Reason & Brand, 1975; Bles et al., 1998; Bos et al., 2008), and reports of motion sickness like symptoms have been found throughout human history (Huppert, Benson & Brandt, 2017). Furthermore, some recent technology has also exposed individuals to novel motion environments that do not occur in nature, such that of virtual reality and self-driven vehicles, which reduced self-motion information to solely visual, leading to phenomena known as visually induced motion sickness or cybersickness (Kennedy, Drexler & Kennedy, 2010; Keshavarz et al., 2015; Dam & Jeon, 2021).

Which raises the question as to how does the human perceptual system processes novel perceptual pairings or visual information that we did not evolve to process? In the case of optic flow, for example, idiothetic indicators of self-movement (e.g., proprioception, vestibular) covary with the rate of optic flow. Over time through action, we learn to expect the amount of optic flow we should experience as a consequence of having walked a given distance at a given speed, and the resulting perceptual-motor couplings also modulate our anticipated effort for crossing a particular distance. It has been shown that recalibration to a different rate of optic flow while walking transfers to functionally similar action such as crawling (Withagen &

Michaels, 2002) and sidestepping but not to throwing (Rieser et al., 1995). A recent study (Lin & Linkenauger, under review) has examined whether the recalibration to altered optic flow speed while walking influences people's subsequent judgements of their jumping ability. Lin and Linkenauger (under review) had participants estimate their maximal jumping ability following exposure to either fast (associated with low anticipated effort) or slow optic flow (associated with high anticipated effort) at the same walking speed. They found that individuals estimated their jumping ability to be farther when they were calibrated to fast optic flow relative to gait, compared to when they were calibrated to slow optic flow relative to gait. These findings suggest that the recalibration between the rate of optic flow and walking speed may specify an action boundary when scaled to actions such as jumping and that the manipulation of optic flow and the associated anticipated effort for crossing a prescribed distance could influence one's perceived jumping ability. These findings demonstrated that in addition to providing information that enables us to determine the locomotor distance travelled, and to determine the speed and direction at which we are travelling; optic flow relative to gait may also specify the action boundary when scaled to actions such as jumping.

However, what would happen if one were to encounter a scenario where optic flow is presented and experienced in a way that humans were not evolved to process? And more importantly, how does the exposure to novel perceptual-motor couplings affect the way in which we perceived our action capabilities? Consider that perceptual-motor couplings are often consistent, thus providing a reliable frame of reference that specify action boundaries and enable the perceiver to distinguish between possible and impossible actions. Nevertheless, perceived action boundaries are learned over time through past motor experiences, and one cannot execute actions with perfect consistency. Thus, the judgement of one's action boundary is likely based on a probabilistic distribution instead of an exact and immutable borderline.

Recent work has manipulated perceptual-motor couplings to assess how the introduction of variability in those perceptual-motor couplings influences perceived action boundaries. Lin and colleagues (Lin, McLatchie & Linkenauger, 2020; Lin & Linkenauger, 2021a; Lin, Plack & Linkenauger, 2021b) conducted a series of experiments, using large and observable changes in the observer's action capabilities during perceptual-motor experience to assess how individuals account for overt perceptual-motor variability in motor performance and recalibrate to new action boundary following changes in their action capabilities. Lin, McLatcie & Linkenauger (2020) had participants estimate their reaching ability following reaching experience reaching with either a long, short, or variable virtual arm that varied in size every time they reach. They found that following exposure to perceptual-motor variability in their reaching experience, participants have tended towards a liberal estimation of their reaching ability regardless of whether they have experienced random variability or systematic variability in that their reaching experience was biased towards the long or short virtual arm. The authors postulated that the reason why participants have estimated their reaching ability liberally was to maximise the probability of success while ignoring the probability of failure, given that failing a reach in this scenario incurs no negative consequences to the observer. Hence, for this action and particular context, using a liberal approach as a heuristic would provide a sufficient solution as there was no need for careful evaluation. In line with this, subsequent experiments (Lin & Linkenauger, 2021a) examined that investigated the effect of action consequences in two dimensions, a) consequences incurred from the *environmental context* in which the action occurs, and b) consequences associated with failing the particular *action*. Lin and Linkenauger (2021a) had participants estimate their overhead reachability following experience reaching with either a long or short virtual arm, or a virtual arm that varied in length – while standing on the edge of a rooftop or standing on the ground. Their results have shown that when individuals encountered variability in their motor experience for action that has higher task demand (standing overhead reaching) and selecting an inappropriate action boundary/ failing this action may lead to negative consequences (e.g., losing balance), probabilistic information was incorporated into the action boundary selection. In which having substantially more experience with the longer reach has resulted in a more liberal estimate of reaching ability, compared to when all reaches were experienced with equal probability. These results suggest that a weighted average of reaching experience was used to determine action boundary. Thus, the point on the distribution that acts as the judged action boundary may vary as a function of the task. Specifically, the strategy which the perceptual system employs to determine action boundary in the event of perceptual-motor variability is specific to the action itself and the consequences associated with failing to execute the particular action successfully. However, these studies focused primarily on actions in near space (such as reaching and grasping) using the upper body rather than the actions of the lower body which typically occur over far space and are more ballistic and less contingent on the structural morphology of the body.

Hence, the current study sought to investigate how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping. Specifically, we exposed participants to either fast, slow, or variable optic flow during walking to assess how it influences individual’s perceived jumping ability. In this study, participants engaged in a calibration phase where they experience either fast, slow or variable optic flow while walking on a treadmill at the same pace. After the calibration phase, participants estimated their maximum jumping ability. Based on our findings in Lin and Linkenauger (under review), we expect participants to differ in their maximal jumping ability judgements following experience with either fast or slow optic flow, in that experience with the fast optic flow would result in more liberal jumping ability estimates. Whereas in the variable condition, where participants experienced fast, medium and slow optic flow at random intervals. Based on findings reported by Lin and Linkenauger (2021a), we expect that participants would err on the side of caution and would estimate their jumping ability conservatively. Because firstly, the variable optic flow was not something humans have evolved to process and not something that people would have any previous exposure to. Secondly, standing long jumping is not an action that is routinely performed in everyday life, and it is also an action that allows little online movement correction and is often characterised with high motor variability, thus failing to execute this action successfully could result in potential injury/harm. Hence, it would be in the perceiver's best interest to be conservative with their judgements to minimise the probability of error/failure.

In this experiment, we investigated the effect of variable optic flow speed relative to gait on the perception of action boundary for a two-footed jump. Participants walked on the treadmill while wearing a head-mounted display that provided them with either fast, slow or variable optic flow. Following calibration in the virtual environment, participants estimated their maximum jumping ability in a real-world environment.

# Method

## Participants

Forty-one participants (5 males) between 17 to 30 years of age ($M_{age}$ = 20.95, $SD_{age}$ =3.21) were recruited from Lancaster University through opportunity sampling. G*Power software application (Faul, Erdfelder, Lang, & Buchner, 2007) was used to perform an a priori power analysis to estimate sample sizes required to achieve adequate power. The average effect sizes ($\eta p^2$) for differences in reachability estimations following exposure to random perceptual-motor variability in previous studies was .48 (Lin, McLatchie & Linkenauger, 2020: Experiment 1; Lin & Linkenauger, 2021: Experiment 1 & 3; Lin, Plack & Linkenauger, 2021: Experiment 1), and the effect size on the effects of optic flow recalibration on jumping ability estimations was $\eta p^2 = .24$ (Lin & Linkenauger, under review: Experiment 2). A power analysis using G* power indicated a minimum sample of 6 to 12 participants would be needed to detect an effect with a power of .90 at an alpha level of .05. Given that the effects of random perceptual-motor variability and optic flow recalibration relative to gait on the perception of two-footed jumping ability have not yet been investigated, we determined the sample size for a small effect ($\eta p^2 = .1$) using the same alpha level and power parameters. Our analysis shows that a minimum sample of 24 participants in a repeated measures design with 3 conditions and 12 estimations/measurements, would be sufficiently powered to find an effect of this magnitude. All participants had normal or corrected- to normal vision, free of injuries, wore comfortable clothing and footwear to allow full range of motion. All participants provided informed consent. This study was approved by the ethics committee at Lancaster University.

**Stimuli and Apparatus**

For the optic flow calibration phase, participants walked on a treadmill set to a speed of 2.2km/h. Participants wore an Oculus Rift CV1 head-mounted display (HMD) that displayed a stereoscopic image of the virtual environment with a resolution of 2160 x 1200 pixels and a frame rate of 90Hz. The experimental programme and environment were created using Unity 3D© Gaming Engine, the virtual environment consisted of a horizontal ground plane with grass texture and a brick lane; several 3D models of trees and rock were placed along the path. The 3D camera was placed at eye-level enabling the participant to perceive the virtual environment in a first-person perspective, and the position of the 3D camera was consistent with the participant's physical eye height. They were positioned in the virtual environment so that they were standing on the brick lane. The movement of the participant's head was tracked, and graphics were updated as the participant looked around in the virtual environment by moving their head. Three different optic flow speeds were used, for the *fast* optic flow, the virtual environment moved past participants at a rate of 6m/s, for the *medium* optic flow, the virtual environment moved past participants at a rate of 4m/s, and for the *slow* optic flow, the virtual environment moved past participants at a rate of either 2m/s.

For the estimation phase, the ground was covered with a sheet of fabric (150cm x 300cm). The floor was covered with a piece of white fabric to create a uniform background and minimise landmarks that could influence participants' judgements, See Figure 1. A line that served as a reference point was placed 66 cm directly in front of the white fabric and participants were told to make their estimations while standing behind the line.

### Procedure

After providing their informed consent, participants were positioned on the treadmill and were given instructions for both the calibration and estimation phases of the experiment. After donning the Oculus HMD, participants completed all three experimental conditions, and participants were randomly assigned to different orders of conditions. Once they have entered the virtual environment, participants were told to hold onto the treadmill rail and were encouraged to look around to familiarise themselves with the virtual environment before the experiment began.

For each calibration phase, participants walked on the treadmill for 5 minutes whilst being exposed to different optic flow speeds. In the fast optic flow condition, the virtual environment moved past participants at a rate of 6m/s for the entire duration of the calibration period. In the slow optic flow condition, the virtual environment moved past participants at a rate of 2m/s for the entire duration of the calibration period. In the variable optic flow condition, the virtual environment varied between fast, medium and slow optic flow, and the virtual environment moved past participants at a rate of 6 m/s, 4m/s, or 2m/s respectively. In this condition, each optic flow speed was experienced in 10 seconds interval and each optic flow speed was presented 10 times for a total of 5 minutes  in random order.

Figure 3. Left panel: Illustration of a participant completing a calibration trial. Right panel: Image of what the participant would see while completing the calibration phase.

Following each calibration phase was the estimation phase. Each estimation phase consisted of 12 trials, in which participants reported their maximum jumping ability by instructing the experimenter to move the estimation dot (using a laser pointer) closer or farther until it was at the maximum distance the participants believe they could perform a two-footed horizontal jump from a standing position. A two-footed jump is defined as a two-footed take off from a standing position and landing on both feet.

To control for hysteresis, in half of the trials, the estimation dot's starting position was directly in front of the participants' feet and at the reference line in front of them; participants moved the dot away from them. For the other half of the trials, the estimation dot's starting position was at the opposite end of the white fabric covering the floor, at approximately 400 cm away from the participant, and participants moved the dot towards them. Participants were encouraged to make as many adjustments as necessary for an accurate estimation of their jumping ability, and to move the dot beyond the area covered by the white fabric if they thought it was necessary, then close their eyes in between trials while the experimenter measured the distance between the reference line and the final location of the estimation dot. After making all 12 estimations and completing the first optic flow condition, participants were led back onto the treadmill and repeated the procedure with the second and the third optic flow condition.

## Results

A repeated measure analysis of variance (ANOVA) with optic flow condition fast/ slow/variable) as the within-subject variable and the estimated jumping ability as the dependent variable. The analysis revealed a significant effect of optic flow condition on estimated jumping ability, $F(2, 70) = 5.68$, $p = .005$, $\eta_p^2 = .14$. Bonferroni post-hoc analysis revealed a significant difference in estimated jumping ability between different optic flow conditions.

Participants estimated their jumping ability as being significantly farther, *M* = 169.97cm, *SE* = 4.13cm, in the fast optic flow condition than in the slow optic flow condition, *M* = 163.74cm, *SE* = 3.95cm, *p* = .02, and in the variable optic flow condition, *M* = 165.51cm, *SE* = 3.92cm, *p* = .03. However, no significant differences were found between the estimated jumping ability in the variable optic flow reach condition and the slow optic flow condition (*p* = .99), see Figure 2. We found no evidence for an order effect, *F*(5,35) = .54, *p* = .75, $\eta_p^2$ = .07, nor a significant interaction between condition order and optic flow conditions, *F*(10,70) = 1.21, *p* = .30, $\eta_p^2$ = .15. These results suggested that, after exposure to variable optic flow relative to gait, participants were more conservative with their subsequent jumping ability estimations, and they have judged their two-footed jumping ability to be similar to when they were exposed to slow optic flow.

To get a better idea of the relationship between the three optic flow conditions, we created two different scores for each participant. We create one difference score by subtracting the mean variable optic flow jumping estimates from the mean fast optic flow jumping estimates (FV) and the other by subtracting the mean slow optic flow jumping estimates from the mean variable optic flow jumping estimates (VS). If participants have used a weighted average to determine their action boundary for jumping, we should expect no difference between the FV and VS scores. However, if they have taken a conservative approach, we should expect a difference between FV and VS scores, with the VS scores being significantly smaller than the FV score. A paired-sample t-test was conducted to compare the difference between the FV and VS scores. The t-test found no evidence for a difference between the FV score (M = 4.23 cm, SD = 11.16cm) and the VS score (M = 2.17cm, SD = 12.05cm), t(40) = .70, p = .49, see Figure 2. These findings suggest that, after experiencing variable optic flow whilst walking, participants have used a weighted average to determine their action boundary

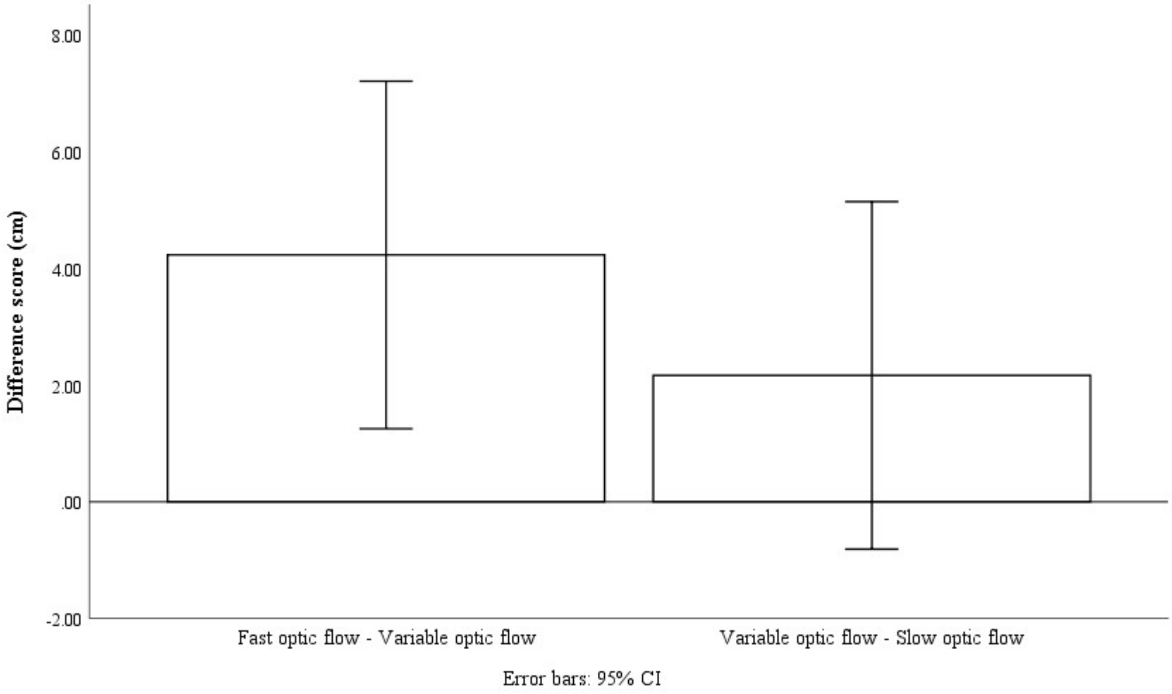

Figure 4. The FV and VS difference scores. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994)

To explore whether optic flow recalibration experience from the prior condition would influence jumping ability estimates in the latter conditions, we created an order variable in which we dummy coded participants who engaged in the fast optic flow condition before the slow optic flow condition as 1, and those who engaged in the slow optic flow condition before the fast optic flow condition as 2. We expected if the prior condition had any meaningful influence on the subsequent condition, then the estimates in the slow optic flow condition would be larger if it was conducted after the fast optic flow condition, and the estimates in the fast optic flow condition would be smaller if it was preceded by the slow optic flow condition.

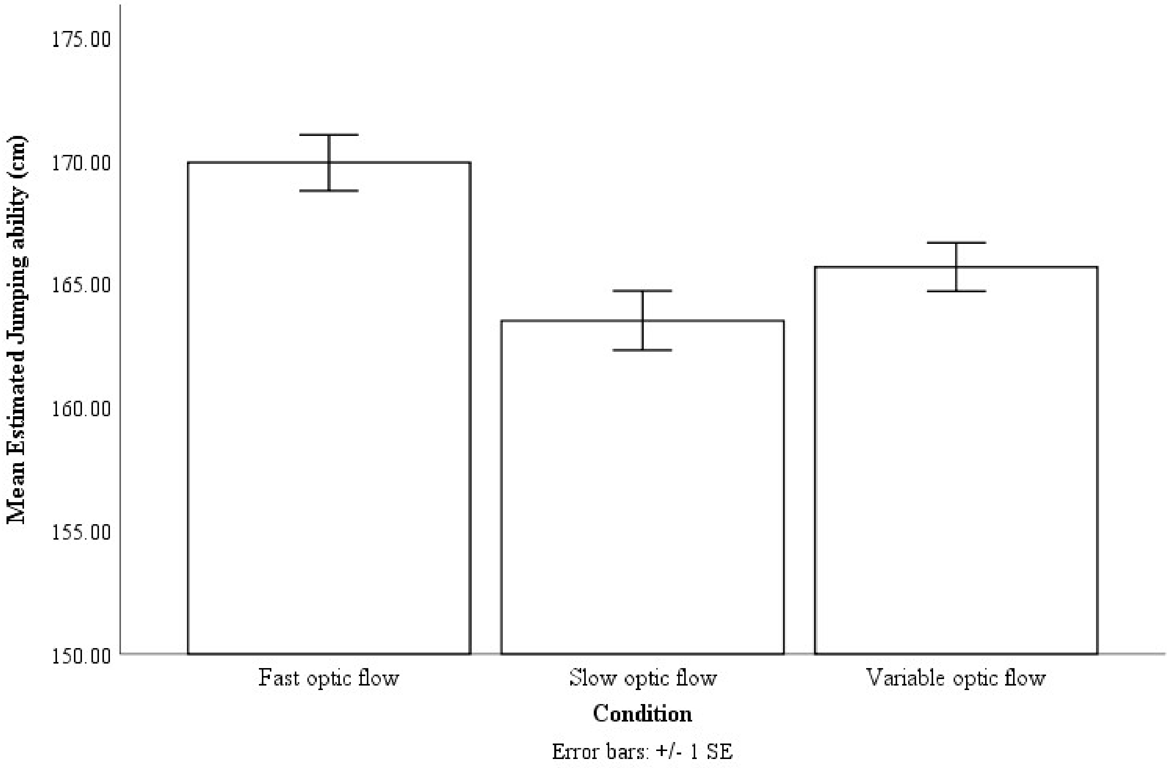

*Figure 5* .The mean estimated jumping ability of the three optic flow conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

To assess this possibility, we conducted a repeated measure ANOVA, with optic flow condition (fast vs slow) as the within-subject variable, and condition order as a between-subject variable. If there were order effects, then the jumping ability estimates in both fast and slow optic flow conditions should be higher in order 1 in comparison to order 2. If there weren't order effects, then the estimates in optic flow speed condition would be similar in both orders 1 and 2. We found a significant effect of condition, *F*(1, 39) = 9.35, $p = .004$, $\eta_p^2 = .19$, with estimates in the fast optic flow condition being larger, *M* = 169.85cm, *SE* = 4.06cm, than those in the slow optic flow condition, *M* = 163.40cm, *SE* = 3.86cm, $p = .004$.We found no evidence for an effect of the order, $p = .43$, nor an interaction between condition and order, $p = .28$, see Figure 3.

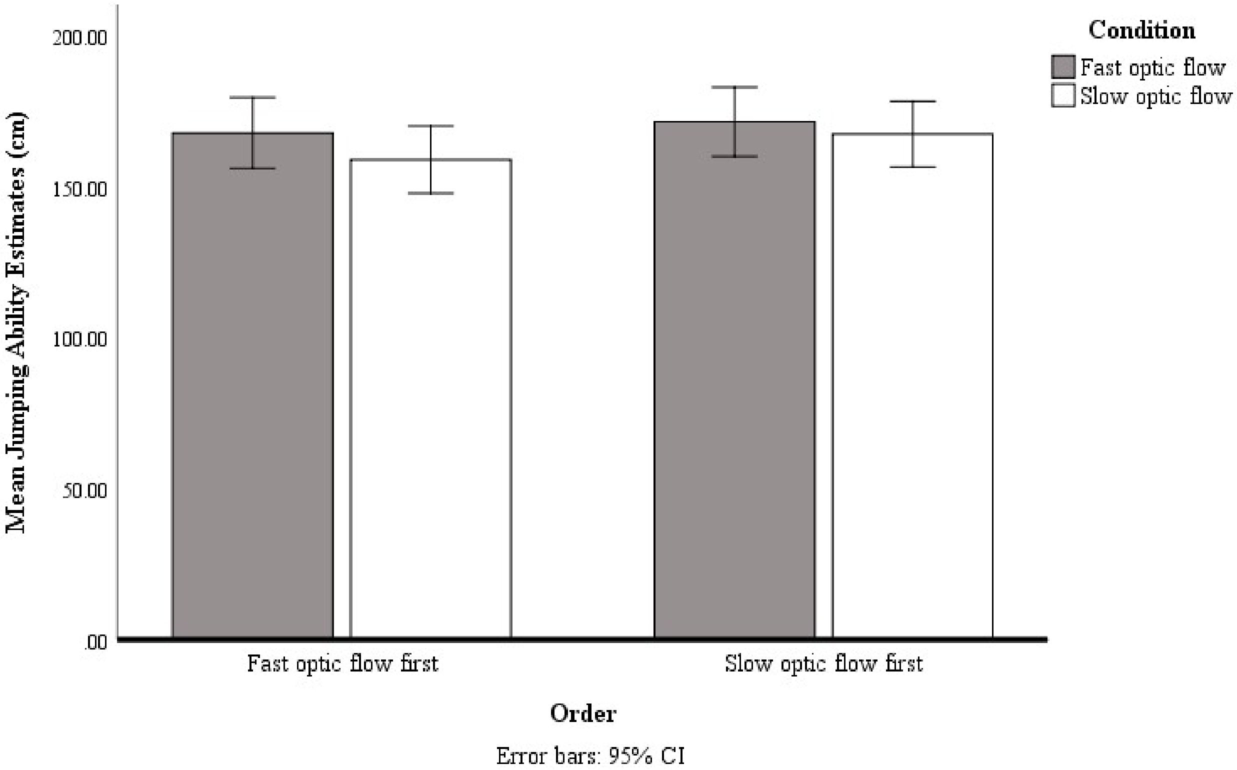

*Figure 6*. Jumping ability estimates for the fast and slow optic flow conditions for those who completed the fast versus the slow optic flow condition first. Error bars represent 95% CIs.

## Discussion

Like other species in the animal kingdom, the human perceptual-motor systems have evolved to extract and process information that is necessary and appropriate to support adaptive interactions with the environment. Yet, with recent progress made in technological advancement, not only the way we experience and move about the world has changed, but we are also exposed to novel perceptual-motor information that we did not evolve to process. Hence, how does the perceptual system handle these novel perceptual-motor couplings, and more importantly, how does the exposure to these novel perceptual-motor couplings influence our subsequent judgements of our action capabilities? In the current study, we examined how the introduction of variability in the perceptual-motor couplings between optic flow and walking influences perceived action boundaries for jumping. Participants were asked to estimate the maximum extent of their jumping ability following calibration to either fast optic flow, slow optic flow, or optic flow that varied between fast, medium, or slow at random intervals.

Firstly, we found that individuals have calibrated to different sized action boundaries for jumping following experiences with different optic flow speeds. Participants estimated that they would be able to jump farther after experiencing fast optic flow compared to after they have experienced slow optic flow. This difference in jumping ability estimation across the two conditions suggested that people were able to recalibrate the perceptual-motor coupling between optic flow and walking, and have used this new perceptual-motor coupling to estimate their subsequent jumping ability. This finding is consistent with those reported by Lin and Linkenauger (under review), thus providing further evidence that the manipulation of optic flow speed relative to gait and the associated anticipated effort for crossing a prescribed distance could influence one’s perceived action capabilities for jumping.

Secondly, we found that after experience walking with variable walking speed, participants had estimated their jumping ability conservatively in that their jumping ability estimates were similar to when they had experienced slow optic flow relative to gait. However, when we compared the difference between the differences between conditions, no difference was found between the difference between fast and variable optic flow conditions and the difference between the variable and conservative optic flow conditions. This suggested that participants appeared to have taken some probabilistic information into account when determining their action boundary for jumping. Nevertheless, if participants had utilised the weighted average approach to determine their action boundary, the estimates in the variable optic flow condition should be significantly different from both the fast optic flow and the slow optic flow conditions. Hence, we would expect their jumping ability estimates in the variable condition to be farther than those in the slow optic flow condition, but not as far as estimates in the fast optic flow condition. Given that participants have experienced all three optic flow speeds with equal probability and equal duration. Taken together, our results indicate their while participants have utilised something akin to weighted average to determine their action boundary but overall, they have taken a *conservative approach* when estimating their action boundary for jumping.

One possible interpretation for our current findings in the context of previous findings is that for actions that carry a higher cost-benefit ratio like jumping, the perceptual system may employ a heuristics strategy in which the most conservative sized action boundary is used to determine action boundary under conditions of uncertainty. Recent studies using a similar paradigm have investigated the influence of perceptual-motor variability on the perception of action boundaries for horizontal seated reaching and standing overhead reaching and found that the different approach was used for different actions to determine action boundaries. It has been found that for seated horizontal reaching, an action that has little to no consequences following a failed execution, participants tended towards a liberal estimation of their action capabilities regardless of whether they had experienced all reaching with equal probability or when their reaching experience was systematically biased towards a long or short reach (Lin, McLatchie & Linkenauger, 2020). Whereas for standing overhead reaching, an action that has more postural demand and the observer must maintain their balance while executing the action, participants had taken probabilistic information into account and a strategy akin to a weighted average was used to determine action boundaries under conditions of perceptual-motor uncertainties (Lin & Linkenauger, 2021a). The perceptual system may employ different strategies to determine action boundaries to accommodate demands arising from the consequences and costs-benefits ratios of a particular action.

Hence, we suspect that the resulting consequences associated with failed action were the reason why participants tended towards a conservative estimation of their jumping ability following experience with the variable optic flow. Firstly, the visual information that they experienced during walking was not something they had prior experience with, and nor was this type of visual information/visual motion something humans have evolved to process. Hence, individuals were possibly conservative, because of mere uncertainty. Secondly, compared to horizontal reaching and standing overhead reaching, jumping was far riskier as the performance outcomes tend to be more variable and jumping allows little room for online corrections, and the costs to making motor errors are high. Previous research has shown that individuals tend to make more conservative motor decisions when navigating through doorways when the penalty associated with motor decision errors was falling in comparison to when the penalty for error was to become wedged (Comalli et al., 2013; Franchak & Adolph, 2012). Therefore, when the penalties for selecting the inappropriate action boundary is severe, individuals may be more conservative with their judgements to avoid potentially negative consequences, especially in the event of perceptual-motor uncertainties and/or novel perceptual-motor information.

Alternatively, our current findings were also consistent with previous studies that have shown that individuals tended to underestimate in the perception of affordance for launching behaviours such as leaping (Cole et al., 2013) and vertical jumping-reach (Ramenzoni et al., 2010). Some authors have attributed this underestimation to poor information. Cole et al., (2013) compared participants' affordance judgements across different actions, specifically, they had participants make affordance judgements about their ability to perform launching action (e.g., leaping) versus non-launching actions (e.g., stepping). They found that participants consistently underestimated their ability to perform launching actions, despite these actions being highly familiar in everyday lives. The authors argued that unlike non-launching actions, which are mainly constrained by anthropometric properties such as arm length and shoulder width, launching actions required the integration of these body information with dynamic information such as the production of explosive force. Information about body dimensions is constantly present optically or abilities are constantly updated through perceptual-motor interaction, whereas information about one's dynamic abilities such that of force production is not optically specified and given that people rarely engage in actions that required them to routinely produce explosive force, this information is less readily available which result in a deficit of information. Because of this, the perceptual system is unable to integrate one's explosive force capacity into account when making affordance judgements about launching actions, which could explain participants tended to underestimate their ability and/or estimate their action capabilities conservatively.

In summary, the present study extended findings from previous studies that examined the effect of perceptual-motor variability on perceived action boundaries for different types of reaching action. Our findings demonstrated that when participants were presented with the variable optic flow while walking, they have taken a conservative approach when estimating their subsequent jumping ability. This suggested that the perceptual system had utilised different approaches for different actions on an ad hoc basis to determine action boundaries to maximise the efficiency of information processing in the event of perceptual-motor uncertainties while minimising the exposure to potentially dangerous situations and aversive consequences.

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# Chapter 5: The influence of perceptual motor variability on the perception of action boundaries for reaching in a real-world setting

Chapter 2 has assessed individuals' judgement of action boundaries for reaching following changes in their action capabilities in virtual environments. However, experiments in chapter 2 were conducted in a virtual environment and the extent to which these findings are generalisable to the real world is as yet unknown. Therefore, this study presented in this chapter aimed to assess whether the strategy used to determine action boundary would also be used in a real-world setting.

# Abstract

The ability to accurately perceive the extent over which one can perform an action is requisite for the successful execution of visually-guided actions. Yet, like other outcomes of perceptual-motor experience, our action boundaries are not stagnant, but in constant flux. Hence, the perceptual system must account for variability in one’s action capabilities in order for the perceiver determine when they are capable of successfully performing an action. Recent work has found that, after reaching with a virtual arm that varied between short and long each time they reach, individuals selected action boundaries using the most liberal reaching experience. However, these studies were conducted in virtual reality, and it’s possible that the perceptual system handles variability differently in a real-world setting. To test this hypothesis, we created a modified orthopaedic elbow brace that mimics injury in the upper limb by restricting elbow extension via remote control. Participants were asked to make reachability judgements after training in which the maximum extent of their reaching ability was either unconstricted, constricted or variable over several calibration trials. Findings from the current study didn’t conform to those in virtual reality; participants were more conservative with their reachability estimates after experiencing variability in a real-world setting.

# The Influence of Perceptual-Motor Variability on the Perception of Action Boundaries for Reaching in a Real-World Setting

Successful performance of action relies on the accurate perception of opportunities for action in the environment; in particular, action boundaries. Action boundaries are learned over time and are the limitations of a perceiver's action capabilities. They distinguish between possible and impossible actions, and an action is only possible if it is within the perceiver's action boundary (Fajen, 2005). For instance, when intending to reach, the length and flexibility/range of movement (ROM) of an individual's arm determine the maximum extent of their reachability. For an object to be reachable, the distance to the target must be within the perceiver's action boundary for reaching. The ability to accurately perceive one's action boundaries in relation to the environment is requisite for the successful execution of visually guided actions.

An ample body of research has demonstrated that people could readily perceive their action boundary for different types of actions and across different environmental contexts. For example, individuals are remarkably accurate at judging the maximum height of step that they can climb, and irrespective of body height, individuals consistently judge the climb-ability of steps as a constant proportion of leg length (Warren, 1984). Other studies have demonstrated people's sensitivity to their action boundaries for a variety of actions, including, but not limited to, passing through doorways (Franchak & Adolph, 2012; Warren & Whang,1987), fitting hand through apertures (Ishak, Franchak, & Adolph, 2014), grasping (Linkenauger, Witt & Proffitt, 2011), and reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, 2009). Furthermore, individuals have been shown to be able to recalibrate to new action boundaries following changes in their action capabilities and/or environmental constraints. Such examples include updating their maximum sitting and stepping height judgements while wearing blocks under their feet (Hirose & Nishio, 2001;

Mark ,1987), adjusting their judgement of passability when fitting one's hand through an opening with a prosthesis attached to their hand (Ishak, Adolph, & Lin, 2008), and updating their reachability judgement when their arm's reach have been extended or constricted in virtual environment (Linkenauger, Bulthoff, & Mohler, 2015).

However, like other outcomes of perceptual motor experience, our action boundaries are not immutable, but in constant flux. These changes take place over different timescales and have consequences for actions. Long term changes take place via naturally occurring changes in physiology and perceptual-motor capabilities associated with growth and aging (Konczak et al., 1992; Comalli et al., 2013), whereas short term changes in action boundaries, such as injuries, fatigue and posture, could occur at any time and bring about inconsistent fluctuations in the perceptual motor feedback specifying one's action boundaries, which has consequences for motor performance (Franchak & Adolph, 2014). In addition to these changes, like any learning system, feedback from the perceptual motor systems is inherently noisy, and it is not possible for one to execute actions with perfect consistency. Thus, regardless of how consistent an action's outcome may appear, some degree of variability is always present in the perceptual motor information specifying action boundaries. Consequently, when determining one's perceived action boundary, the perceptual motor system must account for variability in perceptual motor feedback in order to perform actions adaptively and minimise performance errors. How does the perceptual system determine the maximum extent over which an action can be performed when the information specifying this extent is inconsistent?

One possible method the perceptual system could employ would be to use the average experienced reach to generate the most statistically likely outcome (Kording & Wolpert, 2006; Deneve & Pouget, 2004). Take, for example, an observer that has experienced two different sized action boundaries (large and small) with equal probability during their reaching experience. If they use the average of their reaching experience to determine the action boundary, the selected action boundary should be identical to the mean, as the two action boundaries experienced were of equal probability. Conversely, if the smaller action boundary was experienced significantly more often than the larger, then we would expect a shift towards the smaller action boundary as it would be more statistically likely than the larger action boundary.

Whilst this approach may allow the perceiver to determine perceived action boundaries under conditions of uncertainty in a more optimising manner, it would also be a more time consuming and energetically costly approach due to the amount of information processing involved (Howarth, Peppiatt-Wildman & Attwell, 2009). Furthermore, both human cognitive and bioenergetic resources are limited (Niven & Laughlin, 2008), and not every action execution nor circumstance is important enough to justify expending resources to integrate probabilistic information and/or to formulate optimal solutions. Therefore, as another approach, the perceptual system could use heuristics as an effort-reduction strategy, or when the cost of information processing outweighs potential gain in judgement accuracy. It should be noted that the current study was framed as a test between optimising versus satisficing approaches, and our hypothesis was not based on ecological approaches of visual perception, but rather evolutionary approaches. Hence, one could consider fewer alternatives by disregarding probabilistic information to make decisions that are just ‘good enough’ (Hogarth & Karelaia, 2007; Gigerenzer & Gaissmaier, 2011). One such heuristic would be to select the action boundary using the most liberal reach experienced; this method would maximise the number of successful attempts, but at the same time it may also result in the highest number of unsuccessful attempts. Thus, this approach would only be appropriate in the absence of negative consequences associated with failed action. Another possible heuristic would be to select an action boundary using the most conservative sized reach experienced, such as in particular in situations where the penalties for selecting the inappropriate action boundary are high. This approach would result in the smallest number of successful attempts, but also the smallest number of failed attempts. Alternatively, the perceptual system could select a moderate sized action boundary; selecting an action boundary size that is in between the most liberal and most conservative action boundary would allow the perceptual system to balance the number of successful attempts with the number of unsuccessful attempts. Taken together, it is reasonable to postulate that, in order to maximise efficiency, the perceptual system would utilise different strategies on an ad hoc basis to determine perceived action boundaries under conditions of uncertainty.

Recent research has investigated participants' judgement of action boundaries for reaching following changes in their action capabilities in virtual environments. Lin, McLatchie & Linkenauger (2020) had participants estimate their action boundary for horizontal reaching following calibration to a long virtual arm (extended reach condition), a short virtual arm (constricted reach condition), or a virtual arm that varied in size randomly between a long virtual arm, medium virtual arm and short virtual arm each time they reached. They found that individuals were able to calibrate to changes in their action capabilities and their selected action boundaries were consistent with their reaching experience during calibration. They estimated their reachability to be significantly farther in the extended reach condition than in the constricted reach condition. However, in the variable condition in which they experienced three arm's reaches with equal probability, individuals tended to indicate that their perceived action boundary for reaching more resembled their experience with the longer reaches than with the shorter reaches. Had they used the averaged reaching experience to determine their perceived action boundary, the difference between extended and variable conditions would be similar to the difference between constricted and variable conditions. Instead, they found that the difference between the extended and variable conditions was significantly smaller than the difference between the variable and constricted conditions, indicating that the estimates in the variable reach condition were closer to the extended reach estimates than the constricted reach estimates, and individuals in the variable reach condition had estimated liberally rather than conservatively. These findings suggest that the perceptual system employs a liberal tactic rather than an average to determine perceived action boundaries for reaching in the event of perceptual motor variability.

Actions cannot be performed the same way repeatedly and variability in the outcome is always present, but the link between variability and perceptual estimates is often ignored in affordance literature. This set of studies has provided insights into the possible mechanism by which the perceptual system accounts for perceptual motor variability when determining perceived action boundaries, and they have exposed a gap in the literature that is important to fill if we are to fully understand the nature of affordance perception. However, these studies were conducted in virtual environment and the extent to which these findings are generalisable to the real world is as yet unknown. In the real world, some research has demonstrated that people are sensitive to their own movement variability and take their task-relevant movement variability into account when making action boundary judgements for actions such as aperture passing (Wilmut & Barnett, 2010; 2011; Wilmut, Du & Barnett, 2015; Hackney & Cinelli, 2011; Lucaites et al., 2020) and stepping over obstacles (Snapp-Childs & Bingham, 2009). However, only individual variability in natural postural sway and stability/motor control during movement were considered. As mentioned above, not all perceptual motor variability is large enough to be detectable when learning action boundaries, but in some instances perceptual motor variability is quite evident. Hence, in order to assess how the perceptual system account for overt perceptual motor variability in motor experience and recalibrate to new action boundary following changes in action capabilities in the real world, it would be desirable to use large and observable changes in arm's reach during the perceptual motor calibration/experience.

In Lin, McLatchie and Linkenauger (2020), reaching ability was manipulated by modifying the length of the virtual arms by 50% more or less than the participant's actual arm length. Yet, similar changes in arm length would be difficult or nearly impossible to accomplish in the real world due to the constancy of the body morphology. Therefore, in the present study, we opt to manipulate reaching ability by restricting the range of motion of the elbow using a modified orthopaedic elbow brace. In addition to its use in rehabilitation treatments, previous research has used a similar device to identify the necessary functional range of motion of the elbow for everyday activities (e.g., Vasen, Lacey, Keith & Shaffer, 1995). Elbow mobility is essential for upper limb function; a 50% reduction of elbow motion represents approximately 80% loss of upper limb function (Fusaro, Orsini, Sforza, Rotini & Benedetti, 2014). Stiffness of the elbow is a common occurrence after injury, and can be defined as a loss of extension greater than 30° and/or a flexion of less than 120° (Søjbjerg, 1996), and the loss of elbow extension is more frequently encountered than flexion loss (Charalambous & Morrey, 2012). Hence, it is a debilitating condition which has detrimental consequences for the individual's ability to perform daily activities (Bartoszek et al., 2015). By isolating the allowable range of motion of the elbow, we would be able to simulate the movement of the arm in a state of injury and introduce variability into one's perceptual motor feedback for reaching in a controlled manner while still in the real world.

The present study aimed to use the elbow brace to establish whether the perceptual system utilises the same strategy in a real-world situation as in virtual environments. Participants were asked to make reachability judgements after training that the maximum extent of their reaching ability is either constricted (limited to 60° extension), unconstricted (0° extension), or variable (varied randomly between 0°, 30° and 60° extension). Our manipulation was intentionally large to create a detectable difference in the dependent measure across the different conditions. In light of the findings from Lin, McLatchie and Linkenauger (2020), and given the context and task similarity, we expected participants to remain relatively liberal with their reachability estimates as they did in a virtual environment, but to a lesser degree. The latter is because, while the action they had to perform was the same (i.e., reaching horizontally), the changes in their reaching ability were less drastic. Additionally, the changes in their reaching were employed in a different manner. In the virtual environment, arm length was modified, and range of motion was intact; whereas, here, we limited range of motion while arm length remained intact. Thus, it is possible that limiting elbow range of motion mimics the movement of the arm in a state of injury, and the perceptual system would treat the restricted movement of the arm as if it were a real injury, which could induce participants to be more conservative to prevent further injury.

# Method

## Participants

G*Power software application (Faul, Erdfelder, Lang, & Buchner, 2007) was used to perform an *a priori* power analysis to estimate sample sizes required to achieve adequate power. The required power was set at $1-\beta = .85$, and the level of significance was kept at $\alpha = .05$. We expected a medium effect size of .25 due to the novelty of the paradigm. Power analysis indicated that a sample of $N = 8$ would be sufficient to achieve a power of .85 and an alpha of .05. We have doubled the number and increased our sample size to 16 participants.

Sixteen participants (four males) between 18 and 21 years of age ($M_{age} = 19.13$, $SD_{age} = .89$) were recruited from Lancaster University through opportunity sampling. All participants but three were reported to be right-handed. All participants had normal or corrected-to-normal vision. All participants provided informed consent. The study was approved by the Faculty of Science and Technology Research Ethics Committee at Lancaster University.

## Stimulus and apparatus

The participant sat in front of a rectangular table onto which stimuli were projected from a projector mounted on the ceiling.  The table (120 cm x 80 cm x 71 cm) was covered with a piece of black cardboard (56 cm x82 cm) to create a uniform background and minimise landmarks which could influence participants' judgements. A white dot (2 cm in diameter) was projected on the edge of the black cardboard directly in front of the centre of the participant's body from the projector. This dot served as a reference point and represented the egocentric location of the participant.

Reachability was manipulated by using a device that was made of a modified orthopaedic elbow brace with adjustable ROM. The modified elbow brace was 42 cm in length and weighed 0.6 kg. Two electric mini motors were added to the rotation hinge of the elbow brace to allow systematic manipulation of the ROM by restricting extension of the elbow. Three different reaches were used, and the amount of extension of the elbow was limited in 30° increments. For the long reach, the ROM of the elbow was not limited (0° of extension); for the medium reach, elbow extension was limited to 30°; and for the short reach, elbow extension was limited to 60° (see Figure 1).

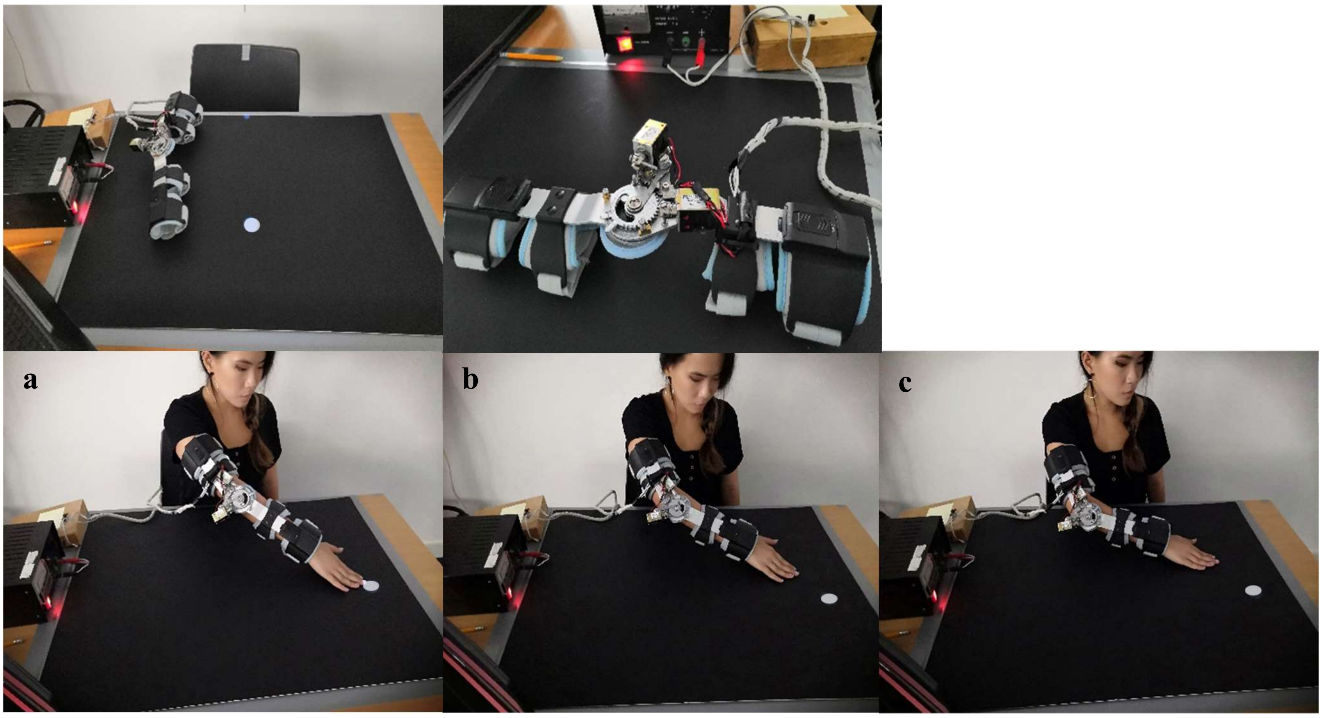

*Figure 1*. Top panel: Experimental set-up and apparatus. Bottom panel: Illustration of a participant completing a calibration trial with either a long reach (a), medium reach (b) or short reach (c).

## Procedure

After providing informed consent, participants were asked to sit between the table and the wall, in that their body was touching the table and their core was aligned with the reference point projected onto the table. They were given instructions for both the calibration and estimation phases of the experiment. After donning the elbow brace on their right arm, participants completed all three experimental conditions, and participants were randomly assigned to different orders of conditions. In the **unconstricted** reach condition, despite wearing the elbow brace on their arm, participants' elbow ROM was completely unconstricted (0° extension). In the **constricted** reach condition, participants' elbow extension was limited to 60°. In the **variable** reach condition, participants' elbow ROM varied between the long reach (0° extension), the medium reach (30° extension), and the short reach (60° extension). In the variable condition, reaches changed randomly in between each calibration trial and participants experienced all three reaches with equal probability (i.e., equal number of trials); all reaches were experienced in a randomised order.

Each condition consisted of two phases: calibration and estimation. The calibration phase consisted of 36 trials in which a white dot (4 cm diameter) was presented on the left, right or in front of the participant. Participants were instructed to reach and touch the white dot with their hand. If the dot was too far for them to reach, they were instructed to point towards it instead. After they reached out and touched/pointed the dot, the dot disappeared and another white dot at a different location appeared. The dots were presented at one of the three horizontal distances from the reference point (20 cm, 35 cm, 50 cm) and the dots were either presented directly in front of the participants or 15, 25, or 35 cm to the left or the right of the central line, for a total of nine possible dot locations. Each location was presented four times in a random order for a total of 36 trials. Participants engaged in an estimation phase after each calibration phase. The estimation phase consisted of 12 trials, in which participants reported their maximal reaching ability by instructing the experimenter to move the estimation dot (using a laser pointer) closer or farther until it was at the maximum distance the participant believe that they could reach. During the estimation phase of all reaching conditions, the elbow brace remained on the participants' right arm, but they were instructed to place their arms underneath the table so that they had no visual feedback of their arm's location. To control for hysteresis, in half of the trials, the estimation dot's starting position was directly in front of the participant and at the reference point; participants moved the dot away from them in one of three directions: contralateral, straight, and ipsilateral (near left, near centre, near right). For the other half of the trials, the estimation dot's starting position was at the central edge of the black cardboard or 41 cm to the left or the right (far centre, far left, far right); these dots moved straight or diagonally towards the reference point. The dots either started close to or far away from the participants and were presented directly in front of or to the left or right, for a total of six locations (near/far left, near/far centre, near/far right) each presented twice for a total of 12 trials. Participants were encouraged to make as many adjustments as necessary for an accurate estimation of their reachability and to move the estimation dot beyond the black cardboard if they thought it was necessary, then close their eyes in after each trial while the experimenter measured the distance between the reference point and the final location of the estimation dot landed. Figure 2 illustrates the dot locations for the calibration and estimation phases.

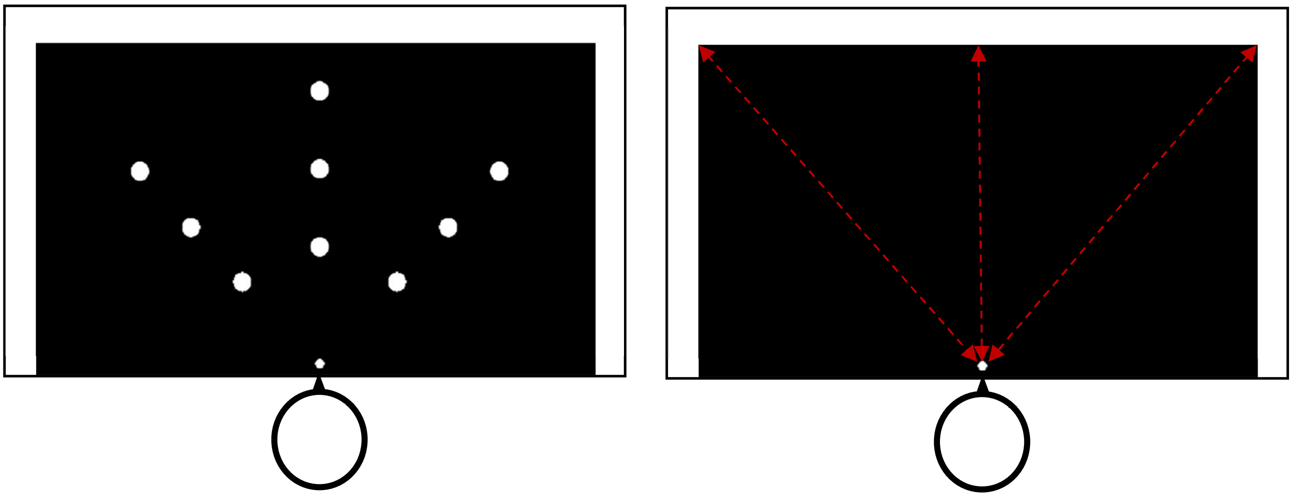

*Figure 2*. Left panel: Diagram of the calibration phase. The large white dots represent the nine possible dot locations and the smaller white dot represents the reference dot. Right panel: Diagram of the estimation phase. The red dotted lines represent the axis upon the red laser pointer moved.

# Results

Estimated reachability was defined as the farthest extent to which participants estimated they could reach. To analyse the influence of reaching condition on estimated reachability, we employed a repeated measures one-way ANOVA with reaching condition (unconstricted/ constricted/variable) and direction (left/right/centre) as within-subject factors and estimated reachability as the dependent variable.

The analysis provided Greenhouse-Geisser corrected degrees of freedom to account for possible violations of sphericity, therefore the degrees of freedom were not always integers. Analysis showed effects of reaching condition on estimated reachability, $F(1.19, 17.90) = 21.84$, $p < .001$, $\eta p^2 = .59$. Bonferroni-corrected post-hoc analysis (t-test) showed that participants estimated the extent of their reach as being farther in the unconstricted reach condition ($M = 51.86$ cm, $SE = .84$ cm) than in the constricted reach condition ($M = 44.35$ cm, $SE = 1.91$ cm, $p = .001$). They also estimated their reachability to be farther in the variable reach condition ($M = 48.93$ cm, $SE = 1.16$ cm, $p = .003$) than in the constricted reach condition. Furthermore, they estimated their reachability to be farther in the unconstricted reach condition than in the variable reach condition ($p = .001$), see Figure 3.

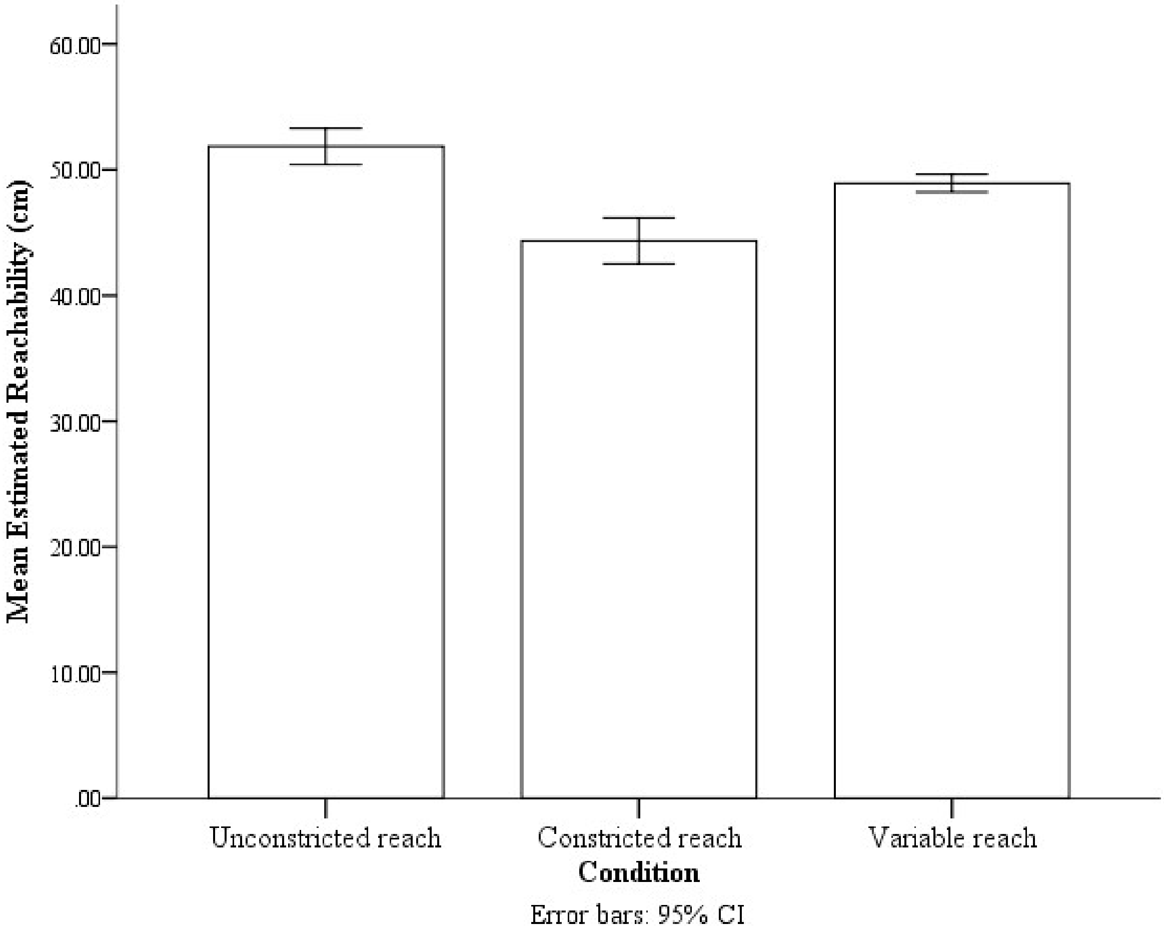

*Figure 3*. The mean estimated reachability of the three reaching conditions. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994).

Direction also significantly influenced estimated reachability, $F(1.41,21.19) = 28.06$, $p<.001$, $\eta_p^2=.65$. Participants estimated their reachability for targets on the right ($M$=51.01 cm, $SE$=1.40 cm) to be farther than targets on the left ($M$=47.72 cm, $SE$=1.21 cm, $p= .003$) and farther than those in the centre ($M$=46.42 cm, $SE$=1.17 cm, $p< .001$). The evidence was inconclusive for the estimated reachability of targets on the left and in the centre, $p=.10$, see Figure 4.

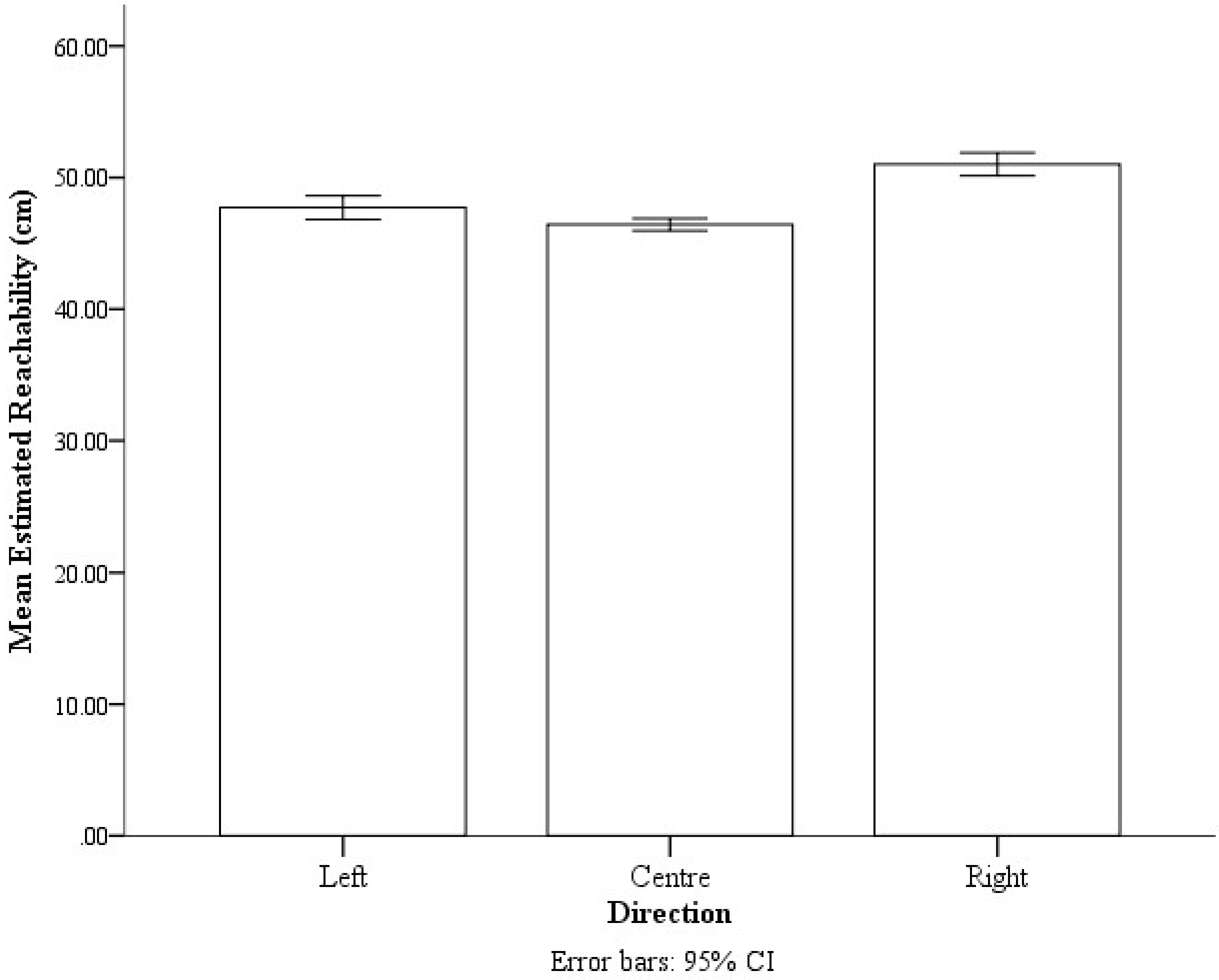

*Figure 4.* The mean estimated reachability of the three reaching directions. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994).

To get a better idea of the relations between the three conditions, for each participant in each condition, we created two scores. We created one difference score by subtracting the mean variable reach estimate from the mean unconstricted reach estimate (UV), and the other difference score was created by subtracting the mean constricted reach estimate from the mean variable reach estimate (VC). If participants used the average experienced reach to determine their action boundaries, we should expect no difference between the UV and VC scores. A paired-sample t-test was conducted to compare the difference between the UV and VC scores. The t-test found no evidence for a difference between the UV scores (*M* = 2.93 cm, *SD* = 2.60 cm) and the VC scores (*M* = 4.58 cm, *SD* = 4.44 cm); *t*(15) = -1.63, *p* = .12, see Figure 5. These findings indicate that, after experiencing random variability in their reaching experience, participants were more conservative with their reachability estimates than those reported in previous studies conducted in virtual reality, and participants selected a moderate size action boundary that was in between the unconstricted reach condition and the constricted reach condition.

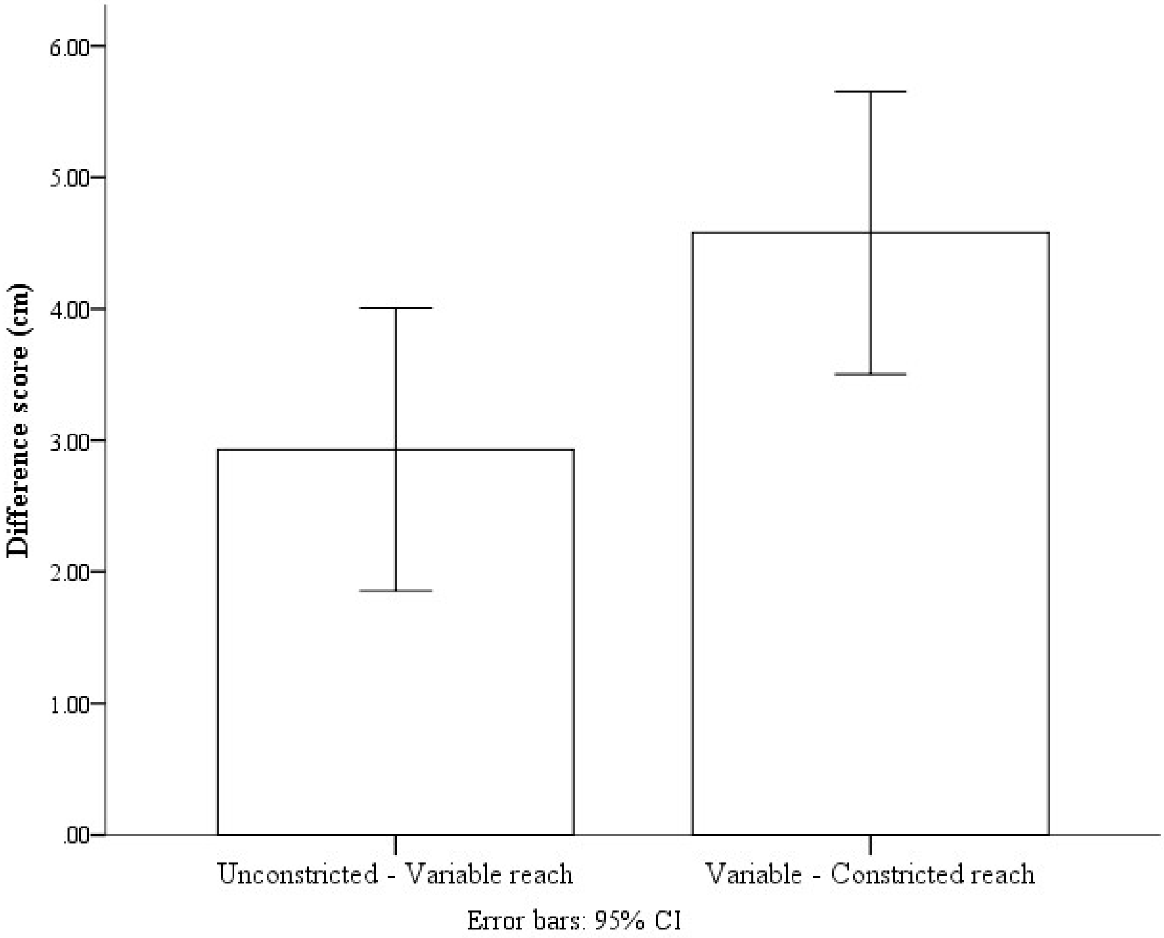

*Figure 5.* The UV and VC difference scores. Error bars are 95% CI calculated within-subject with the method provided by Loftus and Masson (1994)

One possibility is that the reaching experience from prior conditions could influence the reachability estimates in the latter conditions, and we have no doubt that some influence across the conditions occurs as with any form of perceptual motor learning. Although we fully counterbalanced across participants, which would have eliminated/minimized any systematic bias in the conditions as a result of order, we felt it’s important to assess if there was any cumulative effect from reaching experience in prior conditions that influenced estimates in the subsequent conditions.

Hence, we created an order variable in which we dummy coded participants who engaged in the unconstricted reach condition prior to the constricted reach condition as 1, and those who engaged in the constricted reach condition prior to the unconstricted reach condition as 2. We expected that if prior condition had any meaningful influence on the subsequent condition, then estimates in the constricted reach condition would be larger if it was conducted **after** the unconstricted reach condition, and the estimates in the unconstricted reach condition would be smaller if it was preceded by the constricted reach condition. To assess this possibility, we conducted a repeated measures ANOVA, with condition (constricted versus unconstricted) as a within-subject factor and order as a between-subject factor. If there were order effects, then both constricted and unconstricted reach estimates should be higher in order 1 than in order 2. Conversely, if there weren’t order effects, then both constricted and unconstricted reach estimates in order 1 should be similar to those in order 2. As expected, we found a significant effect of condition, $F$ (1, 14) = 23.72, $p< 0.001$, with unconstricted reach estimates being larger, $M$= 51.86 cm, $SE$= 0.79 cm, than constricted reach estimates, $M$= 44.35 cm, $SE$= 1.97 cm. We found no effect of order, $p = 0.49$, or a significant interaction between order and condition, $p = 0.53$, see Figure 6.

To investigate this in more detail, we conducted two between-subjects t-tests to independently assess the effects of order on the constricted reach condition and on the unconstricted reach condition. We found no significant effect of order for either condition ($p = 0.83$ and $p = 0.10$, respectively). These negative results could be due to lack of power. However, the analyses do confirm that the reaching experience within each condition had a large effect on the reachability estimates; whereas, the reaching experience in each condition likely had a small/negligible influence on the other conditions.

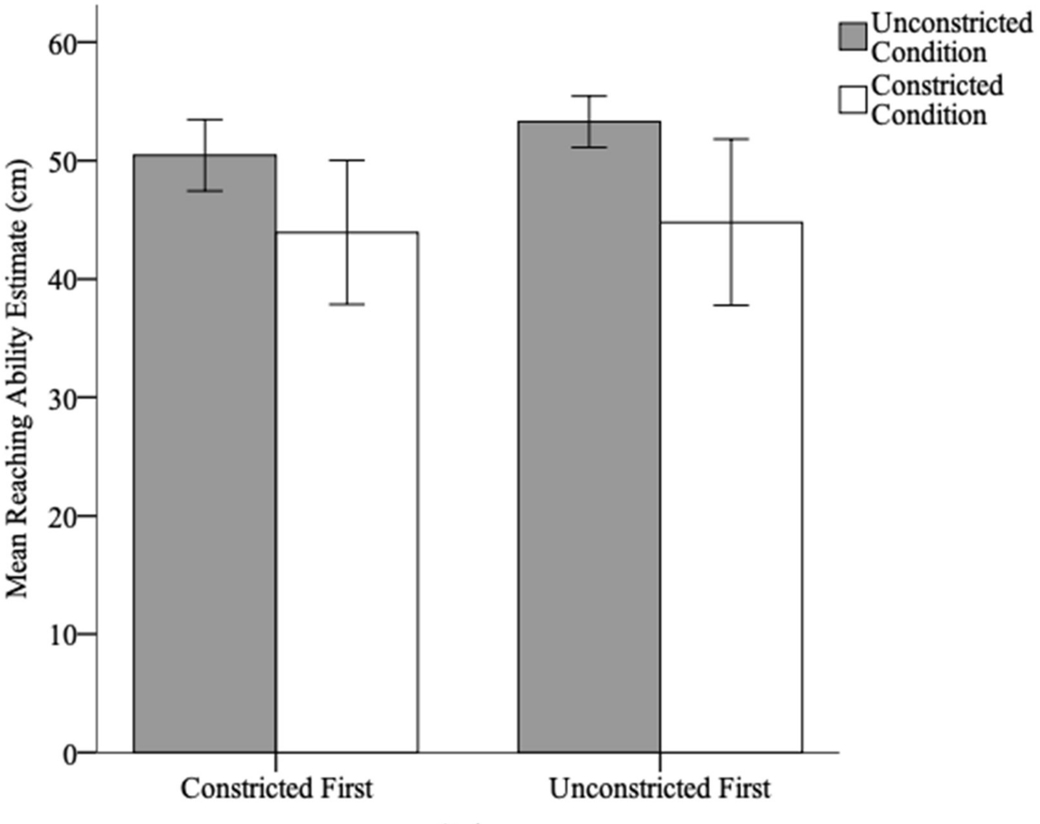

*Figure 6.* Reaching ability estimates for the constricted and unconstricted conditions for those who completed the constricted versus the unconstricted condition first. Error bars represent 95% CIs.

# Discussion

In the current study, we examined the effect of random perceptual-motor variability on action boundary perception for reaching in a real-world setting. We manipulated participants' reaching capabilities by restricting the degree to which they could extend their elbow. Participants were asked to make reachability judgements after training that the maximum extent of their reaching ability is either unconstricted (0°extension), constricted (60° extension) or variable (elbow ROM varied between 0°/30°/60° extension).

We found that the perceived action boundary for reaching significantly varied with respect to reaching calibration condition. The relative difference between conditions was similar to previous studies conducted in virtual reality, suggesting that in addition to artificial body extension and tool use, perceived reachability can also be manipulated by changes in elbow range of movement, and that a large degree of *controlled* perceptual-motor variability can be introduced into one's perceptual-motor feedback associated with motor learning in the real world.

Although participants continued to show a slight trend towards liberal estimates in the variable condition as in the virtual reality studies of Lin, McLatchie and Linkenauger (2020), this effect was not significant. In Lin, McLatchie and Linkenauger (2020), the difference between the extended reach and variable reach was significantly smaller than the difference between the constricted and variable reach, which indicates that participants were estimating liberally rather than conservatively in the variable condition. Whereas in the current study, the difference between unconstricted and variable reach conditions did not significantly differ from the difference between the constricted and variable reach condition, suggesting that a moderate sized action boundary was selected.

One possible reason as to why the current findings did not conform to those in virtual reality may be the context in which the actions were learned. Previous studies were conducted in virtual reality and it is possible that the perceptual system handles variability differently in a real-world setting. Possibly, individuals are less conservative in virtual environments, because they are aware that the environment is not real. Hence, they might glean that they would not suffer the same consequences for failing as they would in the real world. However, this explanation is unlikely due to there being no real consequences for failing to successfully reach in either environment. Another explanation for the differences could be that perceived distances are compressed in virtual environments in comparison to the real world (Loomis & Knapp, 2003). However, previous research has shown that the presence of a fully animated avatar nearly eliminates distance compression in virtual reality (Mohler, Bülthoff, Thompson, & Creem-Regehr, 2008). Moreover, if perceived distances were compressed in the virtual environment, the compression would apply to all calibration distances in all three conditions, hence this compression is unlikely to account for differences between the real and virtual environments.

Another reason as to why we found slightly different results here could be the way by which perceptual motor variability was introduced. In the current study, we used a modified orthopaedic elbow brace with the intention to simulate injury to the upper limb by restricting elbow extension. In the virtual study by Lin, McLatchie & Linkenauger (2020), we modified the length of the arm itself, which left range of motion intact and arm movements in their natural state. In the case of this experiment, we restricted and modified the natural arm movement. Restricting elbow range of motion resembles the movement of the arm in a state of injury. Consider that much of the physical therapy following serious injury to the arm, e.g. bone breakage, involves gradually stretching the arm over time to recover its range of motion. Perhaps, here, the perceptual system was treating the reduction in the range of motion as if it were a real injury. Hence, by selecting a less liberal action boundary the perceptual system may have been trying to maximise the probability of success while minimising the probability of exacerbating a potential injury.

Therefore, the current findings could be a reflection of the differences in the methods used to manipulate reaching ability. Different manifestations of motor variability in the same actions produced different patterns of results. For instance, if perceptual motor variability is introduced by inducing tremors or involuntary muscle contraction in arm muscles, while the arm's length and ROM remain unchanged, the individual's reaching ability will differ from one moment to the next due to inconsistent muscle contractions. Therefore, it is possible that the way in which the perceptual system selects an action boundary may be different in this situation. Consider, for example, the reaching ability variance that occurs in individuals with Parkinson's and stroke patients, whose perceptual motor feedback for reaching is constantly in flux due to abnormalities of neural and muscular activation (Mazzoni, Shabbott & Cortes, 2012). Therefore, understanding the influence of perceptual-motor variability and the way in which it is manifested differently within a given action will provide valuable insights. Future research could explore these factors further by examining whether different strategies are employed for different manipulations.

In summary, the current study demonstrated that the manipulation of elbow range of motion can influence the perception of action boundaries in the real world. Our findings also show that when anticipating our reaching capability in the event of perceptual motor variability in a real-world setting, individuals were not as liberal with their reachability estimates as they were in virtual reality. However, other factors such as the context, methodology, as well as the way in which variability is introduced to perceptual-motor feedback specifying one's action boundary may also influence the size of action boundary selected.

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# Chapter 6: General Discussion

The experiments presented in this thesis demonstrate how the perceptual system accounts for overt perceptual-motor variability in motor performance and recalibrates to new action boundaries following changes in one's action capabilities. The first set of studies demonstrated that the judgement of one's action boundary can be influenced by variable perceptual-motor experiences, and the perceptual system may utilise different strategies to determine action boundary to account for this variability. The second set of studies showed that the point on the distribution that acts as the judged action boundary varied as a function of the task. Specifically, the strategy which the perceptual system employs to determine action boundary in the event of perceptual-motor variability is specific to the action but not the context. The third set of studies provided further evidence that the strategy by which the perceptual system is employed to determine action boundary following variable perceptual-motor experience is dependent on the consequences of a particular action. The final study showed that the perceptual system does not utilise the same strategy as in the virtual environment to determine action boundaries following variable perceptual-motor experience in a real-world situation. Overall, these studies demonstrate that following variable perceptual-motor experiences, the perceptual system flexibly utilise different strategies to determine action boundaries to accommodate demands arising from the consequences and/or costs-benefits ratios of the outcome of a particular action.

**Chapter 2** investigated the influence of perceptual-motor variability on one's subsequent perceived action boundary for seated horizontal reaching in virtual reality. I showed that when one's action capabilities for reaching were constantly fluctuating, the perceptual system determined action boundaries using a liberal approach whilst disregarding the type of variability present in one's prior perceptual-motor experience. **Chapter 3** investigated whether the perceptual system utilises the same strategy to determine action boundaries for all types of reaches over different environmental contexts. I demonstrated that for an action where an erroneous decision and/or failed attempt could lead to potentially negative consequences, individuals were more sensitive to the probabilistic information associated with different action boundaries they have experienced during their prior motor experience; and the perceptual system used a weighted average of one's motor experience to determine action boundary. **Chapter 4** investigated whether the optic flow can be used to specify an action boundary when calibrated or scaled to actions such as jumping and leaping and whether the perceptual system utilises different strategies for different types of action to determine action boundary. I found that optic flow may specify an action boundary when calibrated or scaled to actions such as leaping, and that manipulating optic flow speed and associated anticipated effort for walking a prescribed distance could influence one's perceived action capabilities for jumping and leaping. Furthermore, I found that when participants were presented with the variable optic flow while walking, the perceptual system used a conservative approach to determine action boundary. **Chapter 5** investigated whether the strategy used by the perceptual system to determine action boundary in a virtual environment would also be used in a real-world setting and whether the way in which variability is introduced would influence the strategy used to determine action boundary. I found that a different strategy was used to determine action boundaries in a real-world setting, and participants were more conservative with their reachability estimates after experiencing variability in a real-world setting.

### Implications for perceptual-motor recalibration

How does the perceptual system accounts for overt perceptual-motor variability in motor performance and recalibrates to new action boundaries following changes in one's action capabilities? An abundance of research has demonstrated that people are highly accurate at perceiving the boundaries of their action capabilities and could flexibly update their perceptions to accommodate alterations in their action capabilities. For example, individuals can recalibrate to new action boundaries following changes in their action capabilities, such as updating their maximum sitting and stepping height by wearing blocks under their feet (Mark, 1987). Nevertheless, in the above example, whilst the actor's action capacities have been altered by the blocks placed beneath their feet, the perceptual-motor feedback specifying their action capabilities remained constant. Thus, allowing them to rapidly obtain the necessary perceptual-motor experience and relearn their action capabilities. Consequently, through learning prior perceptual-motor experience, they can update or form a reliable frame of reference about their altered action capabilities to determine whether an action is possible or not. However, how does one recalibrate to changes in their action capabilities when the perceptual-motor information specifying their action boundaries is inconsistent or variable?

Findings from the current thesis suggested that the perceptual system could flexibly utilise different strategies to determine action boundaries for different actions, types of action and across different environmental contexts. Findings demonstrated that the ways in which individuals make judgements about their action boundary following variable perceptual-motor experience were similar to how they make judgements in other decision-making situations. By using a different strategy to decide that not only take into account the consequences and the costs-benefits of the outcome of a particular action, but also the computational costs of processing the necessary information. Such that a more temporal and energetically consuming approach may be used to determine action boundaries when the cost of failure and the need for accuracy outweigh the costs associated with the information processing. In Chapter 3 I showed that for action a failed attempt could lead to potentially negative consequences, in the case of standing overhead reaching, selecting an inappropriate may result in loss of balance and falling.

Hence, a better strategy would be to forgo short term gains in efficiency for a more deliberate and careful evaluation (Beach & Mitchell, 1978; Glöckner, 2008).

Whereas in extreme scenarios where a failed attempt at an action could result in either no negative consequences or severe penalties, then heuristics may be used as an alternative to determine action boundaries. As evidenced by the findings in chapter 2 and chapter 4, in which for seated horizontal reaching (chapter 2), failing an attempt results in little to no negative consequences. Hence, by taking a liberal approach to determine action boundary, individuals were likely maximising their probability of success while ignoring their probability of failure. However as demonstrated in chapter 4, for jumping, failing an attempt is far riskier as the performance outcomes tend to be highly variable and jumping allows little room for online corrections, and the costs of making motor errors are high. Hence, by taking a conservative approach when determining action boundaries, individuals would minimise the number of failed attempts while sacrificing the number of successful attempts, because the costs of failure far outweigh the potential benefits and the costs of additional information processing.

While the aforementioned work has provided insights and speculation into the possible mechanism by which the perceptual-motor system functions under conditions of uncertainty, this line of research is still in its infancy, and more work has yet to be done to fully understand how perceptual systems account for variability when determining one’s action boundaries. Considering that only several actions and environmental contexts have been investigated, the proposed approaches may be wrong or incomplete. However, based on the results obtained thus far, the proposed approaches have sufficiently explained how the perceptual system determines action boundaries under uncertainty for those particular actions and environmental contexts. While it is possible that they might not be the most **optimal** given the action and context, they are undoubtedly sufficient for the given situation and good enough to satisfy the task demands.

Taken together, findings from this thesis suggested that the perceptual system utilises different approaches for different actions, types of action, and different environmental contexts on an ad hoc basis to determine action boundaries to maximise the efficiency of information processing in the event of perceptual-motor uncertainties while minimising the exposure to potentially dangerous situations and aversive consequences.

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