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

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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

***Public Significance Statement*:**

We assessed how far individuals anticipate they can reach after training that the maximum extent of their reaching ability is variable. We found that individuals favoured the liberal sized action boundary after experiencing variability in their perceptual motor feedback for reaching.

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 is 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 calibration 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?

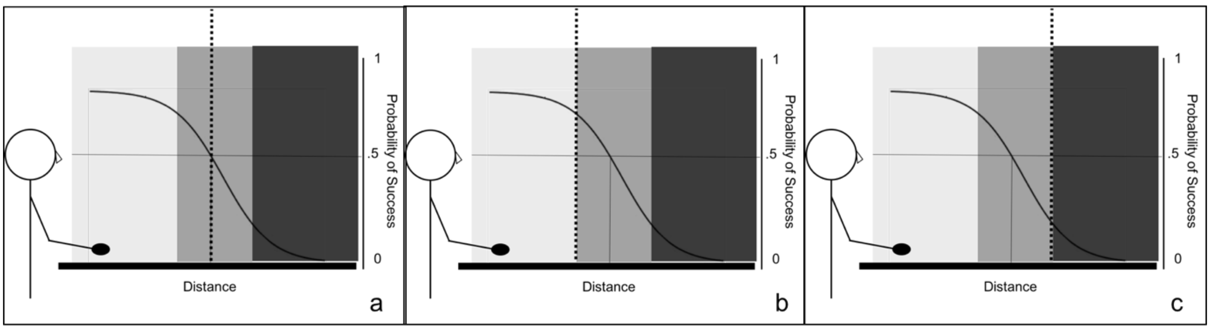

Figure 1. Possible action boundaries in the event of perceptual motor variability for reaching.

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 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. 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.

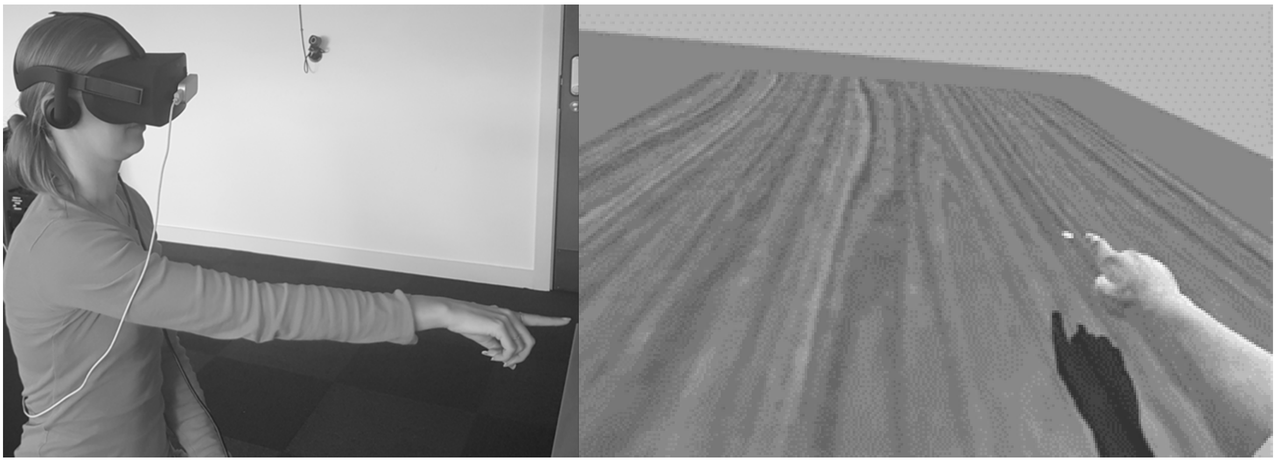

Figure 2. Left panel: Illustration of a participant completing a calibration trial. Right panel: Image of what the participant would see while completing the calibration trial.

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 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.

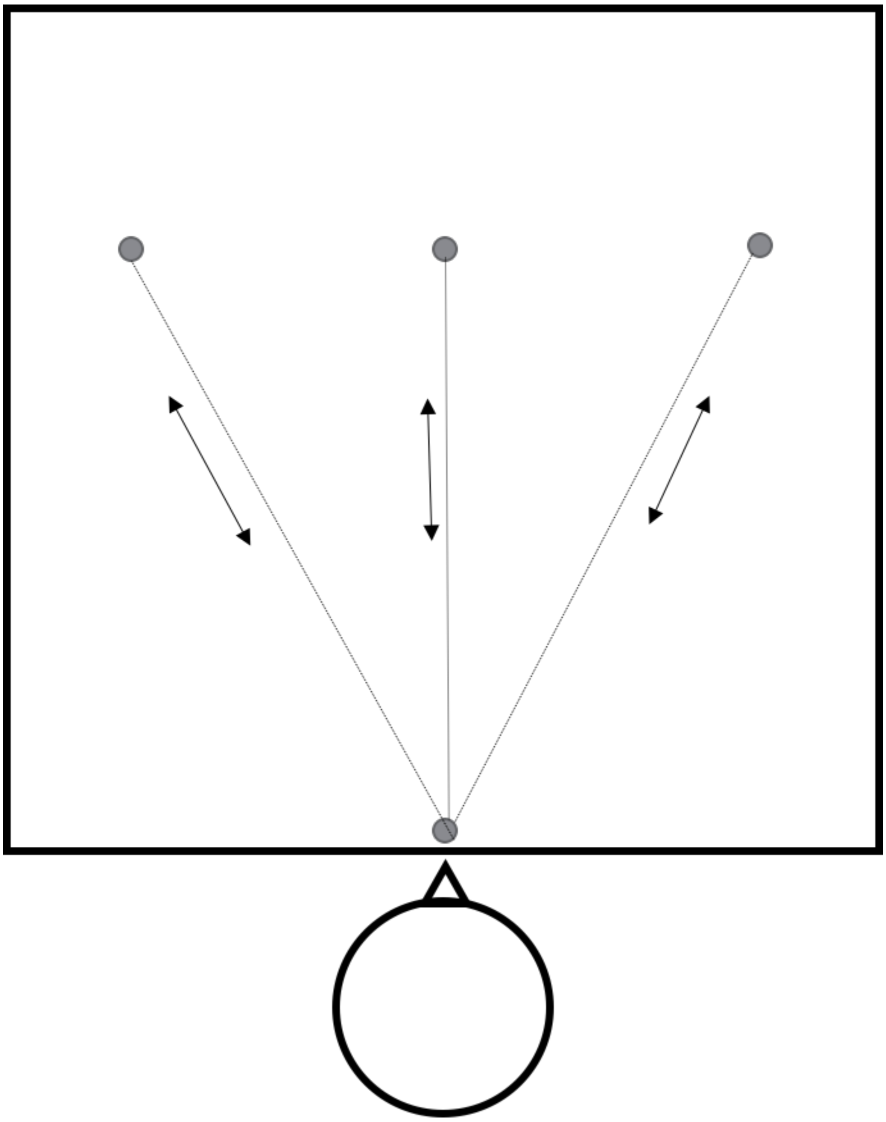

Figure 3. Diagram of the estimation phase. The grey dots represent the initial dot positions and the arrows and dotted lines represent the axis upon each dot moved.

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.

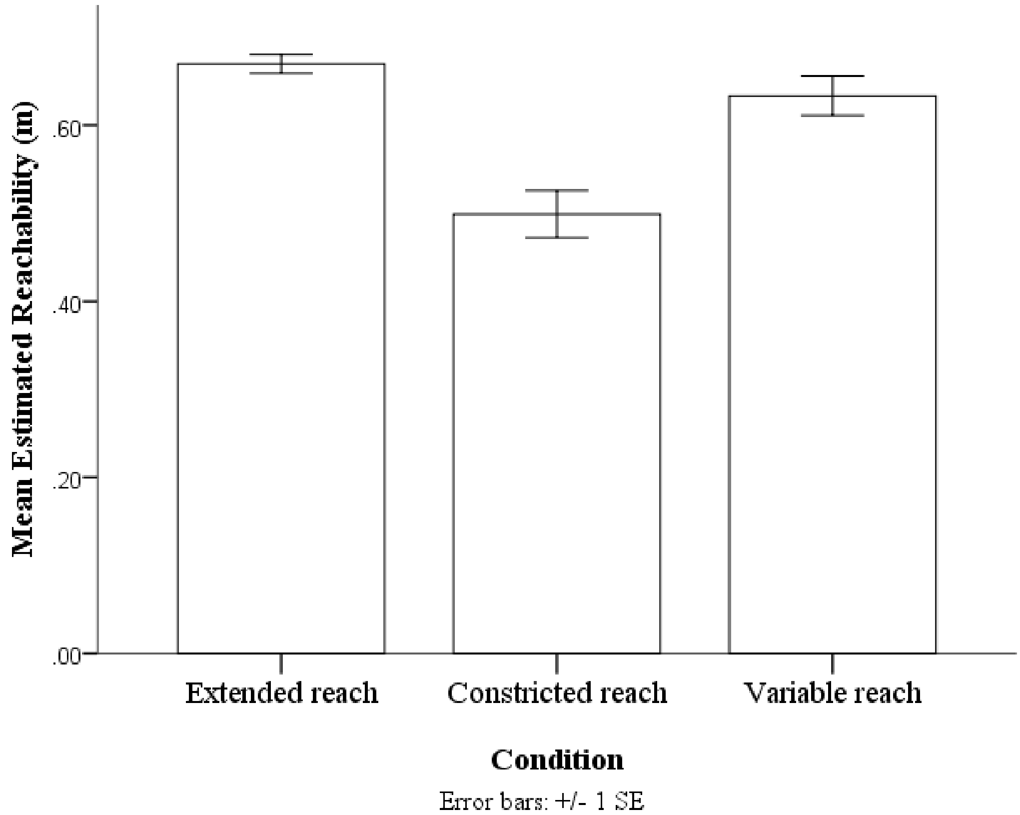

Figure 4. The mean estimated reachability of the three reaching conditions. Error bars are 1±SE calculated within-subject with the method provided by Loftus and Masson (1994).

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, $p < .001$, $B_{\mathrm{H}(0,\ 0.10)} = 1.39 \times 10^{10}$, RR[0.002, 18.59]) and those in the centre ($M = .59$m, $SE = .03$m, $p = .001$, $B_{\mathrm{H}(0,\ 0.10)} = 3.90 \times 10^4$, RR[0.002, 13.48]). The evidence was inconclusive for the estimated reachability of targets on the right and in the centre, $p = .19$, $B_{\mathrm{H}(0,\ 0.10)} = 0.57$, RR[0, 0.17], see Figure 5. The interaction between reaching condition and direction was not significant, $F(4,80) = .60$, $p = .67$, $\eta p^2 = .03$.

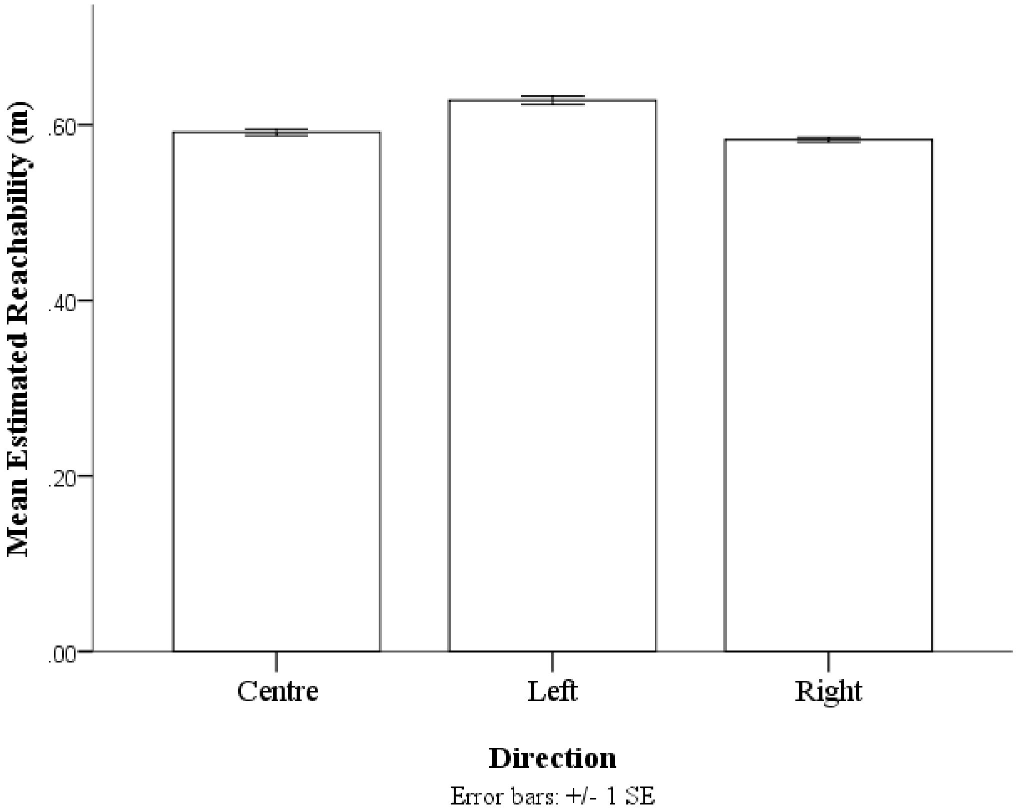

Figure 5. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

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_{age} = 22.62 years, SD_{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.

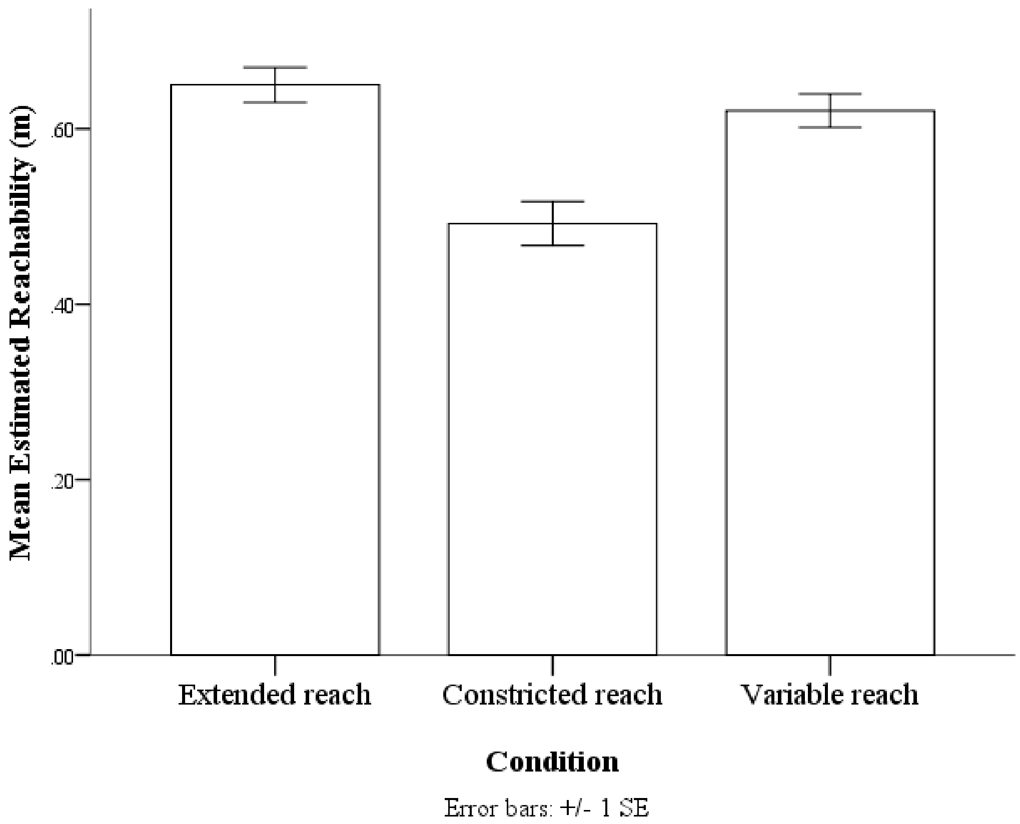

Figure 6. The mean estimated reachability of the three reaching conditions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

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, ($M = .61$m, $SE = .04$m), was longer than those on the right ($M = .58$m, $SE = .04$m, $p < .001$, $B_{H(0,\ 0.10)} = 3.03 \times 10^4$, $RR[0.002, 10.10]$) and those in the centre ($M = .58$m, $SE = .04$m, $p = .001$, $B_{H(0,\ 0.10)} = 6.09 \times 10^6$, $RR[0.001, 10.76]$). 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.

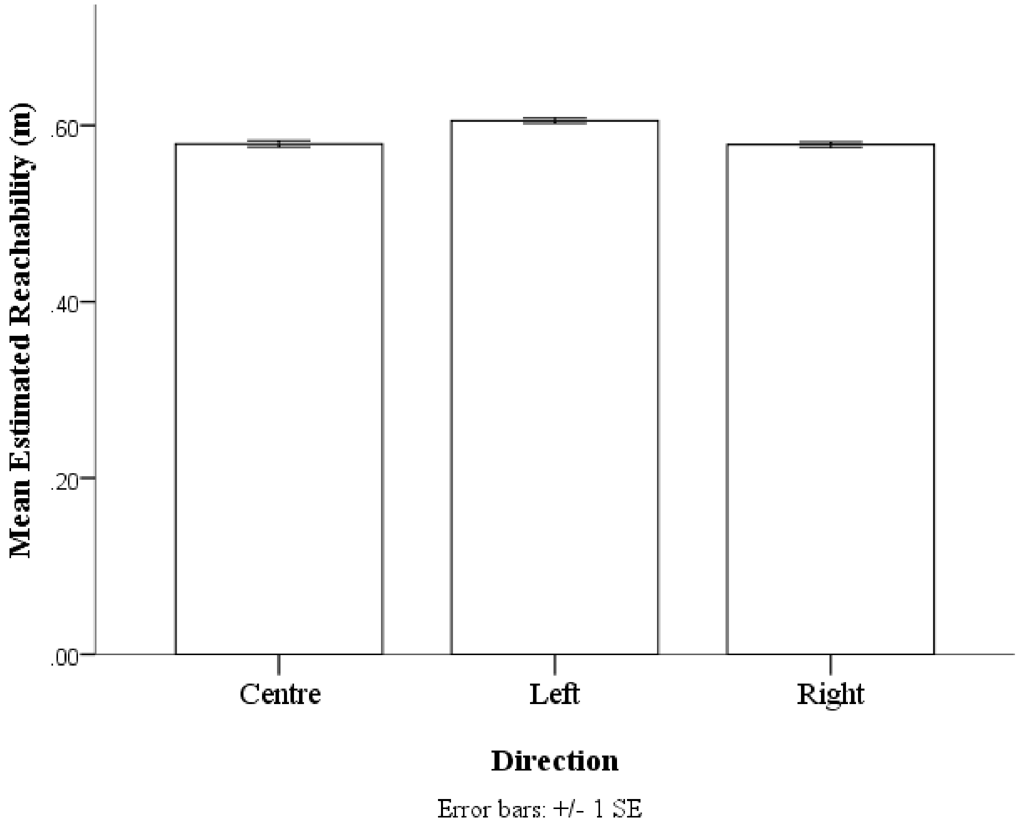

Figure 7. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

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 ($M = .49$, $SE = .04$, $p < .001$, $B_{H(0, 0.10)} = 7.24$ x 105, RR[0.008, 75.43]). They also estimated their reachability to be farther in the variable condition ($M = .62$, $SE = .03$, $p = .001$, $B_{H(0, 0.10)} = 1943.48$, RR[0.009, 40.64]) than in the constricted reach condition. Furthermore, we found evidence for a

[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.

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.

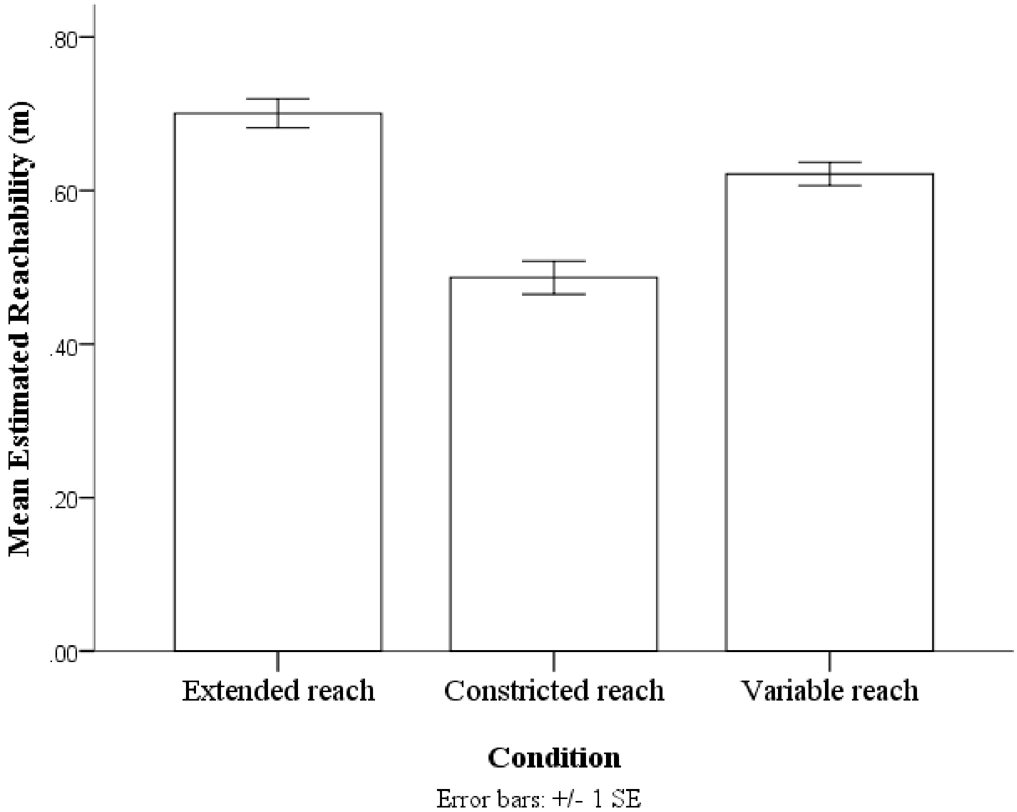

Figure 8. The mean estimated reachability of the three reaching conditions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

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 = .63m, SE = .03m), was longer than those on the right (M = .58m, SE = .03m, $p < .001$, $B_{H(0, 0.10)} = 2.99 \times 10^{16}$, *RR*[0, 17.22]) and those in the centre (M = .60m, SE = .03m, 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, η_p^2 = .03.

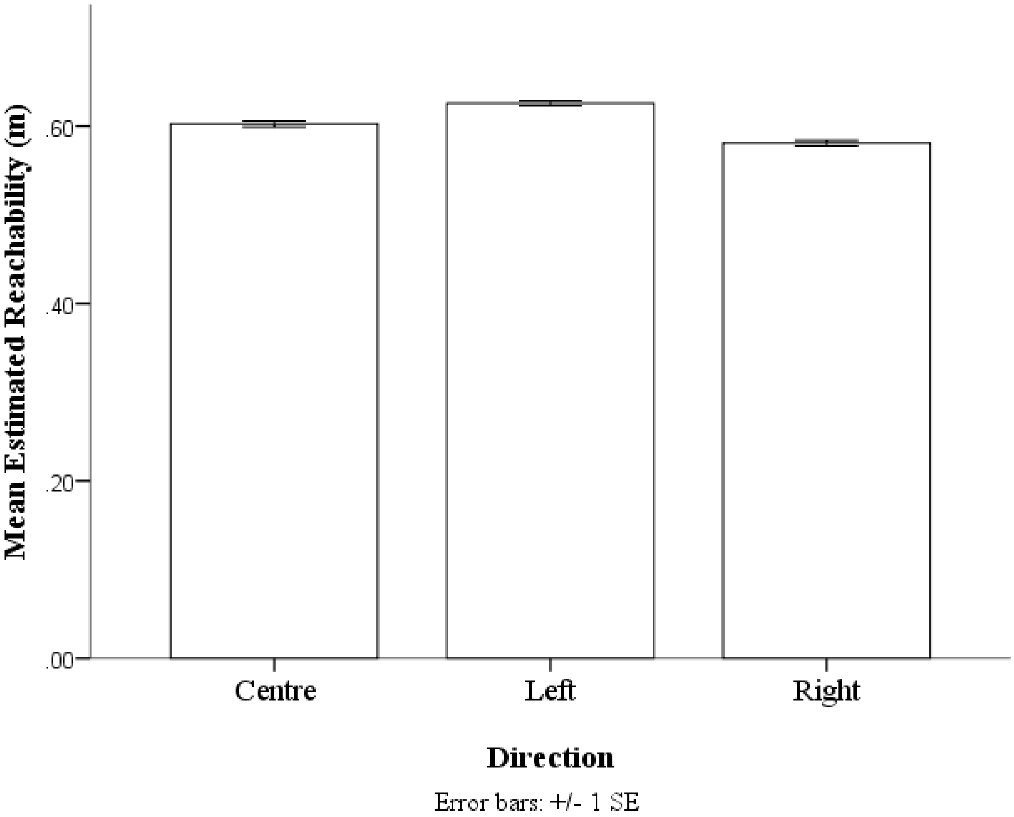

Figure 9. The mean estimated reachability of the three directions. Error bars are 1± SE calculated within-subject with the method provided by Loftus and Masson (1994).

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.

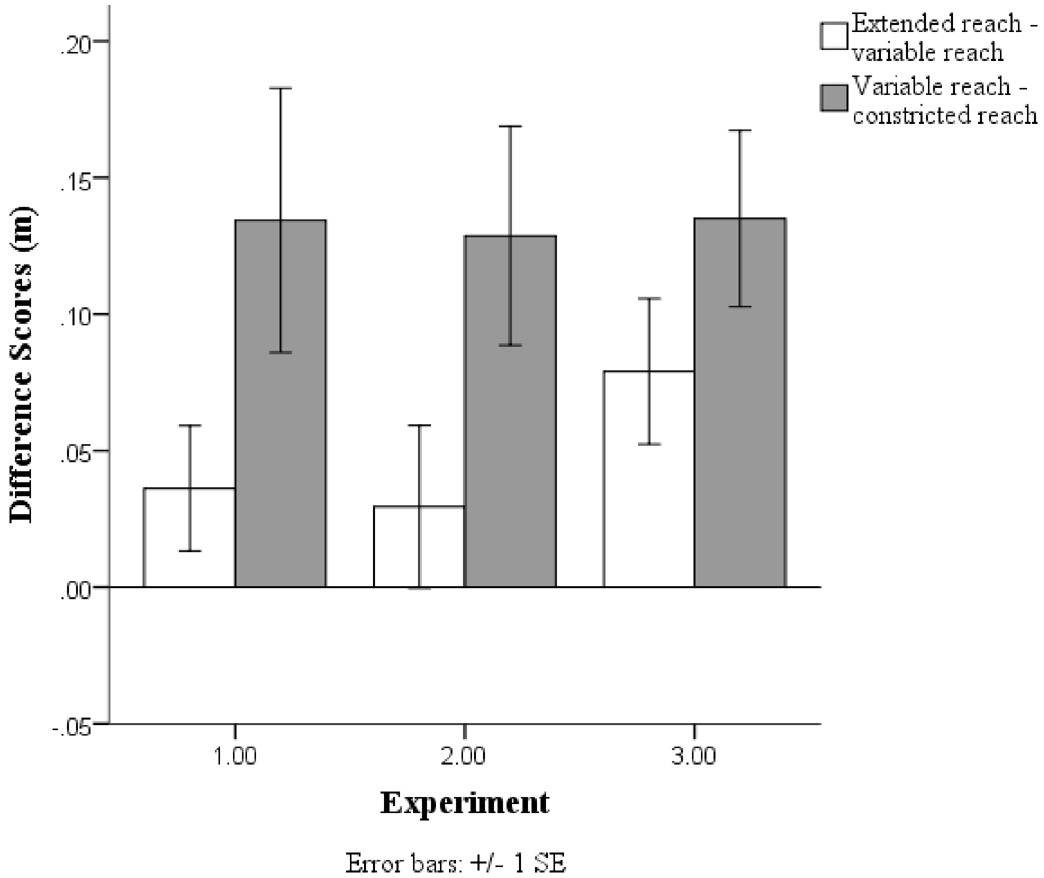

Figure 10. The difference FV and VN difference scores plotted per each experiment. Error bars are 1± SE calculated as within-subject with the method provided by Loftus and Masson (1994).

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.

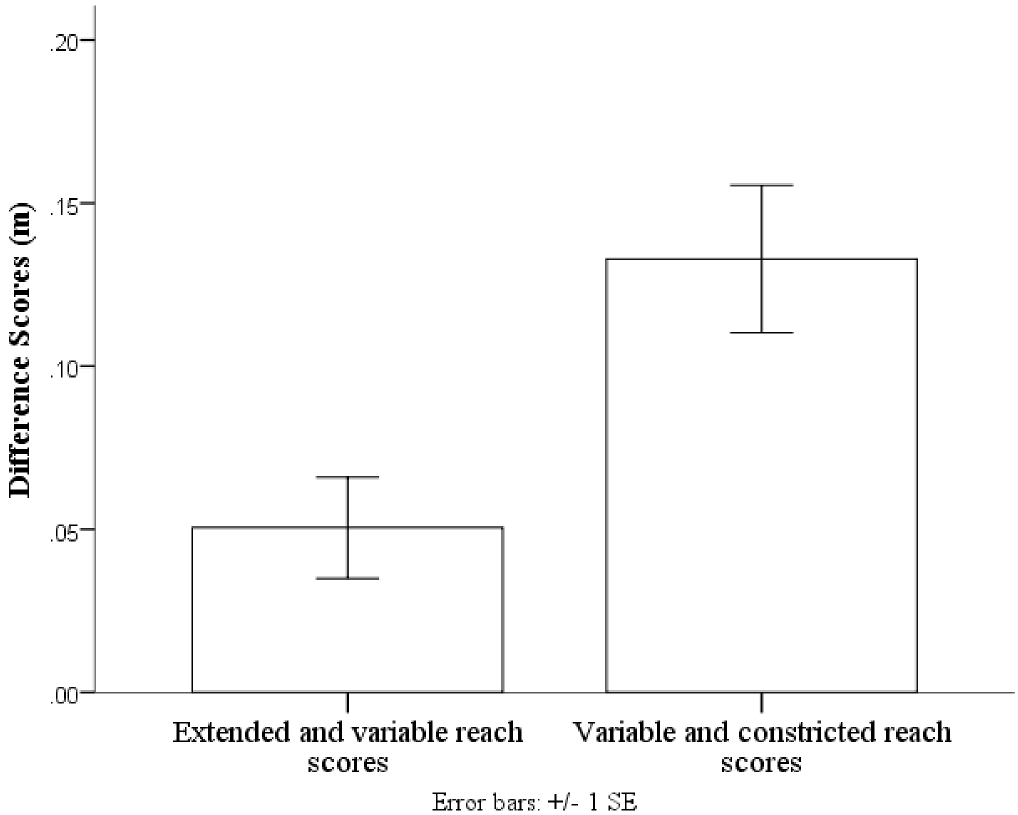

Figure 11. The difference FV and VN difference scores collapsed across all 3 Experiments. Error bars are 1± SE calculated as within-subject with the method provided by Loftus and Masson (1994).

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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