



Kent Academic Repository

Taylor, Rachael L., Bindemann, Markus and Linkenauger, Sally A. (2026) *When left is right: The perception of the action capabilities of mirrored hands*. Visual Cognition, 33 (9). pp. 593-610. ISSN 1350-6285.

Downloaded from

<https://kar.kent.ac.uk/115464/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.1080/13506285.2026.2669902>

This document version

Publisher pdf

DOI for this version

Licence for this version

CC BY-NC-ND (Attribution-NonCommercial-NoDerivatives)

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal**, Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).

ISSN: 1350-6285 (Print) 1464-0716 (Online) Journal homepage: www.tandfonline.com/journals/pvis20

When left is right: The perception of the action capabilities of mirrored hands

Rachael L. Taylor, Markus Bindemann & Sally A. Linkenauger

To cite this article: Rachael L. Taylor, Markus Bindemann & Sally A. Linkenauger (16 May 2026): When left is right: The perception of the action capabilities of mirrored hands, Visual Cognition, DOI: [10.1080/13506285.2026.2669902](https://doi.org/10.1080/13506285.2026.2669902)

To link to this article: <https://doi.org/10.1080/13506285.2026.2669902>



© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 16 May 2026.



Submit your article to this journal [↗](#)



Article views: 95



View related articles [↗](#)



View Crossmark data [↗](#)

When left is right: The perception of the action capabilities of mirrored hands

Rachael L. Taylor ^{a,b}, Markus Bindemann^a and Sally A. Linkenauger^b

^aSchool of Psychology, University of Kent, Kent, UK; ^bDepartment of Psychology, Lancaster University, Lancaster, UK

ABSTRACT

In virtual reality, observers readily calibrate to the bodies of digital human characters and consider changes to these in estimates of their action capabilities. This study investigates whether such calibration persists when somatosensory and visual information specifying the spatial location of limbs are incongruent. Across four experiments, virtual hand size and location was manipulated systematically while participants were placed in an immersive environment. Participants performed a calibration exercise to gain experience with the virtual hand before estimating their perceived grasping and reaching capabilities. In all experiments, observers consistently calibrated to the virtual hands and considered this in their perceived grasping and reaching estimates. This demonstrates that the properties of an artificial limb are integrated into observers' perception of their action capabilities, even when conditions for embodiment are not optimal.

ARTICLE HISTORY

Received 11 August 2025
Accepted 30 April 2026

KEYWORDS

Affordances; grasping ability; reaching ability; virtual reality; embodiment

Introduction

The perception of affordances, which refers to opportunities for action in the environment, is vital for survival. Affordances are highly varied, ranging from horizontal surfaces that provide support for walking, to objects such as tools that allow for manipulation with the hands (Gibson, 1979). To successfully interact with affordances, the relationship between our bodies and environmental properties must be perceived accurately (Wagman, 2012). This depends on our morphology, which dictates the maximum extent to which an action can be performed ("action boundary" – Fajen, 2005; Linkenauger et al., 2013). People are generally accurate at perceiving their action capabilities (Carello et al., 1989; Linkenauger et al., 2009) since they gain experience with a vast range of actions throughout the lifespan (Fajen et al., 2009).

Since our environments and action capabilities can change, affordances are dynamic (Turvey, 2004). These changes to our action capabilities can occur over long and short timescales. Short-term changes can happen naturally as someone becomes fatigued (Pijpers et al., 2007) or changes their posture (Wagman, 2012). Changes can also occur through artificial means, such as holding a tool that can

extend a person's reach (Witt et al., 2005) or wearing a glove that increases hand width (Ishak et al., 2008). People attune to these changes to their body and update perceptions of their action capabilities and affordances accordingly (Ishak et al., 2008; Witt et al., 2005).

Similarly, people can incorporate changes to virtual simulations of their bodies. Linkenauger et al. (2013) manipulated the size of virtual hands that tracked to participants' real hand movements. Participants' perception of object size changed with the size of the virtual hands, whereby bigger hands elicited smaller estimates of object size. In contrast, placing a familiar object next to the target object did not change its perceived size, suggesting that people use their body to scale the size of objects around them. It follows that changes to a virtual body will also elicit changes to affordance perception, since successful action execution requires understanding of the dynamic relationship between one's body and their environment (Turvey, 2004; Wagman, 2012).

There is also evidence that changes to virtual bodies are reflected in people's estimates of their perceived action capabilities. Readman et al. (2021) calibrated participants to small, normal, and large

virtual hands. Then, participants adjusted a virtual block until they believed it was the maximum size they could grasp. The larger virtual hand elicited larger estimates of maximum grip than the normal and small virtual hands. Similar findings have been found for reaching (Lin et al., 2020), which demonstrates that people can embody virtual limbs, resulting in short-term changes to affordance perception.

But what are the requirements for embodying a virtual body? In this domain, the Sense of Embodiment refers to situations where the properties of an artificial body are processed as if they are one's own (Kilteni et al., 2012a). These properties can be split into three subcomponents – a sense of self-location, agency, and body ownership (Longo et al., 2008). The sense of self-location refers to the experience of being inside a body and is determined by the visuospatial perspective of the body, vestibular signals, and tactile input (Kilteni et al., 2012a). Sense of agency reflects motor control over one's actions, which can be elicited through synchronous visuomotor correlations during active body movement (Kilteni et al., 2012a). Finally, sense of body ownership refers to the implicit sense of possession over a body part (Longo et al., 2008; Tsakiris, 2010). Ownership is impacted by bottom-up influences, such as visuo-tactile, visuomotor, and visuo-proprioceptive correlations, and top-down processes such as the degree of morphological similarity an artificial limb has to one's own body (Kilteni et al., 2012a).

Various factors facilitate embodiment of an artificial body. For example, viewing the body or limb from an egocentric perspective is critical for triggering the illusion of ownership (Petkova et al., 2011; Slater et al., 2010), since one's sense of self-location is normally rooted to this perspective (Kilteni et al., 2012a). Sense of agency over a body is sensitive to temporal discrepancies between action execution and subsequent visual feedback (Kilteni et al., 2012a), as well as discrepancies between predicted and actual sensory feedback (Sato & Yasuda, 2005). Therefore, to experience agency over an artificial body it must elicit visuomotor correlations that one would normally experience with their own body (Kilteni et al., 2012a). Finally, sense of ownership is enhanced through morphological similarity and visual resemblance (e.g., skin colour) between one's own body and the artificial body (Kilteni et al., 2012a).

To embody an artificial body, it would be beneficial that this body is presented from an egocentric perspective, and visually resembles and moves in real-time with one's own body. However, sense of location and sense of body ownership are somewhat dissociable entities (Longo et al., 2008), whereby it is possible to experience sensory feedback from an artificial body without feeling that it is one's own. Furthermore, while discrepancies in predicted and actual sensory feedback can reduce sense of agency, this does not reduce sense of ownership (Sato & Yasuda, 2005). Therefore, while subcomponents of embodiment are highly related, they may also be considered independent qualitative experiences (Tsakiris et al., 2010). Thus, embodiment of an artificial body can be possible when sensory feedback contributing to one's sense of location, agency, and bodily ownership are not optimal for all subcomponents.

Previous studies have explored people's capability to update perceptions of their action boundaries after calibrating to changes in a virtual body (Lin et al., 2020; Readman et al., 2021) under optimal conditions. Virtual arms were presented from an egocentric perspective in the same location as participants' real arms. Visual feedback from moving the virtual arms was delivered in real-time, and virtual arms resembled the morphological structure and skin texture of the real limbs. This raises the question of whether observers can update their perceived action estimates when conditions for embodiment are less optimal. For example, if a virtual arm was mirrored so that its location is spatially incongruent to the actual arm, would embodiment occur with temporally synchronous visuomotor feedback? If so, will observers consider changes to a virtual arm in their perceived action estimates as they do when the location of the real and virtual arm is congruent?

To explore this question, participants were placed in an immersive virtual environment while their hands were tracked and animated in real-time. In this environment, the right hand was either presented congruently with its actual physical location or mirrored so that it appeared on the left side of space during calibration. Additionally, we systematically manipulated virtual hand size. Participants then estimated their maximum grasp and reaching ability in a series of experiments. If the subcomponents of embodiment reflect independent processes, disruption in normal processing of one component should

not lead to a breakdown of embodiment for the other components. If so, then there should be no differences in how people calibrate to the virtual limbs and estimate their action capabilities between the congruent and incongruent conditions.

Experiment 1

This experiment explored whether participants calibrate to changes in virtual hand size when visual and somatosensory feedback specifying hand use is incongruent. Specifically, we investigated whether perceived maximum grasp estimates would be greater with large than small virtual hands. We also examined whether calibration to virtual hand size was affected by the congruency of visual and somatosensory feedback between the real and virtual hand. For this purpose, a maximum grasp estimation paradigm was adapted in which participants manipulated the size of virtual blocks until they reached a maximum extent to which participant believed they could grasp (Taylor et al., 2024). The spatial location of this virtual hand either appeared on the same side as participants' right hand or on the contralateral side. Finally, the size of the virtual hands was manipulated, so that these could appear large or small.

Method

Participants

The experiment employed a 2 (virtual hand laterality: congruent, incongruent) $\times$ 2 (virtual hand size: large, small) $\times$ 6 (starting size of the grasp estimation blocks: 6 sizes) within-subjects design. A priori power analysis was conducted with MorePower 6.0 (Campbell & Thompson, 2012) based on a three-way interaction between these factors with an effect size of $\eta_p^2 = .551$, an alpha of 0.05 and desired power of 0.8. The effect size is based on the constricted, extended and variable grasping study in Readman et al. (2021). This suggested a minimum sample size of 10. Considering this small sample size, the possibility of technical failure with virtual reality equipment, and that other studies in this domain typically employ larger samples (see, Lin et al., 2020; Lin & Linkenauger, 2021), we aimed to double this sample size. The sample was twenty-one right-handed (13 female, 8 male) and 3 mixed-handed (3 female, laterality quotients were between +40 - +45.45) participants from

Lancaster University (age range: 20–34 years, $M = 23.38$, $SD = 3.54$). Handedness was assessed using the 10-item Edinburgh Handedness Inventory (Oldfield, 1971), with scores $> +60$ being assigned as right-handed, scores between $+59$ to -59 being assigned as mixed-handed, and scores < -60 being assigned as left-handed. The mixed-handed individuals were recruited as they stated a strong right-hand preference for writing, with writing being a key predictor of handedness (Bryden, 1977; Rigal, 1992).

Stimuli

The environment for the experiment was created using Unity Version 2021.1.24f1 (Unity Technologies, San Francisco, California, United States). While Unity uses unique scaling, a standard assumption is that 1 unit in Unity is equal to 1 real-world metre (Unity Technologies, 2018). The Unity environment consisted of a room with three grey walls and a light wooden floor, with a wooden table (70 cm height, 3 m length) at which the participant sat. A pair of small red circles called "calibration dots" (2 cm in diameter, 2 cm in depth) were placed on top of the virtual table to the left, right or centre of the participant during the calibration. A white block (6, 8, 10, 12, 14 cm or 16 cm in length, 5 cm in width and 5 cm in depth) was placed 20 cm away from the participant on the virtual table during the estimation task. Eye height was set to 40 cm from the top of the virtual table, and participants sat 17 cm away from the virtual table.

Attached to the front of the headset was a Leap Motion sensor that tracked and animated the hands. The virtual hands used were the Leap Motion "capsule hand" models (Leap Motion, Inc., San Francisco, California, United States). These hand models are white with small, coloured spheres placed on the joints and fingertips. The elements of the virtual model of the hand were mapped onto the tracked hand size and arm's reach of the participant. The sizes of these capsule hands changed depending on the condition. The big virtual hand was 125% the size of the regular hand model, while the small virtual hand was 75% the size of the regular hand model (see Figure 1). The capsule hands were used because more realistic hand models we had tested became distorted when we attempted to mirror them.

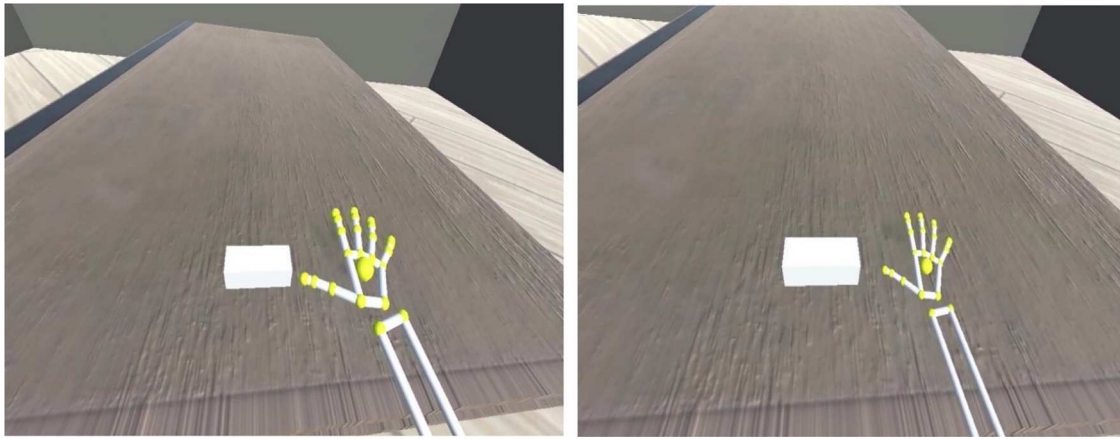


Figure 1. The big (left) and small (right) hand models in experiment 1.

Procedure

Participants wore an Oculus CV1 virtual reality (VR) headset for immersion in the virtual environment. Before entering the virtual environment, participants were told to use their right hand throughout the experiment. Additionally, they were told that they would be using big or small virtual hands, and that their hand might be presented as the right virtual hand (congruent) or mirrored to look like the left virtual hand (incongruent). After entering the virtual environment, participants completed a calibration phase. During the calibration, participants stretched their hand out so that their thumb and little finger were each touching one of two red calibration dots positioned on the virtual table (see Figure 2). Participants moved their hands as these calibration dots changed position from trial to trial. The size of the virtual hand was kept consistently big or small throughout the calibration. The positions of the

calibration dots were presented in a randomized order (see Appendix A for positions of the calibration dots). The calibration dots were placed from the right to the centre of the participant when the right virtual hand was used and placed from the centre to the left of the participant when the left virtual hand was used. This was so that participants could easily reach the calibration dots. This calibration lasted for 60 trials and was conducted so participants could experience the visuo-motor correlations between their own hand and the virtual hand, allowing them to make more informed estimates of their perceived action capabilities.

After calibration, participants placed their hands in their lap so that they no longer received visual feedback from the virtual hand. Then, the first white block appeared on the virtual table in front of the participant (see Figure 2) to start the estimation phase. The researcher increased or decreased

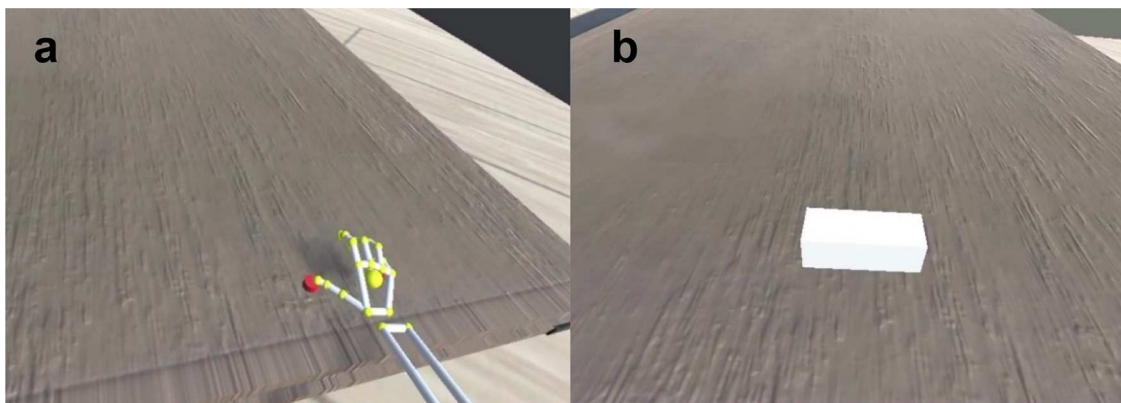


Figure 2. The virtual environment showing: A) A grasp calibration trial; B) The estimation block.

the block's length by 1 mm using the left and right arrow keys on a keyboard until the participant felt that the white block was the maximum length that they could grasp from the top using the thumb and index finger of the right hand. Participants could also request that no adjustment was made to the block. If participants questioned whether they should consider their actual or the virtual hand for these estimates, they were told to use whichever they felt was most appropriate. Throughout the course of the experiments, we recorded that only two participants asked for further clarification and received these instructions. The size of the white block after adjustment was saved after each trial. This estimation phase consisted of 12 trials, with two trials per starting length presented in a randomised order. This procedure was administered four times, once for each congruency and size condition. The order of conditions was counterbalanced, with the order of hand size (big vs. small) and congruency (congruent vs. incongruent) alternating independently between participants.

Results

The data for all experiments reported here are available on the Open Science Framework at <https://osf.io/mksxj/>. To examine whether grasp estimation was influenced by hand congruency and size, a $2 \times 2 \times 6$ within-subjects ANOVA was conducted with real

hand/virtual hand congruency (congruent vs. incongruent), virtual hand size (big vs. small), and white block starting length (6, 8, 10, 12, 14 cm, 16 cm) as the independent variables and maximum grip estimate (as measured by the length of the block after adjustment) as the dependent variable. Bayes factors and p -values are reported for all one degree-of-freedom tests. Bayes factors are calculated as the ratio of probability of the data under one hypothesis (such as the alternative hypothesis, or H_1) against the probability of data under another hypothesis (such as the null hypothesis, or H_0). We calculated Bayes factors using the Dienes and Mclatchie (2018) R script calculator and provide robustness regions (RR) to indicate the range of effect sizes that support our conclusions. Calculation of robustness regions follows the guidance of Dienes (2019). Bayes factors greater than 3 and 10 are interpreted as moderate and strong evidence, respectively, in support of the alternative hypothesis. We interpret Bayes factors less than .33 and .10 as moderate and strong evidence, respectively, in support of the null hypothesis. Bayes factors between .33 and 3 are considered to provide weak or inconclusive evidence. These thresholds are designed to aid interpretation of the hypothesis that is most supported by the data (Lakens et al., 2018).

The cross-subject means of the maximum estimated grasp size are shown in Figure 3 as a function of hand size and congruency. The ANOVA revealed a

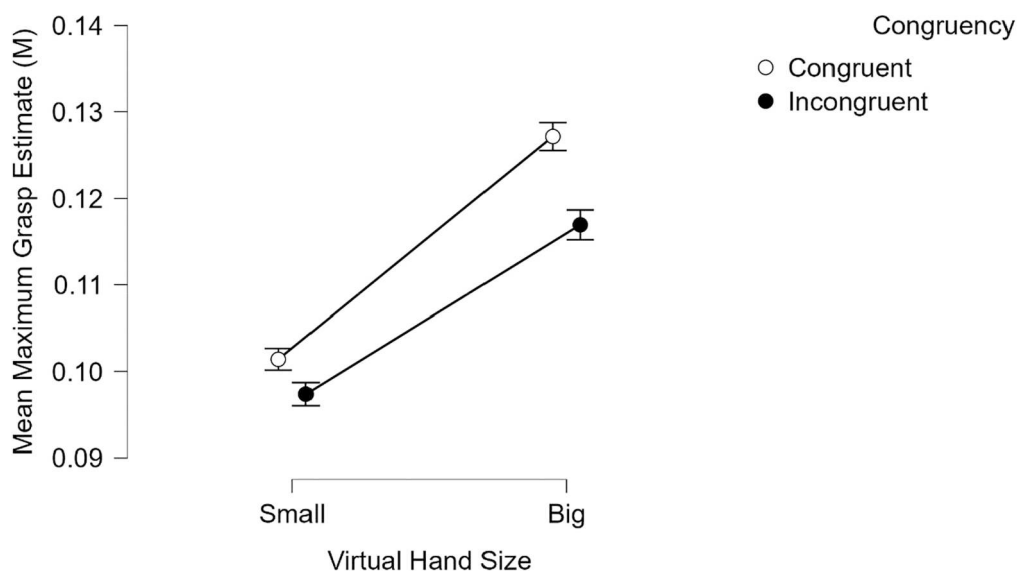


Figure 3. The effect of hand size and congruency on perceived grasp estimates in experiment 1.

Note: Error bars represent standard error of the mean.

main effect of virtual hand size, $F(1, 23) = 40.24$, $p < .001$, $\eta_p^2 = .64$, $B_{H(0, 2.5)} = 9.99 \times 10^7$, $RR[.07, 836.48^1]$, with larger estimates of perceived maximum grasp for big hands ($M = 12.2$ cm, $SD = 3.1$ cm) compared to small hands ($M = 9.9$ cm, $SD = 2.8$ cm), with Bayes factor indicating strong support for the alternative hypothesis. In contrast, a main effect of congruency on perceived grasping estimates was not found, $F(1, 23) = 3.81$, $p = .06$, $\eta_p^2 = .14$, $B_{N(0, 2.3)} = .99$, $RR[0, 7.25^2]$, with similar perceived grasping estimates for congruent ($M = 11.4$ cm, $SD = 3.3$ cm) and incongruent ($M = 10.7$ cm, $SD = 2.5$ cm) presentations of the virtual hands, and Bayes factor providing inconclusive evidence for either hypothesis. An interaction between congruency and hand size was not found, $F(1, 23) = 2.56$, $p = .12$, $\eta_p^2 = .1$, $B_{N(0, 2.5)} = 1.12$, $RR[0, 10.72^3]$, with Bayes factor indicating inconclusive evidence for either hypothesis.

Mauchly's test of sphericity found that the assumption of sphericity was violated for block starting length and its interactions with congruency and hand size. Therefore, Greenhouse-Geisser corrections are reported for these tests. This analysis showed a main effect of block starting length, $F(2.482, 57.096) = 30.06$, $p < .001$, $\eta_p^2 = .57$, with larger starting lengths eliciting greater estimates of perceived maximum grasp. Post-hoc t-tests with Bonferroni show that there were no differences in estimates of perceived maximum grasp between adjacent block starting lengths (i.e., 6 vs. 8 cm, 8 vs. 10 cm, 10 vs. 12 cm, 12 vs. 14 cm, 14 vs. 16 cm), while all other comparisons between block starting distances were significant, whereby larger starting lengths led to bigger perceived grasp estimates (for a summary, see Table 1). Finally, there were no interactions between congruency and block starting length, virtual hand size and block starting length, or congruency, virtual hand size and block starting length, all $F_s \leq 2.07$, all $p_s \geq .12$.

Discussion

Experiment 1 explored whether people's perceived grasp estimates are affected by visual feedback on hand size. Importantly, we manipulated the congruency of visual and somatosensory feedback specifying hand use. The results show that participants can calibrate to different virtual hand sizes and alter their perceived grasp estimates, regardless of whether visual feedback is congruent to somatosensory feedback. The ability for participants to adjust their action estimates whilst experiencing incongruent visuo-somatosensory feedback suggests that people can embody artificial limbs even when the conditions for embodiment are not optimal.

Experiment 2

Experiment 1 demonstrates that participants can calibrate to different virtual hand sizes when estimating their maximum grasp ability, regardless of visuo-somatosensory congruency. This suggests that people can embody virtual hands when visual information is incongruent to somatosensory information specifying their own hand use.

However, the changes in visual hand size were both highly salient and stable. Thus, a key question is whether changes in perceived action estimates reflect a genuine perceptual recalibration or reflect a strategy of overtly altering perceived action estimates in line with the expectations of the experiment. Essentially, the effect of hand size in conjunction with the null effect of visuo-somatosensory congruency may not be because the perceptual system uses the same mechanisms to recalibrate regardless of visuo-somatosensory congruency. Rather, participants might explicitly adjust their estimates in the same manner in both congruency conditions. Such an effect has been found previously, with Durgin et al.

Table 1. Pairwise comparisons of maximum grasping estimate by block starting length for experiment 1.

Block starting length (cm)	<i>M</i> (cm)	<i>SD</i> (cm)	<i>t</i> (23)					
			6	8	10	12	14	16
6	10.4	2.7	–					
8	10.7	2.8	2.01	–				
10	11.9	2.6	4.1***	2.01	–			
12	11.2	3	6.47***	4.38***	2.37	–		
14	11.6	2.9	8.95***	6.85***	4.85***	2.48	–	
16	11.7	2.9	9.85***	7.75***	5.75***	3.37*	0.9	–

Note: * indicates $p < .05$, *** indicates $p < .001$

(2009) finding that participants can be sensitive to the social demands of an experimental context when action ability is manipulated in an obvious manner.

To explore this possibility, we conducted an experiment exploring how participants may recalibrate their grasping ability to variable changes in hand size. Since participants are exposed to a variation of different hand sizes, the predicted outcome of the experiment would be less obvious than with the stable and highly salient changes of Experiment 1. Therefore, the possibility that changes in perceived action estimates reflect the expectations of the experimenters is reduced. Readman et al. (2021) found that, when faced with hands that appeared as small, normal, big, or variable with equal probability within a perceptual-motor calibration task, participant's estimates of perceived grasp reflected an average of all experienced hand sizes. In this study, we explore whether there are differences in how participants recalibrate to variable hand sizes with the added variability of visuo-somatosensory incongruency.

Method

Participants

We carried forward the same power analysis from Experiment 1, since Readman et al. (2021) include a variable grasp condition in their study. Therefore, we recruited 13 right-handed (4 male, 9 female) and six mixed-handed (2 male, 4 female, with laterality quotients ranging from +33.33 to +53.84) individuals (age range: 18–23 years, $M = 20.05$, $SD = 2.07$) from Lancaster University. Handedness was assessed as in Experiment 1, with the same justification for retaining the mixed-handed participants.

Stimuli and procedure

The materials were identical to Experiment 1, except for the following changes. Virtual hand size now varied between 75%, 100%, or 125% during calibration for each trial. Each hand size appeared equally but randomly throughout the calibration, for 20 trials each and a total of 60 calibration trials. The virtual hand was not visible during the estimation phase of the experiment. The procedure was repeated twice, once for each congruency condition. The factor of hand size during the grasping task was dropped, creating a 2 (congruency) $\times$ 6 (object starting size) within-subjects design for the estimation trials. The

dependent measure was maximum estimated grip, as measured by the final length of the estimation block after adjustment.

Results

One participant was removed prior to analysis for failing to adhere to task instructions. A 2 (congruency: congruent vs. incongruent) $\times$ 6 (block length: 6, 8, 10, 12, 14, 16 cm) within-subjects ANOVA was conducted on perceived maximum grasp estimates. We report both Bayes factors and p -values for all one degree-of-freedom tests. There was no main effect of congruency, $F(1, 17) = 1.79$, $p = .2$, $\eta_p^2 = 0.1$, $B_{N(0, 2.3)} = .08$, $RR[.54, \infty^4]$, as perceived grasp ability estimates were comparable in the congruent ($M = 11.2$ cm, $SD = 1.7$ cm) and incongruent ($M = 11.1$ cm, $SD = 1.7$ cm) hand conditions (see Figure 4). Bayes factor indicates that our data strongly support the null hypothesis.

However, a main effect of block starting length was observed, $F(1.919, 32.631) = 26.220$, $p < .001$, $\eta_p^2 = .61$. Block starting length was reported with Greenhouse-Geisser corrections as this test violated sphericity assumptions. Post-hoc t -tests with Bonferroni correction show that, generally, perceived maximum grasp estimates were not different between adjacent block starting lengths. However, bigger starting sizes

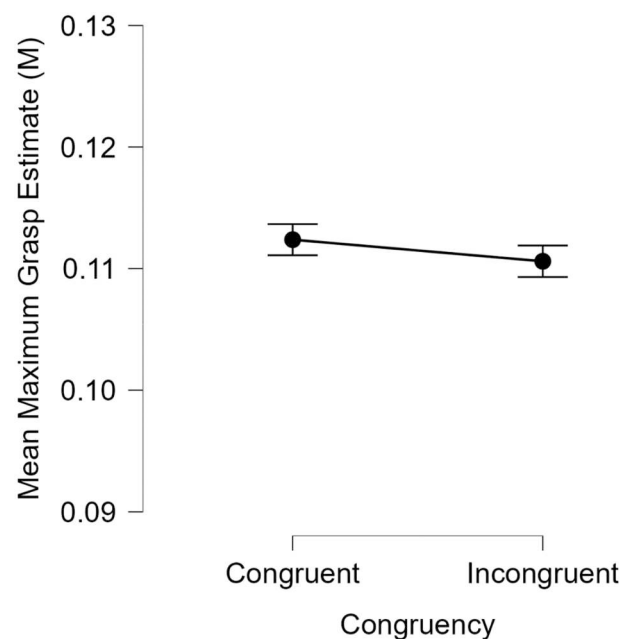


Figure 4. The effect of congruency on perceived grasp estimates in experiment 2.

Note: Error bars represent standard error.

Table 2. Pairwise comparisons of variable maximum grasping estimate by block starting length for experiment 2.

Block starting length (cm)	<i>M</i> (cm)	<i>SD</i> (cm)	<i>t</i> (17)					
			6	8	10	12	14	16
6	10.1	1.9	–					
8	10.8	1.8	3.5*	–				
10	11	1.8	4.58***	1.09	–			
12	11.2	1.6	5.76***	2.26	1.17	–		
14	11.8	1.6	8.5***	5***	3.92**	2.75	–	
16	12.1	2	10.13***	6.63***	5.55***	4.37***	1.63	–

Note: * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$.

led to larger perceived grasp estimates (see Table 2). Finally, an interaction between congruency and block starting length was not found, $F(5, 85) = .91$, $p = .48$, $\eta_p^2 = .05$.

Discussion

This experiment demonstrates that there are no differences in perceived grasp estimates between congruent and incongruent presentation of real and virtual hands when the virtual hand size varies randomly throughout calibration. This suggests that the results of Experiment 1 do not reflect sensitivity to experimental demands. Rather, the perceptual system undergoes a process of recalibration to variable changes in hand size and this process appears to be consistent regardless of visuo-somatosensory congruency.

Experiment 3

Experiment 1 and 2 indicate that people recalibrate grasping estimates in response to changes to their action capabilities when visual and somatosensory feedback specifying hand use is incongruent. In this experiment, we extend the investigation into whether observers also update estimates of their perceived action capabilities in the context of reaching. Reaching is a relatively unskilled action when compared to grasping, with little consequence arising from a failed reach (Readman et al., 2021). Consistent with its lower risk, people tend to overestimate their reaching capabilities (Carello et al., 1989; Heft, 1993). However, the introduction of visuo-somatosensory conflict may alter the skill needed to successfully complete a reach, especially as reaching has a directional component that grasping does not. Therefore, it is important to assess reaching as a separate action from grasping.

Previous research indicates that people can calibrate to dramatic changes in hand size when estimating reach (Lin et al., 2020). Therefore, estimates of

maximum reach were expected to be higher with big than small virtual hands. Moreover, given the absence of congruency effects between real and virtual hands in Experiment 1 and 2, it was also expected that observers use virtual hand size in their perceived reach estimates regardless of the congruency of visuo-somatosensory feedback specifying hand use.

Method

Participants

Using the effect size from the results of the constricted, extended and variable reach study in Lin et al. (2020), we conducted an a priori power analysis using MorePower 6.0 (Campbell & Thompson, 2012) with the real hand $\times$ virtual hand $\times$ hand size being the key area of interest, with an effect size of $\eta_p^2 = .42$, an alpha of 0.05 and desired power of 0.8. The analysis suggested a minimum sample size of 14. We recruited 14 right-handed (10 female, 5 male) and 5 mixed-handed (3 female, 2 male, laterality quotients were between +27.27 – +45.45) individuals from Lancaster University (age range: 18–32 years, $M = 20.7$, $SD = 3.31$). Handedness was ascertained using the same method as Experiment 1.

Stimuli

The same virtual environment as in Experiment 1 and 2 was employed, except for the following changes. To create a reaching task, a singular small red circle (2 cm in diameter, 2 cm in depth) was placed on the virtual table to the left, right or centre of the participant during the calibration phase. In the estimation phase, a small red circle known as the “estimation target” (2 cm in diameter, 2 cm in depth) was placed on the virtual table 27.4 cm away centrally from the participant on “near” trials. On “far trials”, for reaching towards the centre, the estimation target was presented centrally 90 cm away from the participant.

For reaching towards the left or right on “far” trials, the estimation target was presented 100.6 cm away to the left or right.

Procedure

The procedure of the study was similar to Experiment 1, though there were key differences during the calibration and estimation task. During the calibration task, participants used their index finger to control the virtual hand to point and touch a single calibration circle. This circle then changed position from trial to trial throughout the calibration phase (see Figure 5; see Appendix B for exact locations of the calibration dots). As in Experiment 1, visuo-somatosensory feedback specifying hand use was either congruent or incongruent, and the virtual hand was consistently presented as big or small depending on

the condition that the participant had been assigned (big vs. small).

After completing the calibration, participants moved onto the estimation task (see Figure 6). Participants were told to imagine they were estimating the maximum distance they could reach with the right arm, without bending forward at the hip. As in Experiment 1, visual feedback of the hands was removed at this stage. An estimation target appeared either far away or close to the participant (hysteresis), and appeared either on the left, right, or centre from the participant’s perspective (reach direction). The researcher would adjust the distance of the estimation target by 2.25 cm either away from or towards the participant depending on its starting position. The participant told the researcher to stop moving the estimation target when they believed it

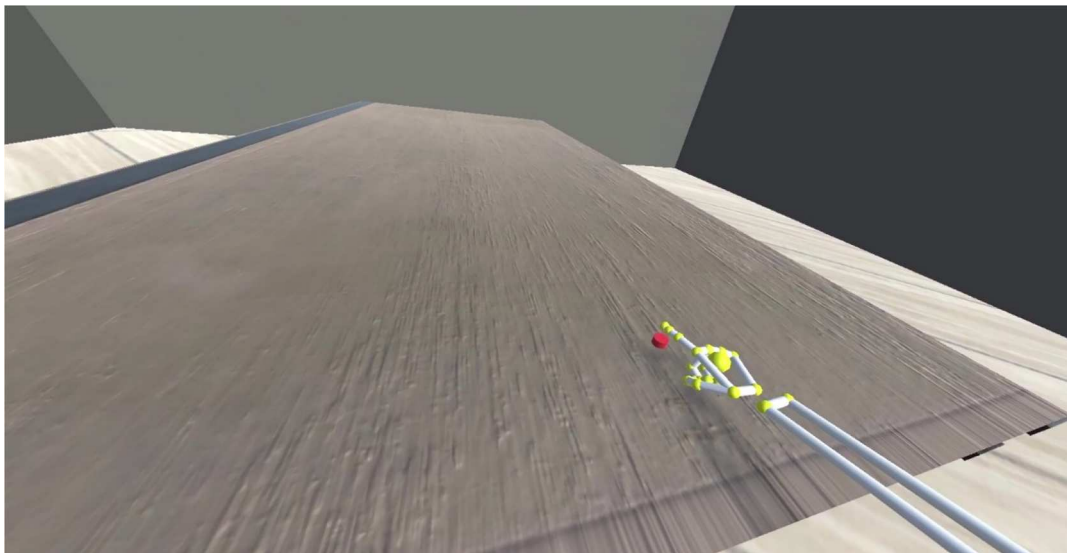


Figure 5. An example of a reach calibration trial in experiment 3, as shown when using the small right virtual hand.

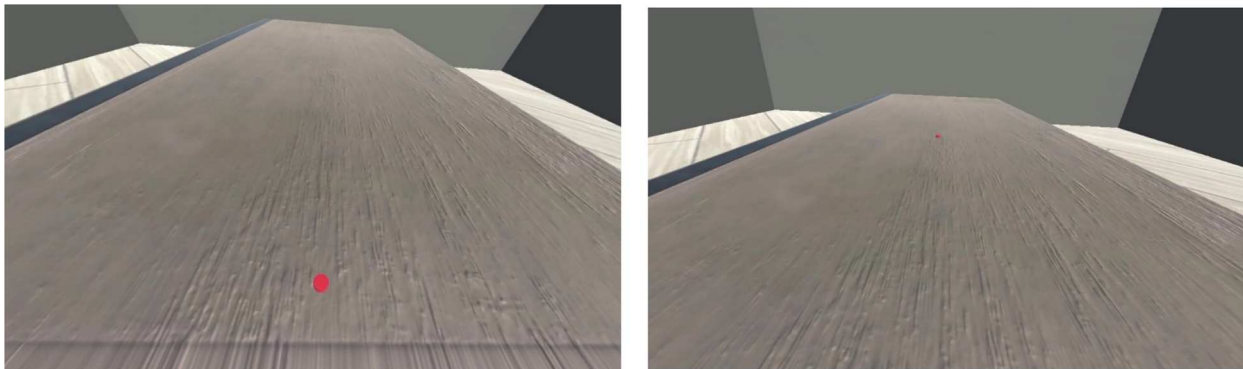


Figure 6. An illustration of the reaching estimation task in experiment 3, showing near-centre and far-centre Trials.

to be at the maximum distance they could reach. The estimation phase lasted 12 trials, with 2 trials per estimation target start position presented in a randomised order. This procedure was repeated four times, once for each condition. Overall, the experiment took around 30 min to complete.

Results

Three participants were removed prior to analysis for failing to adhere to task instructions. A 2 (hand congruency: congruent vs. incongruent) $\times$ 2 (hand size: big vs. small) $\times$ 2 (hysteresis: near vs. far) $\times$ 3 (reach direction: centre, left, right) within-subjects ANOVA was conducted on perceived maximum reach estimates. This showed no main effect of congruency, $F(1, 16) = 0.91$, $p = .35$, $\eta_p^2 = .05$, $B_{N(0, 3.8)} = .33$, $RR[0, 3.83^5]$, reflecting comparable estimates for congruent ($M = 47.2$ cm, $SD = 9.8$ cm) and incongruent hands ($M = 48$ cm, $SD = 11.4$ cm), with Bayes factor indicating weak support for the null or inconclusive evidence. However, a main effect of virtual hand size was found, $F(1, 16) = 10.86$, $p = .005$, $\eta_p^2 = .4$, $B_{H(0, 8.5)} = 55.53^6$, with greater estimates for big ($M = 49.5$ cm, $SD = 9.8$ cm) than small virtual hands ($M = 45.7$ cm, $SD = 11.7$ cm), with Bayes factor indicating strong support for the alternative hypothesis. There was no interaction between congruency and hand size,

$F(1, 16) = 0.00$, $p = .99$, $\eta_p^2 = 0.00$, $B_{N(0, 8.5)} = .99^7$, $RR[0, 1470.75]$ (see Figure 7), with Bayes factor providing inconclusive evidence.

A main effect of direction was found, $F(2, 32) = 20.95$, $p < .001$, $\eta_p^2 = .57$. Post-hoc t-tests with Bonferroni correction show that perceived reach estimates to the right (ipsilateral; $M = 49.1$ cm, $SD = 10.5$ cm) were greater than estimates to the left (contralateral; $M = 47.2$ cm, $SD = 10.3$ cm; $t(16) = 4.68$, $p < .001$) and centre ($M = 46.5$ cm, $SD = 10.8$ cm; $t(16) = 6.21$, $p < .001$). However, there were no differences in perceived reach estimates between the centre and left, $t(16) = 1.54$, $p = .4$ (see Figure 8). There was no main effect of hysteresis $F(1, 16) = 3.37$, $p = .09$, $\eta_p^2 = .17$, with comparable reach estimates for near ($M = 48.2$ cm, $SD = 10.4$ cm) or far targets ($M = 47$ cm, $SD = 10.8$ cm).

There was an interaction between hysteresis and direction, $F(2, 32) = 3.46$, $p = .04$, $\eta_p^2 = .18$. Analysis of simple main effects show that when the target started near, estimates to the right ($M = 49.5$ cm, $SD = 10.6$ cm) were higher than estimates to the centre ($M = 47.8$ cm, $SD = 11$ cm; $t(16) = 2.89$, $p = .011$, $d = .7$) and left ($M = 47.4$ cm, $SD = 9.9$ cm; $t(16) = 4.94$, $p < .001$, $d = 1.2$), with no differences between estimates to the centre and left ($t(16) = 0.56$, $p = .58$, $d = 0.14$). When the target started far away, estimates to the centre ($M = 45.3$ cm, $SD = 11.1$ cm) were lower

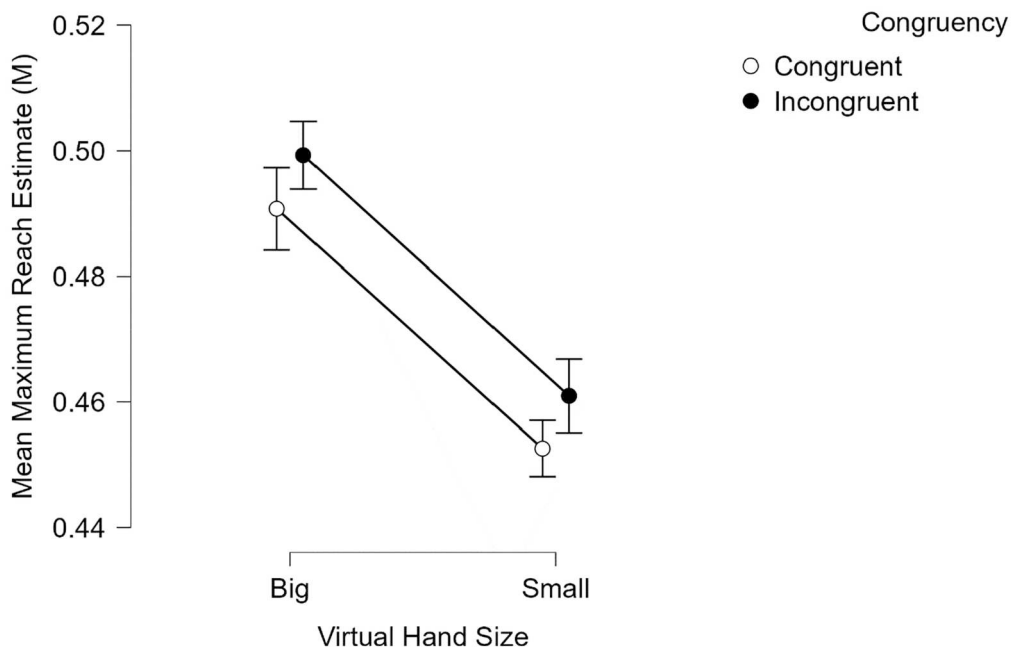


Figure 7. The effect of hand size with respect to congruency on reach estimates in experiment 3.

Note: Error bars show standard error.

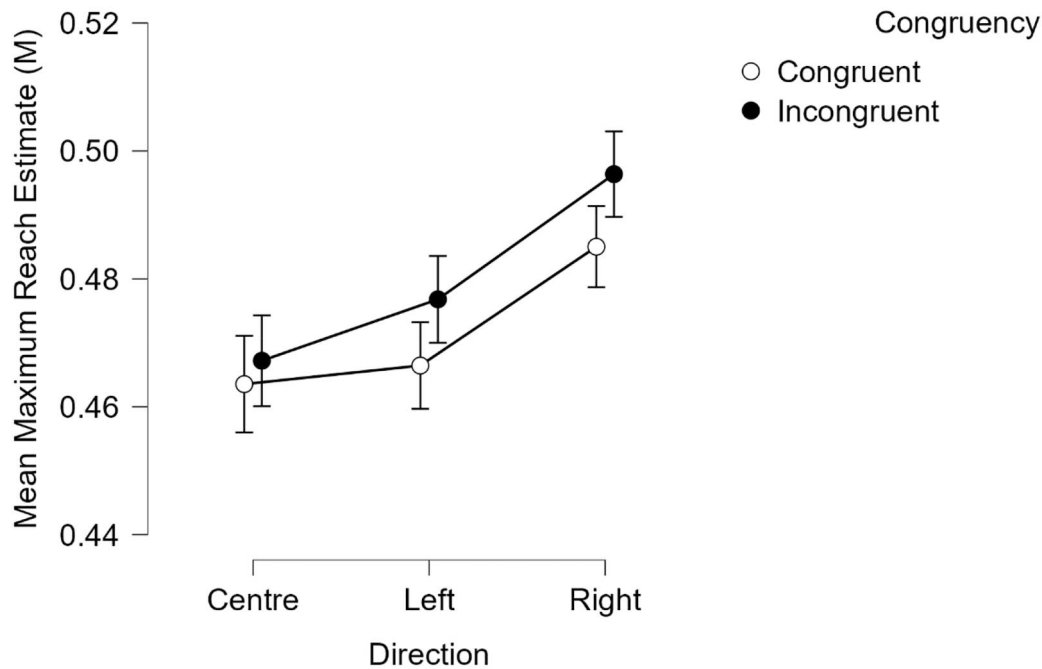


Figure 8. Effect of reaching direction on maximum reach estimates with respect to congruency in experiment 3.

Note: Error bars represent standard error.

than both estimates to the left ($M = 46.9$ cm, $SD = 11$ cm; $t(16) = -2.82$, $p = .01$, $d = -0.68$) and right ($M = 48.7$ cm, $SD = 10.6$ cm; $t(16) = -5.31$, $p < .001$, $d = -1.29$), while estimates to the left were also lower than estimates to the right, $t(16) = -3.38$, $p = .004$, $d = -0.82$.

Furthermore, there was an interaction between size and hysteresis, $F(1, 16) = 4.9$, $p = .04$, $\eta_p^2 = .24$. Analysis of simple main effects shows that with the big virtual hand, estimates when the target started near ($M = 50.4$ cm, $SD = 9.7$ cm) were higher than when the target started far away ($M = 48.6$ cm, $SD = 10.1$ cm), $t(16) = 2.17$, $p < .05$, $d = .09$. However, with the small virtual hand, there was no difference in reaching estimates between the target starting near ($M = 46$ cm, $SD = 11.6$ cm) or far ($M = 45.3$ cm, $SD = 12$ cm), $t(16) = 1.15$, $p = .27$, $d = .05$.

None of the remaining interactions were significant, all $F_s \leq 2.99$, all $p_s \geq .29$, though the three-way interaction between congruency, hysteresis, and direction was approaching significance, $F(2, 32) = 2.99$, $p = .06$, $\eta_p^2 = .16$.

Discussion

Experiment 3 explored whether people's estimates of maximum reach are impacted by visual feedback on

hand size. In addition, we explored whether the congruency of visuo-somatosensory feedback specifying hand use affected how hand size influenced reaching estimates. We found that participants' estimates of perceived maximum reach were greater with the big versus the small virtual hand. Importantly, there were no differences in reaching estimates between congruent and incongruent visuo-somatosensory feedback, and no interaction between congruency and hand size. These results converge with Experiment 1 to show that people can calibrate to changes in hand size regardless of whether the conditions for embodiment are optimal.

Experiment 4

Experiment 3 demonstrates that people can embody a virtual hand and consider changes in hand size even when visual and somatosensory information specifying hand use are not congruent. However, as with grasping, participants may be sensitive to the experimental demand that highly salient and consistent changes to reaching ability elicit. We therefore explored how people recalibrated their reaching estimates with variable hand sizes, since the intended outcome of this manipulation is less intuitive. Lin et al. (2020) found that, when participants calibrated

to small, big, and variable hand sizes when reaching, the perceptual system employed used a heuristic which favoured experience with the larger hand. As such, estimates of reach were more liberal. We therefore investigated whether visuo-somatosensory conflict impacts the mechanism the perceptual system uses to recalibrate to variable changes in reach.

Method

Participants

We carried forward the power analysis from Experiment 3, since Lin et al. (2020) included a variable reaching condition in their study. We recruited 12 right-handed (8 female, 4 male) and 6 mixed-handed (4 female, 2 male, laterality quotients were between +27.27 - +53.84) individuals from Lancaster University (age range: 18–32 years, $M = 20.44$, $SD = 3.26$). Handedness was ascertained using the same method as Experiment 1.

Stimuli and procedure

The virtual environment and procedure were almost identical to Experiment 3, except that the virtual hand varied in size between 75%, 100%, and 125% of the size of the normal hand model during calibration. Each hand size appeared with equal frequency, but in a random order for 60 calibration trials. The estimation phase was identical to Experiment 3, and the virtual hands were not visible during this phase of the experiment. This procedure was repeated twice, once for each condition. Overall, the experiment took around 15 min to complete.

Results

Two participants were removed prior to analysis because they did not adhere to task instructions. A within-subjects ANOVA was conducted with real hand x virtual hand congruency (congruent vs. incongruent), hysteresis (near vs. far), and direction of reach (centre, left, right) as the independent variables and maximum reach estimate (as measured by the final position of the estimation target at the end of each trial) as the dependent variable. Bayes factors were calculated for all one degree-of-freedom tests.

There was no main effect of congruency, $F(1, 15) = 0.09$, $p = .77$, $\eta_p^2 = .006$, $B_{N(0, 3.8)} = .26$, $RR[3, \infty^8]$, with comparable target estimates for congruent ($M = 50.9$ cm, $SD = 8.1$ cm) and incongruent ($M = 50.6$ cm, $SD = 10.2$ cm) hands (see Figure 9). Bayes factor suggests moderate support for the null hypothesis. There was no main effect of hysteresis, $F(1, 15) = 1.37$, $p = .26$, $\eta_p^2 = .08$, with no differences between estimates of reach when the estimation target started near ($M = 51.4$ cm, $SD = 8.7$ cm) or far ($M = 50.1$ cm, $SD = 9.9$ cm) from the participant.

There was a main effect of direction, $F(2, 30) = 16.1$, $p < .001$, $\eta_p^2 = .52$ (see Figure 10). Bonferroni post-hoc t-tests show that perceived reach estimates to the right (ipsilateral; $M = 52.9$ cm, $SD = 9.3$ cm) were greater than estimates to the left (contralateral; $M = 50$ cm, $SD = 8.4$ cm, $t(15) = 4.27$, $p < .001$) and centre ($M = 49.3$ cm, $SD = 9.8$ cm, $t(15) = 5.37$, $p < .001$). However, there were no differences in estimates of reach between the centre and left, $t(15) = 1.1$, $p = .84$.

An interaction between hysteresis and direction was also found, $F(2, 30) = 5.43$, $p = .01$, $\eta_p^2 = .27$. Analysis of simple main effects showed that, when the target started near, there were no differences in perceived reach estimates to the centre ($M = 51$ cm, $SD = 9.6$ cm) and left ($M = 49.8$ cm, $SD = 7.9$ cm; $t(15) = 1.47$, $p = .16$, $d = 0.37$). However, estimates to the

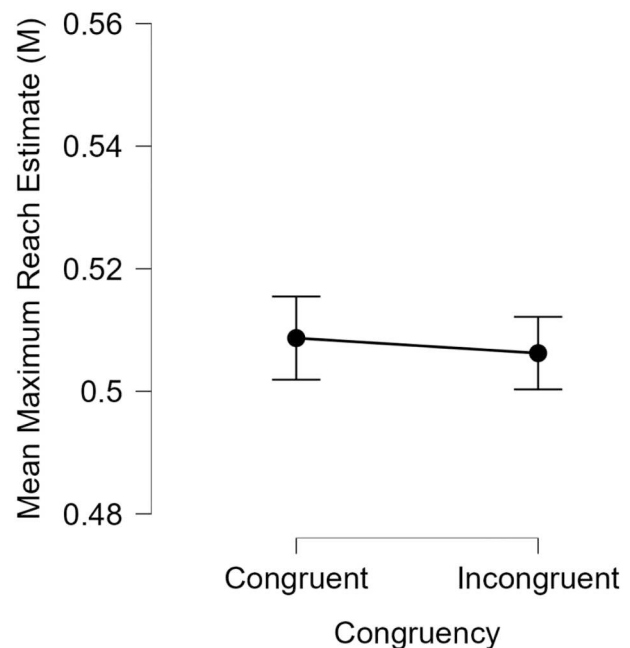


Figure 9. The effect of congruency on reach estimates in experiment 4. Note. Error bars represent standard error.

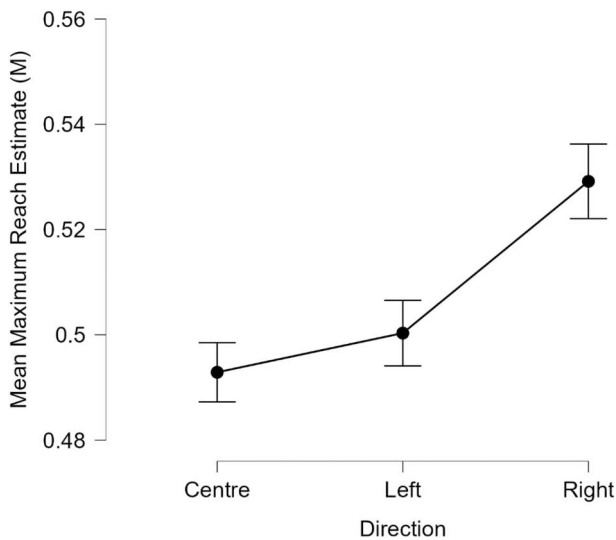


Figure 10. The effect of reach direction on reach estimates in experiment 4.

Note: Error bars represent standard error.

right ($M = 53.4$ cm, $SD = 9.2$ cm) were higher than estimates to the centre ($t(15) = 2.56$, $p = 0.02$, $d = 0.64$) and left ($t(15) = 3.99$, $p < .001$, $d = 1$). When the target started far away, estimates to the centre ($M = 47.6$ cm, $SD = 10.4$ cm) were lower than estimates to both the left ($M = 50.3$ cm, $SD = 9.5$ cm; $t(15) = -3.24$, $p = .006$, $d = -0.81$) and the right ($M = 52.5$ cm, $SD = 10.4$ cm; $t(15) = -4.91$, $p < .001$, $d = -1.23$), while estimates to the left were also lower than estimates to the right, $t(15) = -2.32$, $p = 0.04$, $d = -0.58$. Finally, there were no interactions between congruency and direction, and congruency, hysteresis, and direction, both $F_s \leq 1.36$, all $p_s \geq .27$, while the interaction between congruency and hysteresis was marginally non-significant, $F(1, 15) = 4.15$, $p = .06$, $\eta_p^2 = .22$.

Discussion

This experiment confirms that visuo-somatosensory congruency between the real and virtual hands does not impact perceived maximum reach estimates when virtual hand size varies randomly. This converges with the grasping data from Experiment 2 to suggest that the results of Experiment 3 are not a result of demand characteristics. Rather, observers can calibrate to changes in their action capabilities even when visuo-somatosensory feedback specifying the hand being used is incongruent. In addition, these findings suggest that the perceptual system might use same perceptual mechanisms to

weigh experience with variable hands even with the additional variance of visuo-somatosensory conflict.

General discussion

Across a set of four experiments, this study explored whether there are differences in people's estimates of perceived grasp and reach when visual feedback about hand size is manipulated systematically. Specifically, we were interested in whether the congruency of visuo-somatosensory feedback specifying hand use impacts how people utilize visual feedback on hand size in estimates of their action boundaries. We used estimates of action capabilities as an indirect measure of embodiment. To successfully interact with our environment, we must be able to adapt our action perception based on the dynamic relationship between our bodies and the environment (Turvey, 2004). Thus, if changes to a virtual body are considered in people's estimates of their action capabilities, it follows that those people consider the virtual body to be – to some degree – part of their own.

Sense of embodiment is hypothesized to have three key subcomponents, comprising of the sense of self-location, sense of agency, and sense of ownership (Kilteni et al., 2012a; Longo et al., 2008; Tsakiris, 2010; Tsakiris et al., 2010). These subcomponents can be considered dissociable and independent experiences (Tsakiris et al., 2010). We therefore hypothesised that disruption to one's sense of self-location through mirroring the right hand would not lead to a complete breakdown of embodiment if one's sense of agency over the virtual limb was preserved. Hence, the congruency of visuo-somatosensory feedback specifying hand use would not affect how visual information on hand size was used in action estimates.

In support of this hypothesis, Experiment 1 showed that estimates of maximum grasp were higher when participants calibrated to big than small virtual hands. These hand-size effects occurred independently of the congruency of the hands. This pattern was replicated in Experiment 3, in which participants estimated their maximum reaching ability with respect to the big and small virtual hands. This suggests that observers can calibrate to different virtual hand sizes even when somatosensory and visual feedback specifying hand use is not congruent.

While participants were able to calibrate to the sizes of the virtual hands, it is less clear whether they calibrated to the changed symmetry of the hands. In Experiment 3 and 4, estimates of maximum reach were always further for the right than the left side of space. This effect persisted even when the virtual hand was presented to the left side of space, in which case it should have been easier to reach to the left. There may be several reasons for this finding. One possibility is that the mirroring of the hand requires too much of an adjustment for calibration to occur. The mirroring changes much more than spatial location; it reverses the symmetry of the body. Differing the right and left hand changes more than the spatial location but also the perceived functionality of the limb. Hence, changes in laterality are likely more difficult to adjust to than merely spatial location. As a result, it appears that observers defaulted to estimating their maximum reach relative to their real right arm, since this is the natural laterality/symmetry configuration that people have used throughout their lives.

Previous research has explored whether manipulating visuo-proprioceptive spatial position offset, which refers to the distance between the proprioceptive cues and visual cues specifying hand position (Pritchard et al., 2016), impacts ratings of embodiment. This showed that participants give higher ratings of embodiment-location when there is no spatial offset compared to a 30 cm spatial offset between the real and virtual hands. However, this spatial offset did not affect ratings of agency or ownership. The mirroring of virtual hands in the current study created a considerable symmetrical offset between somatosensory and visual information, whereby specifying the symmetry of the hand potentially lowered participants' sense of being spatially present within the virtual body. Therefore, participants might have relied more on somatosensory cues specifying hand location, to provide estimates of reach that are consistent with the real right hand being used during the calibration.

Alternatively, the phrasing of instructions for the estimation task may have inadvertently encouraged participants to adopt the perspective of their real right hand. Since participants used their real right arm for the calibration, participants were asked to estimate their reach with "the right arm". A key question of these studies was whether estimates of one's

action capabilities could change based on the visual presentation of virtual hands. Therefore, it did not feel appropriate to lead participants to prioritise the properties of the virtual hand if that were not a strategy they would ordinarily use. Since the mirrored virtual hand visually becomes the left hand, this may have influenced participants' decisions to consider the symmetry of their real right hand in their reaching estimates. Regardless, the lack of interaction between virtual hand congruency and reaching direction suggests that there is a dissociation between participants' abilities to update the representation of hand size and the representation of the symmetry of the hand. That is, people can calibrate to dramatic changes in the metrics of their hands, but not to changes in their symmetry.

One key question of these experiments is whether participants embody the virtual hands or are simply using a strategy to estimate the affordances of a third party's hand. For instance, people are not only quite accurate at perceiving affordances for their own actions, but also at judging the action boundaries of others for a range of actions such as sitting, stepping over gaps, and visually-guided reaching (Mark, 2007; Stoffregen et al., 1999). If participants questioned whether to use their real hand or virtual hand in their estimates, they were told to use whichever felt most appropriate. These instructions could arguably provide ambiguity into whether participants estimated the action capabilities of an embodied hand or the capabilities of an external actor – in this case, the virtual hand. However, it should be reiterated that only two participants across all experiments asked for clarification on whether to consider their own hand or the virtual hand in their estimates. In addition, in previous research, judgements made about an external actor are made from an allocentric perspective, whilst judgements about oneself are rooted in an egocentric perspective (Creem-Regehr et al., 2013). Therefore, it seems unlikely that our findings reflect participants estimating the action capabilities of a third party. As an aside, we feel it important to mention that even in the event that our participants were anticipating the actions of an external party, the anticipation of one's own actions and those of others appear to rely on the same or similar motor simulation processes (Jeannerod, 2001).

In addition, the results of Experiment 3 and 4 support the argument that participants' estimates of

their action capabilities reflect embodied recalibration and not estimation of an external actor's abilities. In both experiments 3 and 4, estimates of reach to the right side were always significantly larger than to the left. If participants considered the virtual hand to be from an external actor when estimating their action capabilities, we would expect an effect of reaching direction to the left, i.e., the opposite direction. That is, if the virtual hand is presented incongruently to the real hand (i.e., to the left), it would make more sense that participants would consider the perspective of the virtual hand and adjust their estimates to favour reaching to the left. However, our findings show this not to be the case.

When a perceiver estimates their action capabilities they engage in the motor imagery of the execution of an intended action, a process called internal motor simulation (Witt & Proffitt, 2008). This process is future oriented, based on the motor routines of the actor, has access to the anticipated outcome of the action, and is therefore sensitive to the perceiver's physical limitations (Witt & Proffitt, 2008). In addition, this process recruits the motor system at the subliminal level (Jeannerod, 2001). As such, due the right-reaching direction bias that we found even in the contralateral condition, it is likely that action estimation in our current study employed motor simulation involving the right arm, rooting estimates to the right side of the body even when using a left virtual hand. While the use of internal motor simulation seems to be the most likely explanation for our findings, we cannot completely rule out that participants may have been using another strategy for their action estimates (this is impossible). Importantly, we find our hypotheses do predict the contradictory findings that participants adapt to extensions in arm length but not in reaching direction.

Since we employed action estimates as indirect measures of embodiment, alternative measures of embodiment could be used with this paradigm for further research. For example, Longo et al. (2008) generated an embodiment questionnaire that separately investigated the impact of the rubber hand illusion regarding the subcomponents of self-location, agency, and ownership. Using such a questionnaire may be the next step to further understanding the degree to which certain aspects of embodiment may be affected by mirroring the hands. Specifically, a more precise measure of sense of self-location

after the calibration phase could inform us on whether the felt position of the actual hand changed at all. This would provide more insight into why estimates of reach ipsilateral to the actual hand were always greater than central or contralateral estimates. Currently, we cannot say which subcomponents of sense of embodiment were satisfied for participants to calibrate to the size of the virtual hands. However, from participants' action estimates, we suggest that participants can calibrate to virtual hand sizes even when somatosensory feedback is incongruent to visual feedback. Further research should focus on using more direct measures of embodiment to tease apart why visual changes to hand size were considered in estimates but not changes to the visually specified spatial location of the hand.

Overall, this work extends on previous findings on the flexibility of the perceptual system to recalibrate to changes to the body. Previous research has demonstrated that people can embody dramatic changes to the body, such as an arm three times its normal length (Kilteni et al., 2012), as well as recalibrate to changes in hand size when virtual hands are presented congruently to a perceiver's real hands (Lin et al., 2020; Readman et al., 2021). However, this research is the first demonstrating the capacities and limitations of people's ability to recalibrate their action estimates in the case of visuo-somatosensory incongruency in mirror symmetry. Further research should investigate the impact of manipulating mirror symmetry for the anticipation of actions requiring fine motor control when recalibrating to changes in the body.

Notes

1. H1 was specified from the main effect of virtual hand size in Readman et al. (2021). Readman et al. found a main difference of 5 cm in maximum grasp estimates between virtual hand sizes that were 50% and 150% of normal hand size. As our manipulation used hand sizes that were 75% and 125% of normal hand size, we estimated the effect in our study to be roughly half of that from Readman et al. We assumed a half normal prior distribution with SD of 2.5.
2. H1 was specified from the obtained basic effect of virtual hand size in this study as we could not find previous research on congruency of visual feedback in grasp estimates to model H1. We assumed a normal prior with mode = 0 and SD = 2.3.
3. H1 was specified from half of the main effect of virtual hand size in Readman et al. to provide an approximate

scale of effect for the interaction between virtual hand congruency and virtual hand size. We assumed a normal prior with mode = 0 and SD = 2.5.

4. We could not find previous research exploring the role of visuo-proprioceptive congruency of virtual hands on maximum grasp estimates. Therefore, H1 was modelled off the basic effect of hand size found in Experiment 1. We assumed a normal prior with mode = 0 and SD = 2.3.
5. We could not find previous research exploring the role of visuo-proprioceptive incongruency when calibrating to different virtual hand sizes. Therefore, we used the basic effect of hand size found in this study to model H1. We assumed a normal prior with mode = 0 and SD = 3.8.
6. H1 was specified from the main effect of virtual hand size in Lin et al. (2020). Lin et al. found a main difference of 17cm in maximum reach estimates between virtual hand sizes that were 50% and 150% of normal hand size. As our manipulation used hand sizes that were 75% and 125% of normal hand size, we estimated the effect in our study to be roughly half of that from Lin et al. We assumed a half normal prior distribution with SD of 8.5.
7. H1 was specified from half of the main effect of virtual hand size in Lin et al. to provide an approximate scale of effect for the interaction between virtual hand congruency and virtual hand size. We assumed a normal prior with mode = 0 and SD = 8.5.
8. We could not find previous research exploring the role of visuo-proprioceptive congruency of virtual hands on maximum reach estimates. Therefore, H1 was modelled off the basic effect of hand size found in Experiment 3. We assumed a normal prior with mode = 0 and SD = 3.8.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data used in analysis are publicly available on the Open Science Framework: <https://osf.io/mksxj/>.

ORCID

Rachael L. Taylor  <http://orcid.org/0000-0003-1752-2801>

References

- Bryden, M. P. (1977). Measuring handedness with questionnaires. *Neuropsychologia*, 15(4-5), 617–624. [https://doi.org/10.1016/0028-3932\(77\)90067-7](https://doi.org/10.1016/0028-3932(77)90067-7)
- Campbell, J. I. D., & Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behavior Research Methods*, 44(4), 1255–1265. <https://doi.org/10.3758/s13428-012-0186-0>
- Carello, C., Groszofsky, A., Reichel, F. D., Solomon, H. Y., & Turvey, M. T. (1989). Visually perceiving what is reachable. *Ecological Psychology*, 1(1), 27–54. https://doi.org/10.1207/s15326969eco0101_3
- Creem-Regehr, S. H., Gagnon, K. T., Geuss, M. N., & Stefanucci, J. K. (2013). Relating spatial perspective taking to the perception of other's affordances: providing a foundation for predicting the future behavior of others. *Frontiers in Human Neuroscience*, 7. <https://doi.org/10.3389/fnhum.2013.00596>
- Dienes, Z. (2019). How do I know what my theory predicts? *Advances in Methods and Practices in Psychological Science*, 2(4), 364–377. <https://doi.org/10.1177/2515245919876960>
- Dienes, Z., & Mclatchie, N. (2018). Four reasons to prefer Bayesian analyses over significance testing. *Psychonomic Bulletin & Review*, 25(1), 207–218. <https://doi.org/10.3758/s13423-017-1266-z>
- Durgin, F. H., Baird, J. A., Greenburg, M., Russell, R., Shaughnessy, K., & Waymouth, S. (2009). Who is being deceived? The experimental demands of wearing a backpack. *Psychonomic Bulletin & Review*, 16(5), 964–969. <https://doi.org/10.3758/pbr.16.5.964>
- Fajen, B. (2005). Perceiving possibilities for action: On the necessity of calibration and perceptual learning for the visual guidance of action. *Perception*, 34(6), 717–740.
- Fajen, B., Riley, M., & Turvey, M. (2009). Information, affordances, and the control of action in sport. *International Journal of Sport Psychology*, 40(1), 79–107.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin.
- Heft, H. (1993). A Methodological note on overestimates of reaching distance: Distinguishing between perceptual and analytical judgments. *Ecological Psychology*, 5(3), 255–271. https://doi.org/10.1207/s15326969eco0503_3
- Ishak, S., Adolph, K., & Lin, G. (2008). Perceiving affordances for fitting through apertures. *Journal of Experimental Psychology: Human Perception and Performance*, 34(6), 1501–1514. <https://doi.org/10.1037/a0011393>
- Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *NeuroImage*, 14(1), S103–S109. <https://doi.org/10.1006/nimg.2001.0832>
- Kiltner, K., Groten, R., & Slater, M. (2012a). The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4), 373–387. https://doi.org/10.1162/pres_a_00124
- Lakens, D., Mclatchie, N., Isager, P. M., Scheel, A. M., & Dienes, Z. (2018). Improving inferences about null effects with Bayes factors and equivalence tests. *The Journals of Gerontology: Series B*, 75(1), 45–57. <https://doi.org/10.1093/geronb/gby065>
- Lin, L., & Linkenauger, S. (2021). Perceiving action boundaries for overhead reaching in a height-related situation. *Attention, Perception, and Psychophysics*, 83, 2331–2346. <https://doi.org/10.3758/s13414-021-02293-2>
- Lin, L., Mclatchie, N., & Linkenauger, S. (2020). The influence of perceptual-motor variability on the perception of action boundaries for reaching. *Journal of Experimental Psychology: Human Perception and Performance*, 46(5), 474–488. <https://doi.org/10.1037/xhp0000724>

- Linkenauger, S. A., Leyrer, M., Bülthoff, H. H., & Mohler, B. J. (2013). Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PLoS One*, 8(7), <https://doi.org/10.1371/journal.pone.0068594>
- Linkenauger, S. A., Witt, J. K., Stefanucci, J. K., Bakdash, J. Z., & Proffitt, D. R. (2009). The effects of handedness and reachability on perceived distance. *Journal of Experimental Psychology: Human Perception and Performance*, 35(6), 1649–1660. <https://doi.org/10.1037/a0016875>
- Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition*, 107(3), 978–998. <https://doi.org/10.1016/j.cognition.2007.12.004>
- Mark, L. S. (2007). Perceiving the Actions of Other People. *Ecological Psychology*, 19(2), 107–136. <https://doi.org/10.1080/10407410701331967>
- Oldfield, R. C. (1971). *Edinburgh handedness inventory*. PsycTESTS Dataset. <https://doi.org/10.1037/t23111-000>
- Petkova, V. I., Khoshnevis, M., & Ehrsson, H. H. (2011). The Perspective Matters! multisensory integration in ego-centric reference frames determines full-body ownership. *Frontiers in Psychology*, 2. <https://doi.org/10.3389/fpsyg.2011.00035>
- Pijpers, J. R., Oudejans, R. R., & Bakker, F. C. (2007). Changes in the perception of action possibilities while climbing to fatigue on a climbing wall. *Journal of Sports Sciences*, 25(1), 97–110. <https://doi.org/10.1080/02640410600630894>
- Pritchard, S. C., Zopf, R., Polito, V., Kaplan, D. M., & Williams, M. A. (2016). Non-hierarchical influence of visual form, touch, and position cues on embodiment, agency, and presence in virtual reality. *Frontiers in Psychology*, 7, <https://doi.org/10.3389/fpsyg.2016.01649>
- Readman, M., Cooper, D., & Linkenauger, S. (2021). It's in your hands: How variable perception affects grasping estimates in virtual reality. *Psychonomic Bulletin & Review*, 28(4), 1202–1210. <https://doi.org/10.3758/s13423-021-01916-x>
- Rigal, R. A. (1992). Which handedness: Preference or performance?. *Perceptual and Motor Skills*, 75(3), 851–866. <https://doi.org/10.2466/pms.1992.75.3.851>
- Sato, A., & Yasuda, A. (2005). Illusion of sense of self-agency: Discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership. *Cognition*, 94(3), 241–255. <https://doi.org/10.1016/j.cognition.2004.04.003>
- Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010). First person experience of body transfer in virtual reality. *PLoS One*, 5(5), <https://doi.org/10.1371/journal.pone.0010564>
- Stoffregen, T. A., Gorday, K. M., Sheng, Y.-Y., & Flynn, S. B. (1999). Perceiving affordances for another person's actions. *Journal of Experimental Psychology: Human Perception and Performance*, 25(1), 120–136. <https://doi.org/10.1037/0096-1523.25.1.120>
- Taylor, R. L., McLatchie, N., & Linkenauger, S. A. (2024). Can the left hand benefit from being right? The influence of body side on perceived grasping ability. *Attention Perception & Psychophysics*, 86, 2834–2843. <https://doi.org/10.3758/s13414-024-02983-7>
- Technologies, U. (2018, April 19). *Preparing assets for unity*. Unity. Retrieved January 26, 2023, from <https://docs.unity3d.com/2019.3/Documentation/Manual/BestPracticeMakingBelievableVisuals1.html>
- Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia*, 48(3), 703–712. <https://doi.org/10.1016/j.neuropsychologia.2009.09.034>
- Tsakiris, M., Longo, M. R., & Haggard, P. (2010). Having a body versus moving your body: Neural signatures of agency and body-ownership. *Neuropsychologia*, 48(9), 2740–2749. <https://doi.org/10.1016/j.neuropsychologia.2010.05.021>
- Turvey, M. T. (2004). Space (and its perception): The first and final frontier. *Ecological Psychology*, 16(1), 25–29. https://doi.org/10.1207/s15326969eco1601_3
- Wagman, J. B. (2012). Perception of maximum reaching height reflects impending changes in reaching ability and improvements transfer to unpracticed reaching tasks. *Experimental Brain Research*, 219(4), 467–476. <https://doi.org/10.1007/s00221-012-3104-x>
- Witt, J., Proffitt, D., & Epstein, W. (2005). Tool use affects perceived distance, but only when you intend to use it. *Journal of Experimental Psychology: Human Perception and Performance*, 31(5), 880–888. <https://doi.org/10.1037/0096-1523.31.5.880>
- Witt, J. K., & Proffitt, D. R. (2008). Action-specific influences on distance perception: A role for motor simulation. *Journal of Experimental Psychology: Human Perception and Performance*, 34(6), 1479–1492. <https://doi.org/10.1037/a0010781>

Appendices

Appendix A: Coordinates of Calibration Circles for the Grasping Calibration

Calibration circle 1 (x-axis)	Calibration circle 2 (x-axis)	Both calibration circles (z-axis)
.05	.22	.1
.05	.1	.1
.05	.12	.2
.05	.1	.2
.0625	.175	.1
.0625	.175	.2
.075	.25	.1
.075	.15	.2
.0875	.225	.1
.0875	.125	.2
.1	.28	.1
.1	.2	.2
.1	.28	.2
.125	.275	.1
.125	.275	.2
.15	.25	.1
.15	.25	.2
.175	.225	.1
.175	.225	.2
.2	.38	.1
.2	.3	.1
.2	.3	.1
.2	.3	.2
.2	.38	.2
.225	.375	.1
.225	.375	.2
.25	.35	.1
.25	.35	.2
.275	.325	.1
.275	.325	.2

Note: The y-axis was kept constant at .47 across all trials. The x-axis was flipped (i.e., negative) when reaching to the left side of space.

Appendix B: Coordinates of Calibration Circles for the Reaching Calibration

X-axis	Z-axis
.05	.1
.05	.1
.05	.2
.05	.2
.0625	.1
.0625	.2
.075	.1
.075	.2
.0875	.1
.0875	.2
.1	.1
.1	.2
.1	.2
.125	.1
.125	.2
.15	.1
.15	.2
.175	.1
.175	.2
.2	.1
.2	.1
.2	.1
.2	.2
.2	.2
.225	.1
.225	.2
.25	.1
.25	.2
.275	.1
.275	.2

Note: The y-axis was kept constant at .47 across all trials. The x-axis was flipped (i.e., negative) when reaching to the left side of space.