The visual and haptic contributions to hand and foot representation

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Abstract. Research has shown systematic distortions in hand representation. It has been argued that these distortions reflect the somatosensory homunculus, and it is through vision that the distortions are corrected. However, in those previous studies the haptic and visual tasks used were considerably different from one another. Therefore, in the current study, we devised a task that had identical requirements for each sensory condition. To be specific, the participants haptically and visually deciphered if various sized gloves and shoes were bigger than their hands and feet. We found that participants overestimated their hand size significantly more in the haptic condition, while the feet were estimated similarly between conditions. Moreover, hand distortions in the haptic condition were significantly larger than feet distortions. Lastly, we also found sex differences, as females overestimated both hand and feet size significantly more than males. Taken together, our results support the suggestion that distortions in haptic body representation tasks are more somatotopic.

Keywords: Body representation, vision, haptics, distortions, somatosensory.

1 Introduction

The internal representation of the size, shape, and state of the body are characteristics of body representation. While body representations are perceptual in nature, they also provide us with the necessary tools to interact with our environments. In fact, it has been argued that to metrically guide our actions, our brains must rely on a mental image of our body [1]. Intriguingly, these internal representations do not necessarily reflect anatomical body size. For example, it has long been established that the somatosensory homunculus (S1) is a distorted representation of the human body in the cortex [2]. In this representation, body parts with fewer tactile receptive fields are represented as smaller (e.g., back), and those with larger amounts are represented as big (e.g., hands, mouths).

The formation and updating of body representations occur through the available sensory modalities. For example, when typing on a keyboard, we may visually see the position of our hands, feel the keys with our fingertips, and hear each key being pressed. Therefore, a complete body representation is a by-product of multisensory integration. However, some research has proposed that vision is necessary to build an accurate representation of the body [3]. These studies have argued that the haptic representation of our bodies retains characteristics from the somatosensory homunculus, and it is through vision that these distortions are reduced [3]. In one such study, participants completed a localization and a template matching task [4]. For the localization task, the participants hand was hidden beneath a tabletop, and the participant had to estimate where various landmarks on the hand were located. This task has been argued to be primarily haptic in nature [5,6]. The template matching task, however, is visual. In this task, participants must identify from an array of hand photographs, which best matches their own physical dimensions. Surprisingly, participants showed highly distorted hand maps in the localization task but were accurate at identifying the dimension of their own hand in the template matching task. This dissociation may be due to differences in sensory modality required for the two tasks [7]. Alternatively, it is also possible that the considerably different demands between the localization and template matching tasks, resulted in different accuracies in hand representation.

The purpose of the present study was to compare the visual and haptic representation of the hands and feet, using tasks with identical requirements. We chose to focus on the hand because the distortions in body representations have been repeatedly reported in the hands [3-7], making it the ideal target for our study. In addition, as we know that the hand is overestimated in S1, if the homunculus is influencing haptic body representations, we expect the hands to be overestimated if measured haptically. With regards to the feet, there are not that many studies, and to our knowledge none of the foot representation studies have investigated how vision and haptics contribute to the representation of this body part. By investigating both hand and foot representation, we increase the novelty of the current study. In addition, the feet would make an ideal control for the hands because they are physically similar but have a smaller cortical representation. Therefore, if haptic representations retain characteristics of the somatosensory homunculus, participants should overestimate hand more than foot size in this condition. Furthermore, if vision reduces distortions driven by the somatosensory homunculus, participants' estimates should be less distorted in the visual condition.

2 Methods

32 participants (18 females) were told to visually (visual condition) and haptically (haptic condition) judge if the size of a glove or shoe, was larger than their hands or feet (see Fig. 1). Each target item was placed in front of the participant on a tabletop. Gloves ranged in length from 17cm- 23.5cm (XS-XXL), and shoes ranged 23.7cm-28.3cm (size 35-46). For a description of object size, see table 1. All participants were presented with the same six sizes of each clothing item. To keep the number of stimuli identical between the gloves and shoes, we either presented the participant with the odd or even shoes (this was counterbalanced across participants). So, each participant saw/felt 6 of the 12 pairs of shoes. There were separate blocks for the two clothing items, during

which the experimenter presented a different sized object on every trial in a randomized fashion. Within each block, the participant saw/felt each item six times. There was a total of 36 trials for each item, meaning every participant completed a total of 72 trials per condition (144 trials total). In the vision condition, the participant placed their hands on their lap below the tabletop (no vision of their hands) and had to visually judge if each clothing item was larger than their target body part (e.g., hand). If they believed the object was larger than their hand, they were told to respond “yes”, otherwise they were instructed to say “no” (two-alternative forced choice task). Participants were given a maximum of 10 seconds to explore each item. The instructions were identical in the haptic task, except participants were blindfolded, thus having to use haptics. Condition, block, and trial order were all randomized between participants.

Table 1: The sizes of each of the presented gloves or shoes. Each participant was presented with the same 6 pairs of gloves and shoes. For the shoes, we selected either the odd or even pairs (counterbalanced across participants), to keep the number of stimuli identical for both the hands and the feet.

Object	Size	CM
Gloves	XS	17
	S	18
	L	19
	XL	21
	XXL	21.5
	XXXL	23.5
Shoes	35	23.7
	36	24
	37	24.4
	38	25
	39	25.3
	40	25.8
	41	26.3
	42	27
	43	27.5
	44	28
	45	28.3
	46	29

Fig. 1. Participants in both conditions responded if the glove was bigger than their hand. We presented various sizes of gloves (XS-XXL) to the participants in a randomized fashion. In the vision condition, they could only see the object (not touch), and in the haptics condition the participant was blindfolded and therefore could only haptically explore the glove.

2.1 Analysis

We calculated perceived body part size by plotting the proportion of trials that the participant said "yes" (i.e., the item was bigger than their body part) against the size (cm) of each of the target items. This was then fit with cumulative Gaussian functions. The point at which the participant was 50% likely to say yes/no defines the point of subjective equality (PSE), see fig. 2 frame A. We took the PSE as the measure of perceived body size. We also calculated Just Noticeable Differences (JNDs) as a measure of precision. As with similar studies [8], we defined the JND as the standard deviation of the Gaussian fit. We calculated PSE biases by taking the PSE and subtracting the participants actual body part size. If there was an overestimation the PSE bias would be positive and vice versa if participants underestimated.

We conducted a series of pair-samples t-tests to determine if the PSE bias (cm) was distorted compared to the participants physical body part size. This analysis was similar to those from previous studies on hand representation [e.g., 6, 9]. These results are listed in table 2.

To determine if PSE distortions differed between body parts, conditions, and sexes we conducted a mixed-design repeated measures ANOVA. We used the normalized value of PSE bias, meaning all variables are expressed as percent of physical body size. In addition, to control for the differences in physical hand/foot size (i.e., extremely big or extremely small), we reran these analyses with participants divided into two groups: above mean hand/foot size, and below mean hand/foot size. To ensure that any difference between body part, condition, and sex was not due to the level of precision in these variables, we repeated the analyses with the JND's as the dependent variables. For all results, means and standard errors are reported. Multiple comparisons were corrected with Bonferroni.

Table 2. The results of the series of pair-samples *t*-tests: Female participants significantly overestimated hand and foot size in both conditions (*p*'s<.01). Male participants, however, were accurate at estimating hand/foot size in the visual condition, but significantly overestimated the body parts in the haptic condition.

Sex	Condition	Body part		Mean	SE	df	*t*	*p*
Females	Vision	Hands	PSE	19.41	.30	17	5.88	<.01
			Physical	17.56	.29			
		Feet	PSE	25.30	.30	17	7.85	<.01
			Physical	23.09	.25			
	Haptics	Hands	PSE	20.81	.36	17	8.86	<.01
			Physical	17.56	.29			
		Feet	PSE	25.83	.27	17	7.86	<.01
			Physical	23.09	.25			
Males	Vision	Hands	PSE	19.75	.36	13	1.64	.50
			Physical	19.08	.31			
		Feet	PSE	26.31	.35	13	2.54	.10
			Physical	25.34	.31			
	Haptics	Hands	PSE	21.04	.43	13	4.41	<.01
			Physical	19.08	.31			
		Feet	PSE	26.40	.34	13	3.21	.03
			Physical	25.34	.31			

3 Results

3.1 Differences between body part, condition, and sex

PSE: There was a main effect of body part [*f*(1,30)=6.0, *p*=.02, n^2=.04], in which participants overestimated their hand size significantly more than their feet. There was a main effect of condition [*f*(1, 30)=29.2, *p*<.01, n^2=.06], which was due to participants overestimating body part size more in the haptic condition compared to in the vision condition. There was also a body part x condition interaction [*f*(1, 30)=22.8, *p*<.01, n^2=.04] which better explains the results, see Fig 2 frames B and C. Specifically, participants overestimated hand size in the haptic condition (14.68±2.34) significantly more than in the vision condition (7.31±2.07, t(30)=-7.21, *p*<.01). The same was not true for the feet (vision= 7.32±1.33, haptics=8.14±1.47, *p*=1). Lastly, there was also a main effect of sex [*f*(1,30)=13.5, *p*<.02, n2=.18], where females (13.1±1.76) overestimated body parts significantly more than males (5.6±1.84). No other interactions were significant.

JNDs: There was a main effect of body part [*f*(1, 30)=8.9, *p*<.01, n^2=.06], where estimates of the hand (4.3±.57) were more variable compared to the feet (3.08±.4). There was also a main effect of condition [*f*(1, 30)=12.11, *p*<.01, n^2=.13], in which the participants estimates in the haptic condition (4.57±.55) were more variable than in the visual condition (2.8±.42). There were no other main effects or interactions.

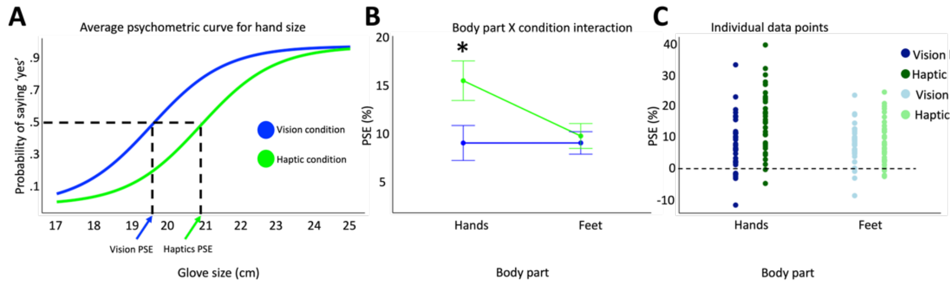

Fig. 2. Frame A: The average psychometric curve for participants during the hand estimation (i.e., gloves) in the vision (blue) and haptic (green) conditions. Expressed as the probability of saying "yes". Here, .5 is the value at which participants were equally likely to say "yes" or "no" (PSE). Participants (n=32) had larger PSEs for the haptic condition. Frame B: The interaction between body parts and condition. Participants overestimated (%) the size of their hands significantly more in the haptic compared to the vision condition. For the feet, estimates were the same between conditions. Frame C: The individual data points for hand and feet size estimates in the vision (blue) and haptic (green) conditions. The dashed black line indicates 0% PSE distortion, in other words an accurate estimate. There were larger PSE% in the haptic hand condition.

When we divided participants into two groups, above mean hand/foot size, and below mean hand/foot size, we found the exact same results. Furthermore, there were no differences between groups, indicating no influence of physical body size on the results.

4 Discussion

The current study finds that hand and foot representations are distorted, particularly when measured under haptic guidance. One proposal is that vision reduces somatotopic distortions in body representation tasks [3]. The results from this experiment support this claim, as we find overestimation of hand size in the haptic condition, while its visual representation was relatively accurate (particularly for males). In addition, there were no differences between the visual and haptic representations of the feet. All together, these results support that under haptics, the representation of the body retains some characteristics from the somatotopic representation. A recent study found that in a mental rotation task, when visual experience was degraded by 60%, the resulting body representation became more somatotopic [10]. Our results support that vision and haptics rely on different representations of the body, one being based on the distorted somatotopic representation, and the other on a relatively accurate spatial visual map [10].

The present study builds off previous reports which have found haptically distorted hand representations, while more accurate representations when visually driven [3.4,5]. Those previous works used different methodologies for the haptic and visual representations, making it difficult to directly compare the accuracy of the two modalities. In the current study, we used an ecologically valid method that is easy to implement. This allowed us to directly compare haptic and visual representations. Without using an identical paradigm for haptic and visual body representation tasks, it is impossible to disentangle the different demands of the tasks from the sensory influence. Our results confirm that the differences found in the localization and template matching tasks in previous work are driven by different sensory modalities. In addition, using this paradigm, future research can include special populations like those with no visual experience (e.g., blind) or younger children, who might find difficult to complete other body representation tasks due to the methodological demands (e.g., the localization task).

The reverse distortion hypothesis posits that areas with less sensory receptors should be visually perceived as larger, to counteract the haptic pattern of representation [11]. Our results do not support this hypothesis, as we found that visually, the hands and feet were perceived similarly. This suggests that there must be other compensatory mechanisms occurring that reduce the somatotopic distortions. One such proposal is that that accurate information about the tactile size and shape of the hand is elucidated through object interaction [12]. This speculation warrants future research.

The finding that females overestimated body part size more than the males replicates a study on hand representation [9]. In that study the authors proposed that an overestimation of hand size in healthy females may be a contributing factor as to why females are more likely to suffer from body representation disorders that are characterized by an overestimation of body size. The results from the current study suggest that both in the visual and haptic domains, females overestimate hand and foot size in comparison to males. To our knowledge this is the first study that has reported sex differences in foot representation. Future studies should investigate if these differences are exaggerated in body part areas that are more sensitive to weight gain/loss (e.g., stomach). Overall, our results support that body representation overestimation in females is not just a feature of clinical body representation disorders, but rather of the population as a whole.

The results from our analysis of the JNDs indicate that increased variability does not drive the significant interaction between body part and condition along with the sex differences found in the PSEs. We did find that participants were more precise overall in the visual condition, probably due to experience with visually selecting clothing items. In addition, judging the feet (overall) was less variable than judging hand size. It is possible that because our hands change size by spreading the fingers in various positions during the day, we have a fluctuating image of hand size. Future research needs to investigate this possibility.

As we previously mentioned we chose to investigate hand representation because it is the body part where haptic distortions have been most identified. In addition, in the cortex this representation is enlarged. We chose to compare the hands to the feet for two reasons 1) anatomically they are similar, but the feet have smaller cortical representation, and 2) few studies have investigated the accuracy of foot representations both visually and haptically. It would be possible and important to explore other areas of the body such as the forearm using a similar paradigm. The forearms have one of the smallest somatotopic representations [11], so we would expect that this would follow an opposite pattern of the hand, i.e., be haptically underestimated.

Cumulatively, the results from this study suggest that when vision is restricted the resulting representation is more somatotopic, retaining some characteristics from the homunculus. One way to further this finding is to test-long-term visually deprived individuals to investigate if the perception of their bodies more closely aligns to a somatosensory representation. Research is ongoing to investigate this possibility. In the future, researchers and engineers should consider the enlarged haptic representation of the hand when designing handheld haptic devices.

There are a few limitations with the present study. First, as participants had different sized hands and feet, but were presented with the same stimuli, each participant had a different number of gloves/shoes that were bigger or smaller than their own body part. To control for this, we first normalized all data when we compared between participants. In addition, we ran secondary analyses where we split our participants into those who had above mean hand/foot size, and those who had below mean hand/foot size.. We found identical results for both groups, i.e., the sex differences remained and there was a body part x condition interaction in which participants overestimated their hand size more in the haptic condition. In addition, there were no differences between the groups. Therefore, we do not believe that this limitation influenced the results. Future research could measure hand and foot size prior to the experiment and include only a couple smaller and larger options for each participant. One additional limitation is that in the visual condition we asked participants to place their hands on their lap, underneath the table, so that they could not use vision of their hands to guide their judgments. However, it is possible that in this position, the participants could have used tactile feedback to guide their estimates in the visual condition. This setup has been used in previous studies to evaluate haptic hand representation (for example see [13]). In addition, it is likely that within a few seconds of having their hands placed still on their lap sensory adaptation occurred. Sensory adaptation is the phenomenon that after a stimulus is presented for a given amount of time (usually <14 seconds [14]), neurons stop firing in response to said stimulus. Therefore, in the present study it is unlikely that participants relied on haptic feedback to base their estimates in the visual condition. However, it is possible that it played a small role. In the future, researchers could use numbing cream (e.g. EMLA cream) to fully investigate the role of haptics in visual body representations.

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