Title

The perception of real and illusory weight differences with grasping tools

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Abstract

Humans routinely use tools to extend their repertoire of skilled behavior, using their action capabilities to enhance reach, dexterity, or strength. Little is known, however, about how using a tool affects our experience of object properties, such as heaviness. To better understand how using a tool to manipulate our environment affects perception, participants (n=44) lifted and reported the felt heaviness of objects which varied independently in size and mass. In a blocked repeated-measures design, they lifted with their anatomical hands and with a grasping tool. Contrary to our hypotheses, which was based on earlier work with prosthetic hands (Buckingham et al., 2018), participants experienced real and illusory weight differences just as robustly with a grasping tool as they did with their anatomical hands. These findings add to the growing body of work examining perception tool use and suggest that grasping tools may be incorporated differently into the representation of the body in action than prosthetic hands.

Introduction

Our perceptual experience often diverges from our sensory inputs. One powerful example of this phenomenon in the somatosensory domain is the size-weight illusion (SWI), which describes the experience that large objects when lifted feel heavier than equally-weighted smaller object (Charpentier, 1891; for reviews see Buckingham, 2014, Dijkers, 2014). This effect is present in young children (Gordon, Forssberg, Johansson, & Westling, 1991), elderly adults (Buckingham, Reid, & Potter, 2017), and even some species of non-human animals (Jablonski et al., 2015). Although a range of different mechanisms have been put forward to explain this effect, arguably the most pervasive explanation is that the SWI highlights the contrastive nature of how prior expectations (in this case, of object weight) are integrated with sensory input from the hand and arm (Flanagan & Beltzner, 2000). Although the specific mechanisms underpinning this integration are not well understood, this top-down, cognitive, explanation does account for a range of weight illusion data which are not easily understood through low-level frameworks (Buckingham & Goodale, 2010; Buckingham & MacDonald, 2016; Dijkers, 2014; Flanagan, Bittner, & Johansson, 2008).

One area which remains surprisingly understudied in the context of perception is how our experiences of non-visible object properties are affected by tool use. Humans are unique in the scale and scope of their ability to use tools to manipulate our environment in a skilled fashion (Johnson-Frey, 2003). The direct use of a tool not only subserves actions which would not be possible with the anatomical limbs, but also affects our perception of reachable space (Witt, Proffitt, & Epstein, 2005), disrupting the representation of the hand itself (Bourgeois, Farnè, & Coello, 2014). And, although we routinely use our upper-limbs to experience the non-visible

properties of objects, very little is known about how these properties are experienced when using a tool. What little evidence does exist on the topic suggests that most somatosensory phenomena still manifest when using a tool. Klatzky and Lederman (1999) showed that individuals are able to discriminate between different levels of surface roughness when using a hand-held tool. Kilteni and Ehrsson (2017) similarly demonstrated that sensory attenuation appears to be intact when touching oneself with the end-effector of a tool. Recently, Miller et al (2018) demonstrated that, when wielding a hand-held tool, individuals are able to accurately localize external tactile stimuli, akin to how rodents experience their environment through their whiskers (Miller et al., 2018). Indeed, active tool has even been shown to have a direct impact on somatosensory processing during object interaction (Miller, Longo, & Saygin, 2019). In terms of weight perception, Buckingham et al. (2018) examined how the SWI manifests when using a prosthetic hand – a unique form of tool use. Of particular relevance was the second experiment (E2), where intact individuals who lifted the illusion-inducing stimuli with a myoelectric prosthetic simulator which they wore over their anatomical hand. When participants were lifting with the prosthetic simulator, they reported a significantly smaller SWI than control participants lifting with their anatomical hand, despite experiencing a physical 200-g weight difference just as robustly. This finding suggests that, even though wearing a prosthetic hand appears to leave your experience of object weight unchanged, illusory weight differences are markedly reduced – a finding which is difficult to reconcile with the typical top-down, cognitive, explanations of the SWI. However, it is unclear if this dissociation is related to tool use, or specific to prosthetic hands. Here, we examined weight perception in the context of the SWI when individuals lifted with a simple single-axis grasping tool. We hypothesized a pattern of data which would match that

seen with prosthetic hands: that the SWI will be markedly smaller when lifted with a grasping tool than an anatomical hand.

Methods

Participants

Forty-four undergraduate students (12 males) took part in a study where they lifted objects with their hands and a grasping tool in return for course credit. Participants, who had a mean age of 23.8 years (SD: 5.83), all gave informed consent prior to testing, and were naïve to the purpose of the study. The local research ethics board approved all procedures.

Materials

Participants lifted four black PLA boxes, which varied independently in volume and mass, were created with a MakerBot Replicator2 3d-printer. The large boxes were 22-cm × 15-cm (length and width) × 5-cm (height), whereas the small boxes were 15-cm × 10-cm (length and width) × 5-cm (height). The heavier variants of the large and small boxes weighed 508-g, whereas the lighter boxes weighed 262-g. All boxes were weighted around their center of mass with lead shot and high-density packing foam. Each box had an identical 3d-printed plastic handle, measuring 13 cm × 1.6 cm (length and width) × 7.5-cm (height), mounted on the top surface designed to afford lifting with the hand or the grasping tool. The grasping tool was an NRS Healthcare M59712 Ready Reacher (length: 38cm) grasping tool (Figure 1A), which participants operated with a fingertip trigger action (Figure 1B).

Figure 1. (A) The grasping tool, (B) the posture used to lift objects in the tool condition and (C) the lifting posture used in the hand condition.

Procedure

Participants lifted the boxes their hands and the grasping tool, in a blocked repeated-measures design. In the hand condition, participants were seated in a height-adjustable chair with their eyes closed. The experimenter placed the box on the table surface in front of the participant and asked them to open their eyes, at which point they lifted the box with the handle using the palm of the preferred hand. They were instructed to lift with their elbows off the table surface to ensure a whole-arm lift until their arm was at a comfortable height (typically ~15cm). At the apex of their lift, participants gave an unconstrained numerical value to represent how heavy the box felt, with larger numbers signaling heavier-feeling objects (i.e., an absolute magnitude estimation), before returning the object to the table surface (Figure 1C). In the tool condition, the procedure was similar to the hand condition apart from that the box was placed on average 78 cm away (for each participant the distance

corresponded to the arm length plus the grasping tool length, in order to obtain a comfortable posture) from the participant and they lifted with the end-effector of the tool (Figure 1B). Participants were instructed to lift to a comfortable height with their elbow off the table surface. Participants lifted each box six times for a total of 24 lifts in each condition in one of four randomized orders. The order in which participants undertook the hand and tool conditions was counterbalanced, and the total procedure took approximately 30 minutes to complete.

Data Reduction and Analyses

Participants' perceptual ratings of heaviness were turned into Z-scores in order to normalize across different ranges of rating scales. The average normalized heaviness ratings for each object were then analyzed in a 2 (size) $\times$ 2 (weight) $\times$ 2 (lifting effector) repeated measures ANOVA, with the size of each effect reported in terms of partial eta squared (η^2_p). All statistical analyses were conducted in JAMOV version 1.0.1.0. Data for this experiment can be found here: <https://osf.io/gyjza/>.

Results

Analysis of hand vs grasping tool

We observed a significant main effect of object weight ($F(1,43) = 4928.55, p < .001, \eta^2_p = 0.99$) and object size ($F(1,43) = 172.90, p < .001, \eta^2_p = 0.80$). There was, however, no main effect of lifting effector ($F(1,43) = 0.008, p = .93, \eta^2_p < .001$), and no interactions between lifting effector and object weight ($F(1,43) = 1.20, p = .28, \eta^2_p = 0.03$; Figure 2A) or between lifting effector and object size ($F(1,43) = 2.91, p = .095, \eta^2_p = 0.06$; Figure 2B). The three-way interaction was also not significant

($F(1,43) = 3.05$, $p=.088$, $\eta^2_p=0.07$). Thus, we found no evidence that lifting with a tool modulated the experience of real or illusory weight differences

Figure 2. How the experience of object weight when lifting with the dominant hand or with a grasping tool is affected by (A) mass differences and (B) volume differences. Error bars show 95% confidence intervals, and dots show individuals' data.

To better visualize these data at an individual level, and compared to previous studies of this nature (Buckingham et al., 2018), we quantified the magnitude of each participant's experience of the SWI and the real-weight difference. To quantify the SWI, we subtracted each participant's average rating given to the smallest objects from their average rating given to the large objects in each condition. To calculate the real weight difference, we subtracted the average ratings given to the lightest objects from the heaviest objects in each condition. Consistent with the analysis above, when we examined these effects with separate paired-sample t-tests, there was no difference in the magnitude of the real weight difference experienced with the hand or the tool ($t(43) = 1.10$, $p=.28$, $d = 0.17$; Figure 3A) and no difference between the magnitude of the SWI experienced with the hand and tool ($t(43) = 1.65$, $p=.11$, $d=0.25$; Figure 3B). This directly contrasts the data shown in Figure 6 of Buckingham et al. (2019).

Figure 3. The difference scores representing (A) the magnitude of the real weight difference and (B) the magnitude of the illusory weight difference (i.e., the SWI) reported by participants when lifting with their anatomical hand and with a grasping tool. Dots and connecting lines show individuals' data.

Discussion

In the current study, we examined the degree to which an individual's experience of how heavy an object feels is contingent upon the end-effector used to lift it. Stimuli which varied in mass (to facilitate the experience of a physical weight difference of ~200-g) and size (to facilitate the experience of the size-weight illusion) were lifted by participants with their anatomical hand and a pincer-like grasping tool (Figure 1). Overall, participants reported experiencing the real weight difference (i.e., that physically-heavier objects felt heavier on average than physically-lighter objects) and an illusory weight difference (i.e., that smaller objects felt heavier on average than larger objects). The magnitude of these real and illusory weight differences did not, however, appear to differ when lifting with a grasping tool or with an anatomical hand.

Although weight illusions have been examined under a variety of special populations (Buckingham, Bieńkiewicz, Rohrbach, & Hermsdörfer, 2015; Buckingham et al., 2017; Li, Randerath, Goldenberg, & Hermsdörfer, 2011), few studies have examined how changes in peripheral feedback stemming from different lifting effectors might influence perceptions of heaviness. The findings from the current work suggest that the perception of real or illusory weight differences are unaffected by changing the length of the moment arm, and having no tactile receptors at the point of contact with the object. This similarity between using an anatomical hand and a hand-held tool is consistent with recent findings showing that tactile perception is readily referred along the length of a solid hand-held tools (Miller et al., 2018).

The findings from the current study contrast those of Buckingham et al. (2018), who demonstrated that individuals who used their regular prosthetic hand/arm to lift SWI-inducing objects experienced a smaller weight illusion than controls, with no concomitant reduction in their experience of a difference in physical mass. This unexpected dissociation between real and illusory weight perception was then replicated in a larger group of intact participants lifting the same stimuli with a myoelectric prosthetic hand simulator. Although it is not feasible to statistically compare the real and illusory weight differences experienced with a prosthetic simulator to those experienced with a tool due to differences in mass and volume of the stimuli between these studies, we can offer some pertinent observations. First, E2 from Buckingham et al. (2018) demonstrated that individuals using a prosthetic hand simulator experienced a smaller SWI than individuals using their anatomical hand, with a p value $< .000001$ – a highly significant effect - using a between-group design. By contrast, the equivalent test in the current study yielded a p value of .11, despite having over double the number of participants and a repeated measures design, which typically yields higher power to detect an experimental effect than a between-group design. Although one must be cautious with the interpretation of null findings in isolation, it seems unlikely that any reduction in the magnitude of the SWI which stems from using a grasping tool is mechanistically similar to that which stems from a prosthetic hand.

Our findings also provide further evidence for the notion that a prosthetic hand might serve a different function than simple a replacement grasping tool (van den Heiligenberg et al., 2018). Nonetheless, the fact that a grasping tool yields more hand-like perception, at least for the SWI, than a prosthetic hand requires further

consideration. This surprising conclusion might be related to the apparent disruption in the representation of their body that users of a prosthetic hand experience in the context of a hand rotation paradigm (Nico, Daprati, Rigal, Parsons, & Sirigu, 2004). It is, at this point, worth emphasizing that in the current work, and E2 of Buckingham et al. (2018), participants had no training or practice in using their new effectors. Future work should examine the degree to which practice with a prosthetic hand yields more tool-like (and thus hand-like) perceptual experiences (van den Heiligenberg, Yeung, Brugger, Culham, & Makin, 2017).

In summary, the current work has shown that, in terms of how one experiences the heaviness of lifted objects, grasping tools do not affect perception in the same way as a prosthetic hand. Indeed, real and illusory weight differences experienced with a grasping tool appear no different from those experienced by an anatomical hand. These findings highlight the ability of the somatosensory system to process stimuli beyond the central nervous system.

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