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The size-weight illusion induced through human echolocation

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Certain blind individuals have learned to interpret the echoes of self-generated sounds to perceive the structure of objects in their environment. The current work sought to examine how far the influence of this unique form of visual substitution extends. In order to determine whether echolocation-induced representations of object size could influence weight perception, a small group of echolocation experts made tongue-clicks or finger-snaps toward cubes of varying sizes and weights before lifting them. The echolocators experienced a robust size-weight illusion, providing the first demonstration of a sensory substitution technique where the substituted sense influences the conscious perception of an intact sense.

Introduction

Echolocation, the process of using the echoes from self-generated acoustic signals in order to navigate, is seen in a number of non-primate species. This skill is one which can be learned - a number of blind humans have taught themselves to echolocate to replace vision (for a recent review see Kolarik, Cirstea, Pardhan, & Moore, 2014). Typically, these individuals use their echolocation ability to process the spatial layout of their environment in order to facilitate successful locomotion (Thaler, 2013). Echolocation is not, however, merely a functional tool to facilitate navigation. Recent work has demonstrated that human echolocators can decode echoes to identify a variety of object properties such as size, shape, and distance (Milne, Anello, Goodale, & Thaler, in press; Milne, Goodale, & Thaler, 2014; Teng, Puri, & Whitney, 2012). This unique self-generated form of sensory substitution appears to lead to cortical reorganization, with blind echolocation experts recruiting regions of primary visual cortex when making echo-based judgements about object identity (Thaler, Arnott, & Goodale, 2011). Furthermore, recent research has shown that echolocation appears to have vision-like properties such as size constancy – the integration of size and distance cues to maintain an accurate percept of object size in spite of variations in the echo equivalent of retinal size (i.e., stimulus strength and aperture, Milne et al., in press). The current work examines whether this unique form of sensory substitution can influence our perceptions of other senses, specifically in the context of heaviness perception and weight illusions.

It is well known that one's perception of object mass can be influenced by an object's appearance. For example, in the classic 'size-weight illusion' (SWI - Charpentier, 1891; Ross, 1969), small objects feel heavier than equally-weighted large objects. This powerful illusion does not require a haptic sense of object size, and can be induced entirely with visual cues (e.g., when objects are lifted with identically-sized handles or string-and-pulley systems - see Buckingham & Goodale, 2010b; Ellis & Lederman, 1993; Masin & Crestoni, 1988). Initial explanations for the SWI proposed that the effect stemmed from efferent/afferent mismatches (Davis & Roberts, 1976), although recent work examining fingertip force control when lifting illusion-inducing objects has rendered such sensorimotor explanations untenable (Flanagan & Beltzner, 2000, although see Dijker, 2014).

The current view is that the SWI is a consequence of a lifter's cognitive expectations of heaviness, based on their implicit understanding of the relationship between object volume and object mass (for review, see Buckingham, in press). Continuous experience of an object's volume is also not necessary to experience the SWI – a short visual preview of object size is sufficient to induce a robust weight illusion when lifting without visual feedback (Buckingham & Goodale, 2010a; Buckingham, Ranger, & Goodale, 2011). The goal of the current work was to determine whether the percept of object size extracted during human echolocation is sufficiently powerful and reliable to influence an echolocator's experience of object mass and induce a SWI. To this end, we examined perceptions of heaviness in a small group of human echolocators as they lifted sets of objects with different sizes, but identical weights.

Materials and methods

Three blind echolocators were recruited from Ontario, Canada to take part in an object lifting task. The blind echolocation group was made up of one 22 year old female and two males aged 49 and 57. All of these echolocators use echolocation techniques throughout their daily lives for navigation during locomotion. The female echolocator lost her sight in adolescence and uses a finger-snap as the sound source for creating echoes; the two males were blinded early in life and use a tongue-click. Their perception of real and illusory weight differences was compared to a group of three non-echolocating blind individuals (two males, one female, mean age = 36.3 years, st. dev = 7.8) and four sighted controls (one male, three females, mean age= 20.5 years, st. dev = 1.1).

Testing took place at the University of Western Ontario in a small (width: 275 cm, length: 300 cm, height: 244 cm) room with walls which were covered with 3.8 cm thick convoluted foam sheets, to dampen echoes. All blind participants wore a blindfold throughout the task, whereas the sighted participants were permitted visual feedback during the entire task except for the periods between trials when the objects were changed over. All participants gave informed consent, and all testing procedures were approved by the university ethics board.

Two sets of these cubes were created - one set was adjusted to weigh 1.5kg (light objects) and another set was adjusted to weigh 2kg (heavy objects). Each set was made up of three cubes – small (15 x 15 x 15 cm), medium (35 x 35 x 35 cm), and large (55 x 55 x 55 cm). The cubes, which were made from 50 mm thick white foam core board, had wooden panels fixed onto the inner panel of their top surfaces to increase their weight and facilitate the attachment of a hook (Figure 1). In order to minimise distracting echoes from the room, only one cube was presented to participants at a time, with the remaining five cubes hidden behind a felt curtain in the corner of the room.

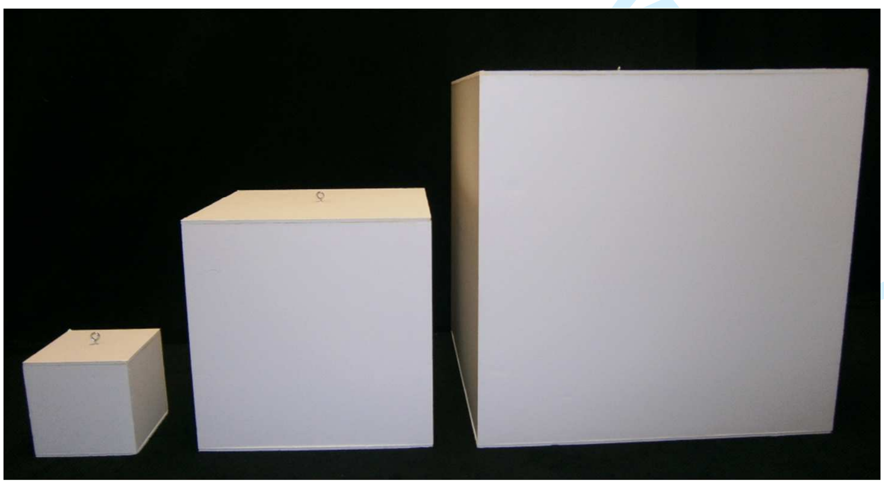

Figure 1. The light set of small, medium, and large cubes lifted by participants in this study. Participants also interacted with a heavier set of identical-looking cubes.

In order to determine if echolocation could induce a SWI, it was essential to ensure that participants received no cues to object size other than those derived through echoes. To this end, we developed a modified version of the task used by Masin and Crestoni (1988), where objects were lifted via a cord and pulley system. All the cubes had a small brass loop screwed into the centre of their top surface, through which a cord was threaded. This cord, which was 329 cm long, was threaded through a small pulley in the ceiling 94 cm directly above the cube, and attached to the wall of the room 87 cm from the ground. The cubes were placed in the centre of the room atop a free-standing pedestal at head height (see Milne et al., 2014; Thaler et al., 2011 for descriptions of similar experimental setups). The height of the pedestal was adjusted for each cube such that the top surface of each object was always 150 cm from the floor and the cable connected to the box via the pulley always maintained the same tension. Participants lifted the objects and made their weight judgements by moving to the edge of the room where the cable was fixed, placing their hands on the cable and pushing it downwards in order to lift the cube off of its pedestal. This procedure eliminated any differences between the cubes' haptically-perceived size and rotational torques, ensuring that subjects' impressions of object volume would stem entirely from echolocation- or vision-derived cues.

Prior to commencing the experimental trials, participants lifted the medium-sized cube of the heavy set of stimuli five times in a row, which they were told weighed 50 out of 100 and on which they were to base their subsequent perceptual judgements. On each trial, participants in all groups were allowed unlimited time and whatever method they wished (without touching the object) to try to determine the size of the cube. Typically, the individuals in the echolocation group made tongue-clicks (the two early-blind males) or finger-snaps (the late-blind female) toward the cube, identifying its edges for 5-15 seconds. The sighted controls looked briefly at the cubes, and the blind non-echolocators used tongue-clicks and hand claps. Once they had finished 'viewing' the cube, subjects retreated to the edge of the room where the wire was affixed to the wall and lifted the object with the cable and pulley system by pushing down on the wire. Once they had lifted the cube, participants gave a numerical rating of how heavy the object felt, relative to the medium-sized object of the heavy set of cubes. A video showing the trial procedure and experimental setup can be found in the supplementary materials. Participants lifted each of the six cubes six times apiece, for a total of 36 lifts. The procedure took between 30 and 60 minutes to complete, depending on the strategy adopted by the participant.

To examine how each group experienced object weight as a function of size, the ratings given to the small, medium, and large objects were collapsed across the 1.5kg and 2kg sets of objects. To combine the ratings given to the heavy and light objects, the ratings given on each trial were transformed into a proportion of the highest value given by each subject in each set. ANOVA and post hoc analyses were run with IBM SPSS Statistics (Version 21), and effect size calculations were performed in Microsoft Excel with Lakens' (2013) open science spreadsheet.

Results

The combined normalized ratings of heaviness (Figure 2) were first examined in a mixed design 3 (object size) × 3 (group) ANOVA. This omnibus analysis revealed a significant main effect of object size ($F(2,14) = 18.39$, $p<.001$, $\eta_p^2 = 0.72$) as well as a significant interaction between object size and group ($F(4,14) = 9.57$, $p<.005$, $\eta_p^2 = 0.73$).

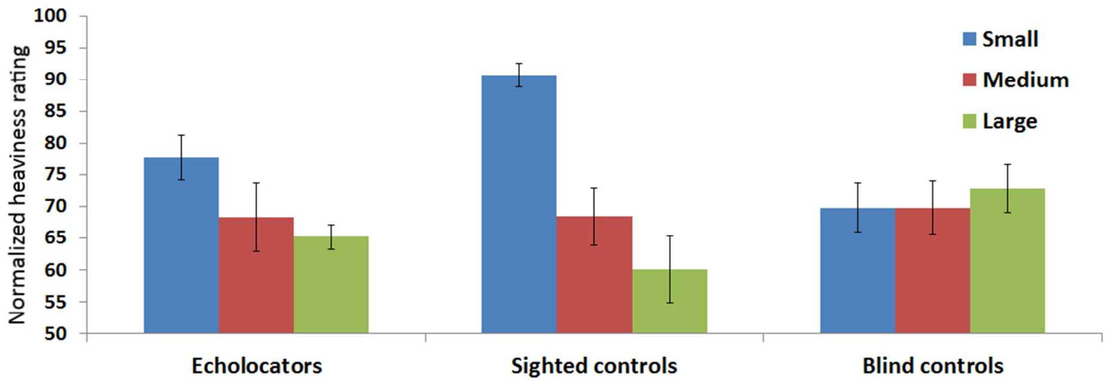

Figure 2. The average normalized ratings of heaviness (averaged across object weight) given by each group for the small, medium, and large cubes. Error bars indicate standard error of the mean.

In order to examine the presence or absence of a perceptual illusion, the magnitude of the SWI was calculated for each individual by subtracting the rating they gave to the large cube from the rating they gave to the small cube (Figure 3A). This value, representing the magnitude of the illusory weight difference, was then compared to zero with one-tailed, one-sample t-tests. Both the echolocation ($t(2)=3.4$, $p<.05$) and the sighted ($t(3) = 8.8$, $p<.005$) groups showed a significant SWI, whereas the non-echolocating blind control group showed no such effect ($t(2) = .66$, $p=.57$). In order to explicitly examine how the SWI varied across the groups, we performed a one way ANOVA, followed by LSD post hoc comparisons. The ANOVA indicated that significant differences existed between the groups ($F(2,7) = 19.45$, $p<.005$, $\eta_p^2 = 0.85$). Post hoc analyses confirmed the sighted group showed a larger illusion than the blind control group (mean difference = 33.6, $p<.001$) and the echolocation group (mean difference = 18, <.05). Crucially, however, the echolocation group also showed a larger illusion than the blind control group (mean difference = 15.6, $p<.05$). By contrast, a one way ANOVA comparing the average difference in raw ratings, collapsed across size, given to the heavy (2kg) and light (1.5kg) sets of cubes found no indication that the groups differed in how they perceived real differences in object mass ($F(2,7) = 4.09$, $p=.07$, $\eta_p^2 = 0.54$, Figure 3B).

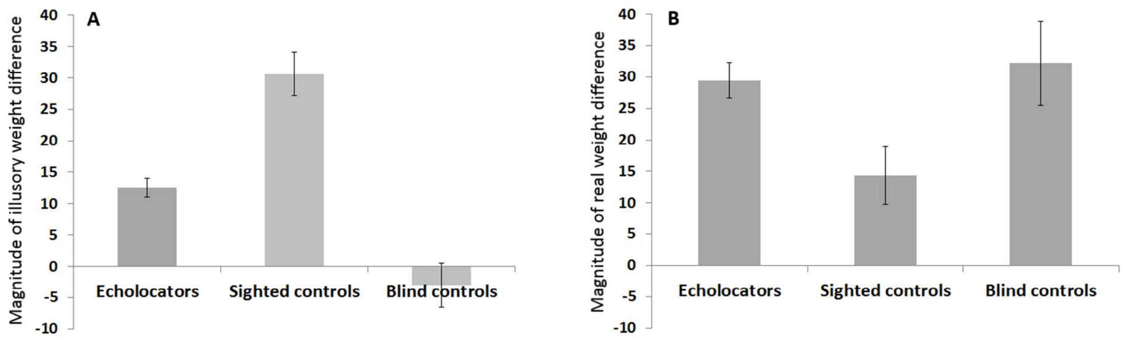

Figure 3. (A) The average rating given to the large objects subtracted from the average rating given to the small objects (collapsed across both object weights) and (B) the average rating given to the light set of objects subtracted from the average rating given to the heavy set of objects (collapsed across all three object sizes). Error bars indicate standard error of the mean.

Discussion

The current work investigated the extent of the perceptual capabilities of human echolocators in the context of the size-weight illusion (SWI). A small sample of blind individuals who regularly use echolocation for navigation made self-generated tongue-clicks or finger-snaps toward a variety of cubes which were balanced at head height atop a free-standing pedestal. Once they had echolocated toward a cube, they reported how heavy it felt after lifting it off the pedestal with a rope and pulley system. The echolocators' perceptions of object weight was compared to a small group of sighted individuals, who lifted the objects with full vision, as well as a small group of non-echolocating blind individuals who received no cues to object size. When judging how heavy the differently-sized cubes felt, the non-echolocating blind individuals reported (unsurprisingly) that the identically-weighted objects felt as if they weighed the same amount as one another. By contrast, the echolocating blind individuals experienced a SWI, reporting that the smallest cubes felt significantly heavier than the largest cubes. Interestingly, the illusion experienced by the echolocators was significantly smaller than that experienced by the sighted controls, who experienced a more robust SWI (presumably due to the higher resolution of vision as compared to echolocation). By contrast, no statistical differences were observed between how each of the groups experienced a 500g weight variation. The numerical trend for the sighted participants to report that weight difference as smaller than the non-sighted groups is consistent with earlier reports that blind individuals show a greater sensitivity for weight discrimination than sighted counterparts (Grouios, Alevraidou, & Koidou, 2001)

It is well-established that blind individuals can experience a robust SWI when given haptic feedback of an object's volume (Ellis & Lederman, 1993). However, no experiment to date has reported blind individuals experiencing this effect through any other modality. The current findings give new insights into the perceptual abilities of blind humans who have taught themselves to echolocate. It has been well-reported that blind echolocators have a wide repertoire of unique perceptual skills which allows them to successfully interact with the world around them (Kolarik et al., 2014). This technique does not merely solve the same spatial mapping problems that visual feedback normally deals with, but shows a range of vision-like properties (Milne et al., in press; Thaler et al., 2011).

Given that other substitutive techniques have been shown to have an automatic influence on sensorimotor control (e.g., Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007), it is likely that echolocation experts would also tend to use this unique perceptual ability to apply initial grip and load forces to objects based upon their size and material properties (Buckingham, Cant, & Goodale, 2009; Flanagan & Beltzner, 2000; Gordon, Forssberg, Johansson, & Westling, 1991). However, the current work has shown that the echolocation-derived representations of object size influence the conscious perception of the ostensibly unrelated variable of object weight. This is, to our knowledge, the first example of a substituted sense influencing the conscious perception of an intact sense (touch), speaking to this technique's efficacy as a full (i.e., not merely functional) form of sensory substitution.

To conclude, our findings highlight the degree of confidence that echolocators place in their echo-induced judgements of object properties, indicating that human echolocation has the potential to replace not only the functional aspects of vision, but also individuals' conscious perception of visual aspects of the world.

Author contributions

G. Buckingham, J. Milne, and M. Goodale developed the study concept. Testing and data collection were undertaken by C. Byrne, and supervised by J. Milne and M. Goodale. Analysis and interpretation was undertaken by G. Buckingham, who also drafted the manuscript. All authors approved the final version of the manuscript for submission.

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Figure 1. The light set of small, medium, and large cubes lifted by participants in this study. Participants also interacted with a heavier set of identical-looking cubes.
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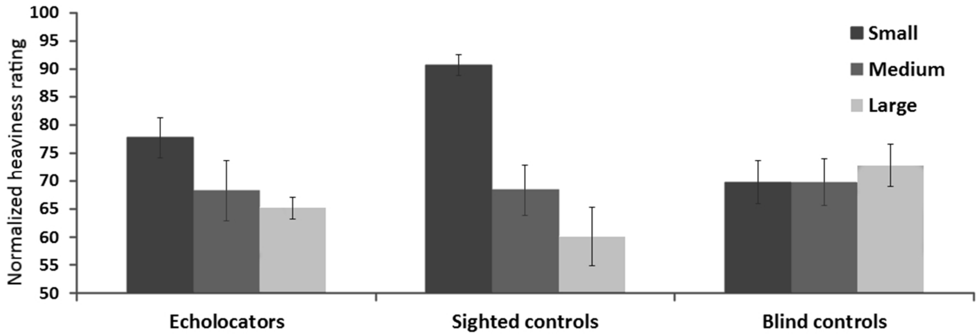

Figure 2. The average normalized ratings of heaviness (averaged across object weight) given by each group for the small, medium, and large cubes. Error bars indicate standard error of the mean.
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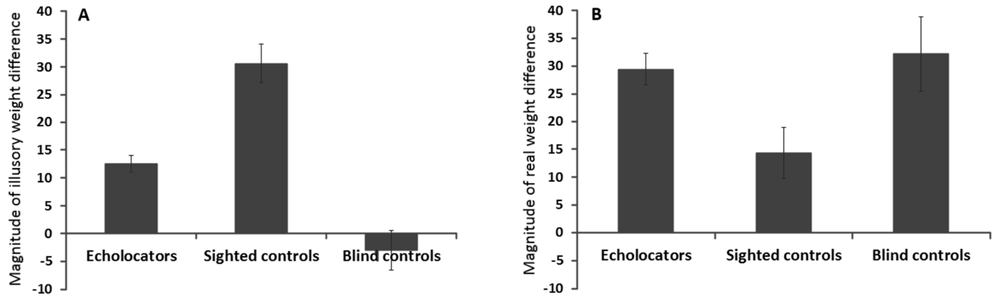

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