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11 **A blind human expert echolocator shows size constancy for objects perceived by echoes**  
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**Abstract**

Some blind humans make clicking noises with their mouth and use the reflected echoes to perceive objects and surfaces. This technique can operate as a crude substitute for vision, allowing human echolocators to perceive silent, distal objects. Here we tested if echolocation would, like vision, show size constancy. To investigate this, we asked a blind expert echocator to echolocate objects of different physical sizes presented at different distances. The expert echocator consistently identified the true physical size of the objects independent of distance. In contrast, blind and blindfolded sighted controls did not show size constancy, even when encouraged to use mouth-clicks, claps, or other signals. These findings suggest that size constancy is not a purely visual phenomenon, but that it can operate via an auditory-based substitute for vision, such as human echolocation.

**Keywords:** blindness, human echolocation, size constancy, vision, multisensory

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## Introduction

A number of studies have confirmed the ability of blind human echolocators to extract information from echoes about object features such as shape, location, motion, and material (for reviews see Stoffregen & Pittenger, 1995; Kolarik, Cirstea, Pardhan, & Moore, 2014). Furthermore, echoes are informative for determining the size and distance of objects (Rice & Feinstein, 1965; Rice, Feinstein, & Schusterman, 1965; Teng & Whitney, 2011). Although it has been confirmed that expert echolocators can extract size and distance information from echoes in isolation, there has been no direct investigation on the echolocation of these factors in combination.

Integrating size and distance cues is critical for accurate perception of object size. For example, the visual system must overcome the fact that altering the distance of an object from the eyes results in changes to the retinal image size. Despite the differences in retinal image size, however, people's percept reflects the true physical size of the object. This perceptual phenomenon has been termed size constancy (Holway & Boring, 1941).

In echolocation a similar situation may arise. Specifically, the size of the acoustic angle of a sound-reflecting surface decreases as its distance increases. Importantly, changes in the size of a sound-reflecting surface (regardless of changes in distance) lead to changes in both the level and spectrum of the reflected sound (e.g. Heinrich, Warmbold, Hoffmann, Firzlaff, & Wiegrebe, 2011). At the same time, the distance of a sound-reflecting surface is reliably coded via pulse-echo delays. Hence, the acoustic information present in echolocation is sufficient for accurate computation of the physical size of a sound-reflecting surface. Given that the human brain shows size constancy in at least one modality (i.e. vision), and given that echolocation in principle provides the information necessary to achieve size constancy, we were interested if size constancy is supported for objects perceived via reflected echoes.

To test this, we recruited a blind human expert echolocator (EE) who lost his sight in early infancy due to idiopathic optic nerve atrophy and has no residual vision. EE developed echolocation

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3 techniques on his own during early childhood and, now in his late fifties, he continues to use  
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5 echolocation on a daily basis.  
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## 7 8 **Methods**

### 9 10 ***Participants***

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12 As mentioned above, we recruited one blind echolocating participant (male, aged 57). Hearing tests  
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14 revealed that EE's pure tone thresholds were within the normal range up to 4 kHz, but he has mild  
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16 hearing loss beyond 4 kHz, consistent with his age. As control groups, we recruited 10 blind (five female;  
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18 mean age = 35.9) and 10 sighted (five female; mean age = 40.4) participants. Control participants  
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20 reported normal hearing and no prior experience with echolocation. All participants were blindfolded  
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22 and took part in three experiments at The University of Western Ontario (London, Canada). Testing took  
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24 place in an echo-dampened room (2.75 m x 3 m, walls covered in 3.8-cm convoluted foam sheets).  
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26 Testing procedures were approved by the University ethics board and participants provided informed  
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28 consent.  
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### 33 ***Stimuli and General Procedure***

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35 Objects used in the experiments included three physical sizes of circles and horizontally-oriented  
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37 rectangles which could be placed at one of three distances (Figure 1). Although shape is not a relevant  
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39 cue for size constancy, we included the different shapes to increase the attentional demands of the  
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41 tasks. The objects and distances used depended on the particular experiment being run (see below and  
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43 Figure 1). Before beginning the experiments, all participants were allowed to haptically explore the  
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45 objects.  
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49 Objects were positioned in isolation directly ahead of the participant, with the center at ear-  
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51 level. Between trials, participants wore ear-bud headphones playing white noise to mask any noise cues  
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53 related to changing the stimulus display. Once the trial began, participants were given a maximum of 20  
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55 seconds to scan the object using the echolocation technique of their choice.  
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## Results

### ***General Details***

Our initial analyses were aimed at determining if there were any differences in performance between blind and sighted control groups for each of the three experiments. We ran mixed analysis of variance tests, with the experimental manipulations as the repeated variable, and 'group' as the between subjects variable for each experiment. The analyses revealed no significant effect of 'group' for any of the three experiments (Figure 2). Therefore, for all subsequent analyses we combined blind and sighted control groups into a single control group.

[Figure2 here]

To compare EE's performance to the combined control group, we ran two types of analyses. First, we used t-tests and effect size measures modified to compare a single case to a control group (Crawford, Garthwaite, & Porter, 2010; Crawford & Howell, 1998). The analyses were conducted on overall percentage correct performance in each experiment. We supplemented these analyses by comparing both EE's and the control group's performance to chance for each experiment using binomial tests and traditional t-tests, respectively. Instead of overall performance, these analyses included the separate conditions within each experiment. An initial analysis had revealed no differences between circular and rectangular shapes for Experiments 2 and 3. Thus, for subsequent analyses, performance was collapsed across shape.

[Figure3, Table1 here]

### ***Experiment 1: Distance***

The modified t-test revealed that EE performed significantly better than the control group on the distance discrimination task (Figure 3A and Table 1). Furthermore, EE performed well above chance level (33%) at each of the distances (near:  $p = 0.004$ ; middle:  $p = 0.004$ ; far:  $p = 0.018$ ), while the control

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3 group's performance was statistically indistinguishable from chance at each distance (near:  $t(19) =$   
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5 2.043,  $p = 0.055$ ; middle:  $t(19) = 1.347$ ,  $p = 0.194$ ; far:  $t(19) = 0.418$ ,  $p = 0.681$ ) (Figure 4A).  
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### 8 ***Experiment 2: Acoustic Size***

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10 For the perception of acoustic size, the modified t-test analysis revealed that EE performed significantly  
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12 better than the control group (Figure 3A and Table 1). EE also performed well above chance level  
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14 (16.67%) for each of the sizes (small:  $p = 0.008$ ; medium:  $p = 0.000$ ; large:  $p = 0.000$ ) (Figure 4A). The  
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16 control group's performance did not differ from chance for any of the object sizes (small:  $t(19) = 0.117$ ,  $p$   
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18  $= 0.908$ ; medium:  $t(19) = 0.972$ ,  $p = 0.343$ ; large:  $t(19) = 1.071$ ,  $p = 0.297$ ).  
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22 [Figure4 here]  
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### 24 ***Experiment 3: Size Constancy***

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26 As mentioned above, Experiment 3 was aimed at determining if an expert echolocator can integrate  
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28 acoustic size and distance information to determine the true physical size of objects. The modified t-test  
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30 analysis revealed that EE performed well above the level of the control group (Figure 3A and Table 1). In  
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32 fact, EE's best performance across all three experiments was in Experiment 3. Comparisons against  
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34 chance revealed that EE performed significantly better than chance level (25%) in three of the  
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36 conditions (small-near:  $p = 0.000$ ; large-near:  $p = 0.000$ ; large-far:  $p = 0.000$ ) but his performance failed  
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38 to reach significance for the 'small-far' condition ( $p = 0.078$ ). The distribution of error responses,  
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40 however, shows that EE's poorer performance in this condition was largely driven by errors in the 'small  
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42 rectangle-far' condition, because he tended to confuse the small rectangle with the small circle (Figure  
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44 4B). Importantly, therefore, almost all of EE's errors in the 'small-far' conditions were errors in shape  
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46 and not size, thus highlighting the fact that EE did in fact perceive the correct size of the objects. The  
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48 control group did not show above chance performance for any of the conditions (small-near:  $t(19) =$   
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50  $0.667$ ,  $p = 0.513$ ; small-far:  $t(19) = 0.17$ ,  $p = 0.867$ ; large-near:  $t(19) = 1.082$ ,  $p = 0.293$ ; large-far:  $t(19) =$   
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52  $1.255$ ,  $p = 0.225$ ).  
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3 Overall, the results of Experiments 1 and 2 agree with previous reports in the literature on size  
4 and distance perception in human echolocation (Rice & Feinstein, 1965; Rice et al., 1965). Most  
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7 importantly, Experiment 3 goes beyond this and shows that a blind echolocator can determine the true  
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10 physical size of an object independent of its distance. These results suggest that size constancy operates  
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13 for object size perception via echolocation.

### 14 Discussion

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17 The aim of the current experiment was to determine if size constancy – a perceptual phenomenon  
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20 linked to vision – also operates for echolocation. We showed for the first time that a blind expert  
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23 echolocator could consistently and reliably indicate the true physical size of objects independent of the  
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26 distance at which they were located. Blind non-echolocators and blindfolded sighted controls did not  
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29 show size constancy, suggesting that echolocation expertise was responsible for EE's performance,  
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31 rather than neuroplasticity due to blindness or ambient sounds.

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33 These findings support the use of echolocation as a viable resource for the blind, because the  
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36 ability to accurately determine the physical size of objects has immediate benefits for navigation. In  
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39 addition, the current findings broaden our basic understanding of the technique. For example, previous  
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42 studies using functional magnetic resonance imaging have implicated 'visual' brain areas for  
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45 echolocation (Arnott, Thaler, Milne, Kish, & Goodale, 2013; Thaler, Arnott, & Goodale, 2011; Thaler,  
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48 Milne, Arnott, Kish, & Goodale, 2013). The current findings suggest further parallels between vision and  
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51 echolocation, in that both modalities show size constancy. This suggests that similarities in brain activity  
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54 may also signify similarities in terms of behavioral principles, and future research should address these  
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57 possibilities.

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60 As laid out in the introduction, object size information can be inferred from the overall intensity  
of the echo as well as spectral changes caused by the 'spread' of angles from which the echoes arrive at  
the ears (aperture). The contribution of each of the cues may depend on the size of the object, with



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3 evidence suggesting that overall intensity cues are best suited for smaller objects whereas aperture cues  
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5 are most relevant for larger objects, at least in the case of echolocating bats (Heinrich et al., 2011).  
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7 Furthermore, there are binaural cues to size (Holderied & von Helversen, 2006). In terms of object  
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9 distance, the cue that indicates distance most reliably is the time delay between the outgoing signal and  
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11 the returning echo, and this cue is independent from other aspects of the sound. Thus, echolocation has  
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13 information sufficient for size constancy.  
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17         Although the current study is the first to investigate size constancy in human echolocation,  
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19 Heinrich and Wiegrebe (2013) tackled the question in the context of bat echolocation. Interestingly,  
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21 their results suggested that bats do not show size constancy, at least for the perception of virtual  
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23 objects. This is curious, because echolocating bats do encode both object aperture (i.e. acoustic size)  
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25 (Heinrich et al., 2011) and pulse-echo delays (i.e. distance) (Wenstrup & Portfors, 2011). Therefore, it is  
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27 surprising that bats would not show size constancy considering the clear neural representation of both  
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29 size and distance. Contrary to these unresolved findings in bats, our results clearly show that a human  
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31 echolocator has stable, absolute size perception. Considering that human echolocators may lack the  
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33 sophisticated neural mechanisms that have evolved in bats, our findings suggest that further  
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35 investigation is warranted into potential size constancy mechanisms in bats and other echolocating  
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*Table 1.* Results of the modified t-test analysis comparing EE's overall performance to the overall performance of the combined control group in each of the three experiments. The modified t-test is a version of the classic t-test used to compare the performance of a single case against a control group. Means (control group only) and case scores are percentage values (percent correct performance). Significance values (p) are one-tailed.

Experiment	EE's Score	Control Sample			Significance	
		n	Mean	SD	t	p
1. Distance	72.22	20	39.31	17.37	1.85	0.039
2. Acoustic Size	61.11	20	18.61	8.55	3.671	0.000
3. Size Constancy	82.5	20	27.31	8.11	6.638	0.000

### Figure Captions

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Figure 1. Stimuli and procedure for Distance, Acoustic Size, and Size Constancy experiments. A) The possible objects to be used in each of the experiments included three physical sizes of circles and rectangles (the medium-sized objects were double the size of the smallest objects, and the large objects were triple the size of the smallest objects). The objects were created from 0.5-cm thick foam board and covered with aluminum foil and were positioned on a 0.6-cm diameter pole. B) The basic layout is shown for each individual experiment. The top panel shows the distance(s) at which the objects could be placed (specific objects used in each experiment are shown in the bottom panel). Note that the spacing of the distances is proportional to the sizes of the objects (i.e. the middle position is twice the distance of the near position, and the far position is three times the distance of the near position). For all tasks, participants stood and were permitted to move side-to-side as well as up and down to allow them to scan the object (for a maximum of 20 seconds) but were not permitted to move toward or away from the object. Note that for Experiment 3 only the near and far positions and small and large objects were used. This allowed for a direct test of size constancy.

Figure 2. Average percent correct performance (+/- SEM) of the blind non-echolocating and blindfolded sighted control groups on the Distance, Acoustic Size, and Size Constancy experiments. Mixed analysis of variance tests for each of the three experiments revealed no significant main effects or interactions for any of the three experiments (similarities in performance are easily seen in the figure). Therefore, for all subsequent analyses the control groups were combined to form a single control group.

Figure 3. Results of the individual case analyses for the Distance, Acoustic Size, and Size Constancy experiments. Panel A shows the results of the modified t-tests comparing the expert echolocator's overall performance (as percent correct) to the combined control group's performance. Significant differences are indicated by asterisks. The Bayesian effect sizes (with error bars showing 95% confidence intervals (CIs)) of each individual t-test are shown in Panel B. The effect size was calculated using adapted z scores (Crawford et al., 2010). The 'abnormality' of the case's scores are presented in Panel C which shows the percentage of the control population (with 95% CIs) that would obtain a lower score than the case.

Figure 4. Results from tests against chance for the expert echolocator (binomial tests) and combined control group (t-tests). Participants' performance (shown as percent correct) was collapsed across shape for Experiments 2 and 3. Chance performance for each of the tasks is indicated by the dashed lines and significant results are indicated by asterisks. The distribution of EE's responses (B) is shown for the size constancy task. Although EE performed statistically at chance for the 'small-far' condition, the error distributions show that this decrease in performance was driven by errors in shape judgement and not size judgement, thus supporting size constancy in these cases.

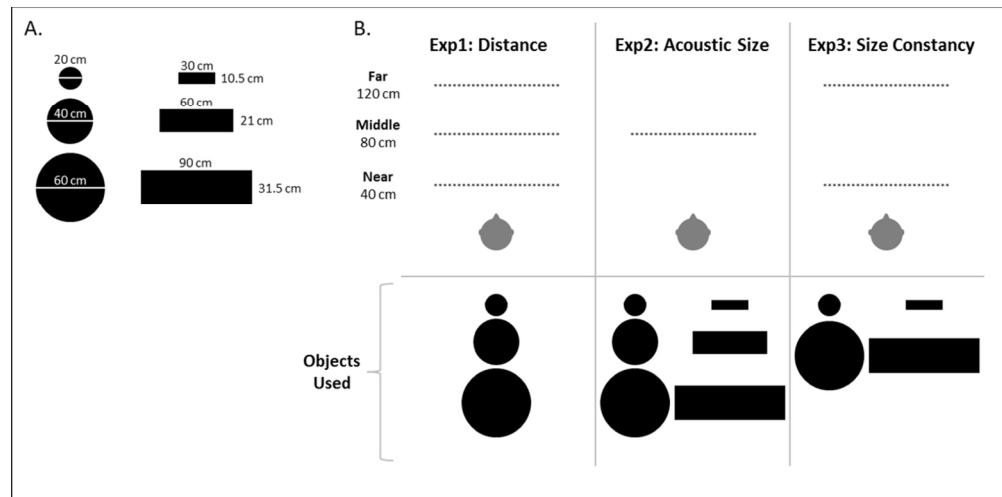


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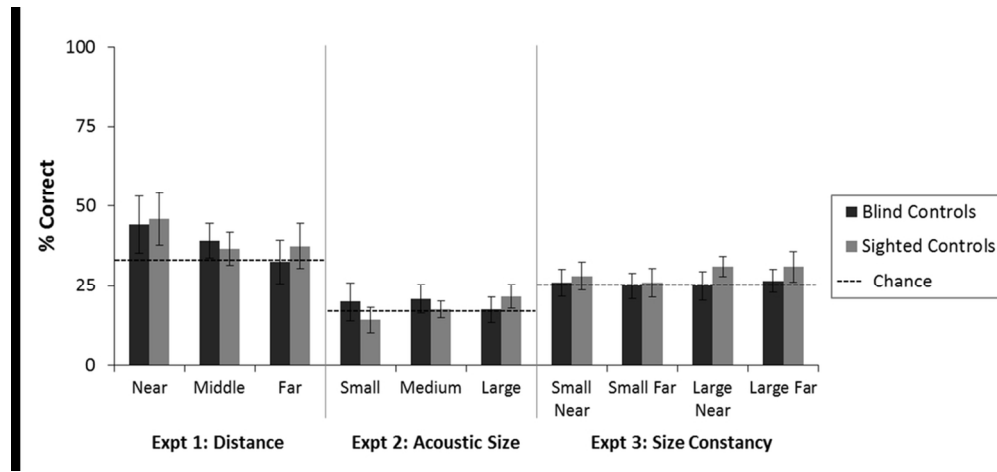


Figure 2. Average percent correct performance (+/- SEM) of the blind non-echolocating and blindfolded sighted control groups on the Distance, Acoustic Size, and Size Constancy experiments. Mixed ANOVAS for each of the three experiments revealed no significant main effects or interactions for any of the three experiments (similarities in performance are easily seen in the figure). Therefore, for all subsequent analyses the control groups were combined to form a single control group.  
97x45mm (300 x 300 DPI)

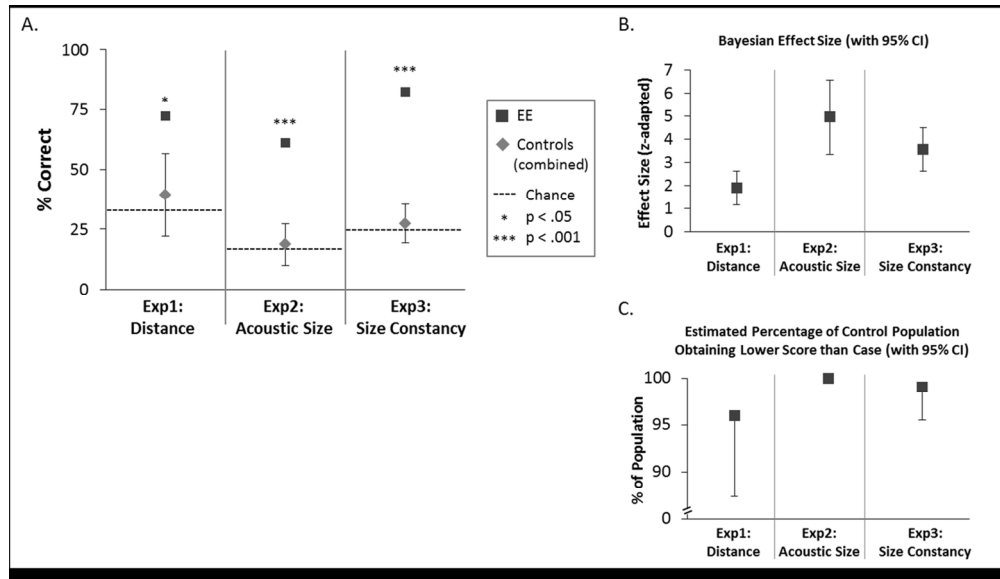


Figure 3. Results of the individual case analyses for the Distance, Acoustic Size, and Size Constancy experiments. Panel A shows the results of the modified t-tests comparing the expert echolocator’s overall performance (as percent correct) to the combined control group’s performance. Significant differences are indicated by asterisks. The Bayesian effect sizes (with error bars showing 95% confidence intervals (CIs)) of each individual t-test are shown in Panel B. The effect size was calculated using adapted z scores (Crawford et al., 2010). The ‘abnormality’ of the case’s scores are presented in Panel C which shows the percentage of the control population (with 95% CIs) that would obtain a lower score than the case.

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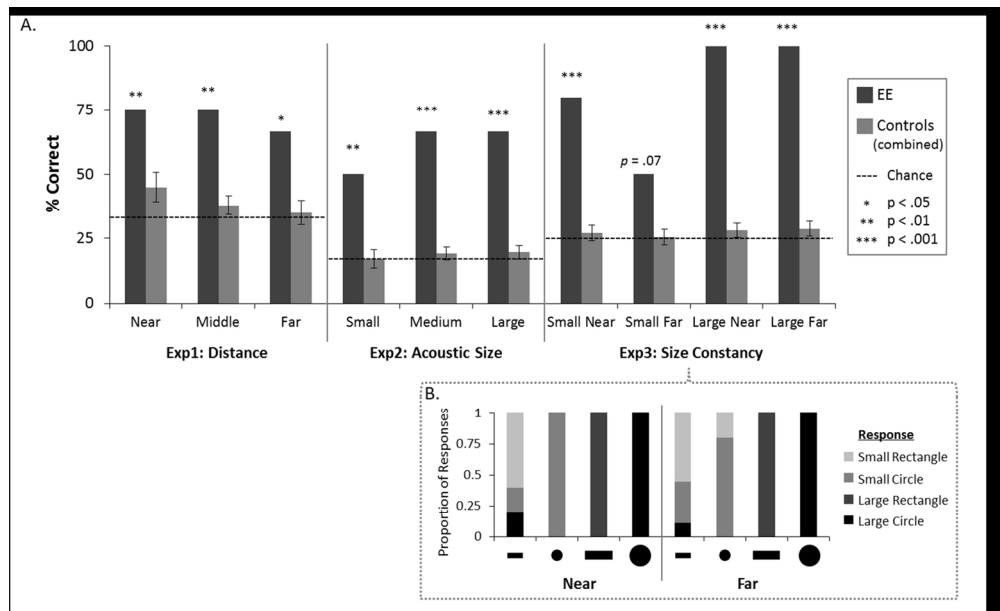


Figure 4. Results from tests against chance for the expert echolocator (binomial tests) and combined control group (t-tests). Participants' performance (shown as percent correct) was collapsed across shape for Experiments 2 and 3. Chance performance for each of the tasks is indicated by the dashed lines and significant results are indicated by asterisks. The distribution of EE's responses (B) is shown for the size constancy task. Although EE performed statistically at chance for the 'small-far' condition, the error distributions show that this decrease in performance was driven by errors in shape judgement and not size judgement, thus supporting size constancy in these cases.

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