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Sensory substitution information informs locomotor adjustments when walking through apertures

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Abstract

The study assessed the ability of the central nervous system (CNS) to use echoic information from sensory substitution devices (SSDs) to rotate the shoulders and safely pass through apertures of different width. Ten visually normal participants performed this task with full vision, or blindfolded using an SSD to obtain information regarding the width of an aperture created by two parallel panels. Two SSDs were tested. Participants passed through apertures of +0%, +18%, +35%, and +70% of measured body width. Kinematic indices recorded movement time, shoulder rotation, average walking velocity across the trial, peak walking velocities before crossing, after crossing and throughout a whole trial. Analyses showed participants used SSD information to regulate shoulder rotation, with greater rotation associated with narrower apertures. Rotations made using an SSD were greater compared to vision, movement times were longer, average walking velocity lower and peak velocities before crossing, after crossing and throughout the whole trial were smaller, suggesting greater caution. Collisions sometimes occurred using an SSD but not using vision, indicating that substituted information did not always result in accurate shoulder rotation judgements. No differences were found between the two SSDs. The data suggest that spatial information, provided by sensory substitution, allows the relative position of aperture panels to be internally represented, enabling the CNS to modify shoulder rotation according to aperture width. Increased buffer space indicated by greater rotations (up to approximately 35% for apertures of +18% of body width), suggests that spatial representations are not as accurate as offered by full vision.

Keywords: Obstacle avoidance, Navigation, Apertures, Locomotion, Sensory substitution, Echolocation

Introduction

A number of recent studies in psychology and neuroscience have investigated how the wealth of spatial information contained in auditory echoic signals may be used to enhance spatial awareness in the absence of a visual signal (Schenkman and Nilsson 2010; Thaler et al. 2011; Teng et al. 2012). Sound echoes can provide substantial information regarding the surroundings of the listener, including distance to a silent obstacle (Rosenblum et al. 2000), size of the obstacle (Rice and Feinstein 1965; Stroffregen and Pittenger 1995), shape and material of the obstacle (Hausfeld et al. 1982; DeLong et al. 2007), room size (Mershon et al. 1989; Kolarik et al. 2013c), and distance to a sound source (Kolarik et al. 2013a; Kolarik et al. 2013b). However, very little is currently known regarding the fidelity with which this information can be utilized to form internal representations of the individualȏs surrounding environment for navigation. Importantly, it is not yet known whether the central nervous system (CNS) is able to utilize echoic information to perform accurate shoulder rotations to allow safe passage through apertures. This is the focus of the current study.

Echoic signals may originate from sound producing objects in the environment (Mershon et al. 1989), self-generated sounds used to obtain information about silent objects in the environment, as used by echolocators (Supa et al. 1944; Schenkman and Nilsson 2011), or from sensory substitution devices (SSDs). These devices work on an echolocation principle and utilize an ultrasound (or optic) source and a receiver to detect signal reflections. These reflections are used to calculate the distance between the SSD and the object using the time delay between emission and reflection, which is converted into an auditory or haptic signal (Kellogg 1962; Hughes 2001). Sensorimotor contingencies can be used to determine spatial relationships between the person and surrounding objects (O'Regan and Noë 2001). Perceptual-motor learning allows individuals to use an SSD, which provides additional spatial information in the absence of a visual signal (Auvray and Myin 2009).

Navigating safely often requires the body to perform precise motor responses to obstacles in the environment. This may involve stepping over an obstacle, walking around it or safely moving through an aperture (which may or may not require rotation of the shoulders). Little is currently known regarding the usefulness of echoic information in tailoring locomotor adjustments when moving through apertures, compared to the relatively accurate adjustments that are made when spatial information is provided by vision (Warren and Whang 1987; Higuchi et al. 2006a). The use of sensory substitution devices by blind individuals is comparatively low (Roentgen et al. 2009), suggesting that echoic information is not necessarily effective in guiding navigation. We investigated how effectively the CNS is able to utilize echoic information obtained using sensory substitution to guide locomotion through apertures, and perform accurate shoulder rotations to allow safe passage.

For normally sighted individuals, a visual signal provides enough information for the CNS to determine whether an aperture is large enough to allow passage. The CNS is also able to accurately determine whether a narrow aperture is passable but requires shoulder rotation. Shoulder rotation is scaled in relation to body width, and an additional buffer (or extra) space is created to avoid collisions with walls when negotiating apertures (Franchak et al. 2012). Warren and Whang (1987) reported that participants consistently judged apertures that were less than 1.3 times shoulder width as those that required rotation in order to allow safe passage without collision.

Higuchi et al. (2006a) showed that a rotation proportional to aperture size is generated by the visuo-motor system, which accurately tailors rotations to aperture size, a finding that was confirmed by subsequent studies (Wilmut and Barnett 2010; Fath and Fajen 2011).

Visual-to-auditory devices that work on an echolocation principle have previously been used to study whether SSD information regarding aperture width size can be used by blindfolded participants (Hughes 2001; Davies et al. 2011), or to provide spatial information to visually impaired patients (Kay 1964; Heyes 1984; Laurent and Christian 2007; Roentgen et al. 2008; Roentgen et al. 2009). Hughes (2001) demonstrated that an echolocation system (Kay's Advanced Spatial Perception Aid KASPAÊ) was able to provide naïve blindfolded users with spatial information regarding locomotor guidance and aperture width between wall panels, suggesting that information embedded within the echoic spatiotemporal flow field provided by the device made spatial layout information available to the user. Furthermore, Hughes (2001) showed that participants using an SSD did not judge aperture sizes that were less than 1.3 times wider than shoulder width to be impassable without shoulder rotation, as is the case when vision is present (Warren and Whang 1987). Instead, participants often judged apertures smaller than themselves to be passable, suggesting that the information provided by the echoes for making judgements was not perceived accurately. In Hughesôs (2001) study, participants were asked to rate the passability of various apertures using an SSD and then manually explore the aperture width, so that a tactile response could be used to update their representation of spatial layout. However, the ability of participants to use the substituted information in the absence of vision to physically negotiate an aperture which may or may not require shoulder rotation for safe passage was not assessed by Hughes (2001).

The current study compared the locomotor adjustments made by the CNS in order to pass through apertures of various widths when visual signals were available, or when vision was not available (via a blindfold) and an SSD was used. The aim was to investigate whether the degree of shoulder rotation (measured using a 3-D motion capture system) made when using an SSD was dependent on aperture size, as in the case when vision is present, and whether total movement time to pass through each aperture with an SSD was dependent on aperture width. In addition, average walking velocity across the trial, peak velocities before crossing, after crossing, and throughout movement were examined, both with normal vision, and blindfolded and using an SSD, were assessed.

The main hypothesis was that information embedded within the echoic spatiotemporal flow field allowed the CNS to perform shoulder rotations proportional to aperture size. Fine spatial detail is known to be limited by SSDs as a consequence of the wavelength of ultrasound (Easton 1992; Lee 1993), and lower accuracy for passability judgements when using an SSD to pass through apertures has been previously reported (Hughes 2001). We hypothesized that participants would take a more cautious approach when passing through apertures under guidance using SSD information compared to using the visual system, which would be reflected by greater shoulder rotations, longer movement times, and smaller peak velocities before crossing, after crossing and over the whole trial. We tested these hypotheses in the current study. Kinematic indices allowed us to measure the comprehensive set of movement variables described above. Previous studies have reported less sensitive measures, including subjective judgements such as the ópassability of apertureô frequencies, and mean confidence ratings in these judgements (Hughes 2001).

Methods

Participants

Ten participants took part (3 male, 7 female), mean age 23.3 yrs (range 18-41 yrs), with mean body widths of 43.2 cm (range 37.5-49.5 cm). All had normal hearing (less than 15 dB HL from 500 Hz to 4 kHz), and none had previous experience with sensory substitution devices. All had normal or corrected to normal vision (6/6 R and L). The experiments were performed with the approval of the Faculty Research Ethics Panel under the terms of Anglia Ruskin Universityôs Policy and Code of Practise for the Conduct of Research with Human Participants. All participants gave their informed consent prior to their inclusion in the study.

Data acquisition and analysis

3-D kinematic data were collected at 100 Hz using a 6 camera 3-D motion capture system (Vicon 460; Oxford Metrics Ltd). Five retro-reflective spherical markers were attached at the following key anatomical locations (placed either directly to the skin or very tightly fitting clothing): the most distal, superior aspect of the second toe, sternum and the acromion process of the shoulder. Two additional markers were attached to the front edge of the aperture to determine the width and location within the laboratory coordinate system. Marker trajectory data were filtered using the cross-valedictory quintic spline smoothing routine, with ósmoothingô options set at a predicted MSE value of 10.

Movement time was determined from the instant the participant began walking to pass through the aperture to when they had passed through the aperture and walked 1.5 m.

Shoulder rotation was calculated from the x and y coordinates of the reflective markers on each acromion process of the shoulder, and normalized such that 0° was facing forward. To ensure that anti-clockwise rotation did not result in a negative angle, opposite to clockwise rotation resulting in positive rotation subsequently affecting the average shoulder rotation, the absolute angle was taken. Increasing shoulder angle means greater shoulder rotation to pass through the aperture. This calculation was based on Wilmut and Barnettôs (2010) work.

Instantaneous velocity was calculated from the sternum. We measured peak positive velocity in the forward/backward (anterior-posterior) direction, thus any shoulder rotation, which by implication would cause the sternum marker to rotate around the longitudinal axis, would have resulted in a negative velocity and not have influenced the value recorded.

Apparatus

Two echolocation devices that provided auditory spatial information were used: the K-Sonar, which utilized KASPAÊ technology similar to the device utilized in the study of Hughes (2001), and the Miniguide (Philips 2013). Both devices employed an ultrasound source which emitted a signal, and a receptor which calculated the distance between the source and an object on the basis of the time taken for the signal to reflect from the object and return to the source. The distance information was then converted into an auditory signal. The K-Sonar provided distance information using multiple tone complexes. The óchirp audioô setting was used for the Miniguide with the vibration option switched off. The device made a short chirp sound which increased in rate as distance between the device and an obstacle decreased. Both devices were set to have a range of 1 m. Two devices were utilized in the experiment to verify that the findings generalized across two sensory substitution devices which differed in the method of audification of distance information, as previous studies have tested only single devices (Hughes 2001; Davies et al. 2011). While using the devices, participants were instructed to tuck their elbow against their side to prevent arm movements in an anterior/posterior direction, and to hold the hand with the device perpendicular to the body. This enabled the standardisation of the auditory feedback participants received across trials without being influenced by arm movements. This was not expected to affect performance, as previous work showed that healthy participants do not show significant difference in gait parameters with an immobilized arm with elbow flexion using a sling (Yavuzer and Ergin 2002). For both devices, Sennheiser HD380 Pro headphones were utilized. Both devices were held in the participantǿs dominant hand.

Testing took place in a room measuring 5.7 x 3.5 m with a ceiling at a height of 2.8 m. Aperture size was altered using two movable panels measuring 1.2 x 1.7 m, composed of solid reflective material (see Figure 1 for a schematic of the room setup). The experiments were conducted in the centre of the room, to avoid possible ultrasound echoes from surfaces that were not the panels. Although not insulated from outside noise, experiments were performed in a quiet environment, and both the experimenter and participants maintained silence throughout testing.

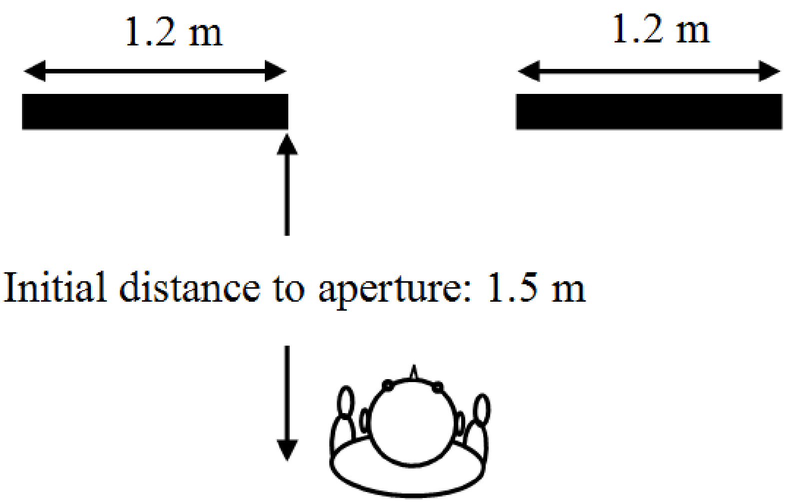

Fig. 1 Schematic of the experimental setup

Procedures

Participants were instructed that they would first take part in a training phase involving monitoring of the output signals of a sensory device to perceive two aperture widths. This would be followed by a testing phase in which they would be presented with various aperture widths and asked to navigate through each aperture.

The participants took part in three conditions: blindfolded using the Miniguide, blindfolded using the K-Sonar, and a control ófull-visionô condition where neither a blindfold nor a SSD was used. The order in which the two SSDs were tested was randomized; however the full-vision condition was always performed last to avoid ótrainingô the participants on the range of aperture sizes tested. For the two SSD conditions, training was provided prior to testing. In the studies of Hughes (2001) and Davies et al. (2011), participants received approximately 5 minutes of free training using a single SSD. In order to extend our participantsô learning during the training phase beyond that of these studies, we gave our participants 15 minutes training for each of the two SSDs studied, and utilized two different aperture widths for this purpose (smaller and larger), in addition to three phases of training (SSD plus vision, SSD plus vision when required, and SSD only).

In the first stage of training, participants stood 1.5 m from an aperture, and with their eyes open and at their own pace, they used an SSD to examine and pass through two aperture widths which were not used during the testing phase: one larger (1.5 m) that did not require a shoulder rotation to pass through, and one smaller (0.5 m), that did require a rotation. Participants were encouraged to actively move the SSD across the aperture and attend to the auditory feedback provided. No formal instructions in how to use the SSD were given. A starting distance of 1.5 m from the aperture was chosen following pilot testing. This was because it was observed that blindfolded participants using an SSD always stopped when near to an aperture regardless of the approach distance, in order to move the device across the aperture before attempting to pass through. Although participants started behind a line that was 1.5 m from the aperture, they were instructed to hold the hand with the device perpendicular to the body (as mentioned above). This resulted in the SSD being within 1 m of the aperture (i.e. within the operable range of the device), and allowed participants to gain information when the trial began. In the second stage, participants were instructed to repeat the process, but with their eyes shut, although they were allowed to open their eyes when they wished to receive visual feedback to assist with training of how to use the device. In the third stage, participants repeated the process for a final time but with their eyes shut throughout. The training phase lasted approximately 15 minutes, and all participants reported that they felt that they had received sufficient training during this period in the skills needed to perform the experiment. Visual feedback was allowed in the first two stages of training in order to maximize the participantsô abilities to associate the changes in auditory SSD feedback with the panel locations. In the second stage, vision was only available when participants required it in an attempt to increase reliance on the SSD and not vision. Although vision was involved while the participant utilized sensorimotor contingencies in the initial stages of learning to use the SSDs to acquire spatial information, they were limited to SSD information alone when vision was unavailable in the testing phase. This determined whether substituted information alone allowed participants to tailor their locomotor actions appropriately. The order in which participants completed training with the two apertures was randomized.

In the testing phase, participants stood 1.5 m from the aperture, and were instructed to pass safely through without impacting the panels. Use of hands to touch the panels was not allowed. There were four aperture widths: +0% (same width as body width), and additional +18%, +35%, and +70% of the individual participantôs body width. Although previous research required participants to navigate through standard aperture widths (Hughes 2001; Davies et al. 2011), the current study used individual percentage widths relative to each participant, as this ensured standardised aperture width across participants with varying body widths. Maximum body width while standing was determined by measuring the distance between the left and right radius whilst participants were stood in the anatomical óneutralô position with their arms down by their sides (Diffrient et al. 1981; Hughes 2001). A single trial consisted of navigating through the aperture without contacting the panels. Participants were informed that they could rotate their shoulders if required. Participants performed five repetitions per width, allowing 60 trials in total to be collected across the three conditions. Aperture width was randomized in each condition. In order to avoid participants using sounds arising from movements of the panels between trials as a cue to aperture width, an auditory SSD signal between all trials and in all conditions was provided. In the full-vision condition, participants were asked to close their eyes between trials and instructed to open them at the commencement of each new trial by the experimenter. This was done to ensure participants did not receive advanced visual information prior to each trial. No feedback was provided during the testing phase. Data was gathered in a single session approximately 1.5-2 hours in duration.

Statistical Analysis

Data were analysed using Repeated Measures ANOVA with three guidance conditions (K-Sonar, Miniguide, and full vision), four aperture widths (0%, +18%, +35% and +70% of the participant's body width) and five repetitions. Level of significance was accepted at $p < 0.05$ and post-hoc analyses, where appropriate and unless otherwise indicated, were performed using Tukey's HSD.

Results

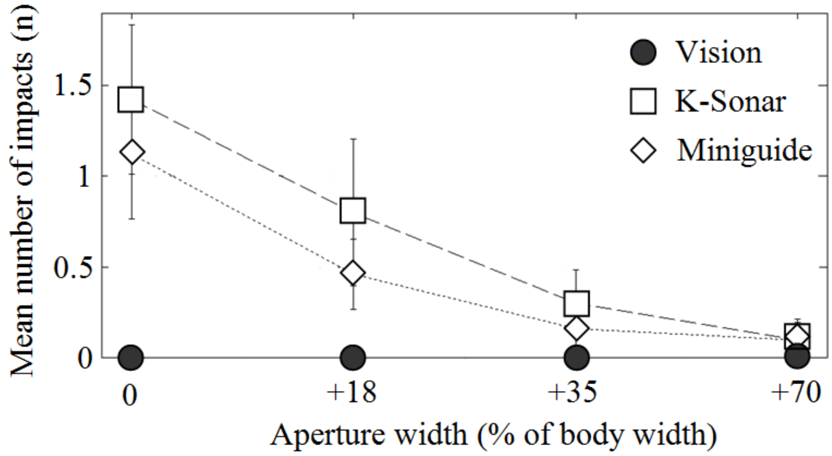

Fig. 2 Mean number of impacts against panels per trial when passing through apertures, for each aperture width. Full vision performance is shown by closed circles joined by black lines, sensory substitution using the K-Sonar is showed by open squares joined by dashed lines, and sensory substitution using the Miniguide is shown by open diamonds joined by dotted lines. Data is plotted as a function of aperture width (reported as percentage of body width). Error bars represent ±1 standard error, and are shown unless smaller than the symbol size

The mean number of impacts made against the panels when moving through the apertures is shown in Figure 2. No impacts were made with full vision. When using the SSDs, the mean number of impacts was less than 1.5 across trials for all aperture widths. It was possible to record greater than 1 impact per trial if, for example, the participant contacted the left aperture and then the right. Statistical analysis was run on the number of impacts when completing the task in different guidance conditions. There was a statistically significant difference in the average number of impacts when completing the task, $\chi^2(2) = 12.20$, p=0.001. Post hoc analysis (Wilcoxon signed rank) indicated that after applying the Bonferroni correction (critical value of .0167) there was a significant increase in the number of impacts in the K-Sonar and Miniguide conditions compared to full vision (*p*=0.005). There was no significant difference between number of impacts between the K-Sonar and Miniguide (*p*=0.032). Statistical analysis was run on the mean number of trials where an impact occurred when completing the task in different guidance conditions. There was a statistically significant difference in the average number of impacts when completing the task, $\text{G}^2(2) = 16.67$, p=0.001. Post hoc analysis (Wilcoxon signed rank) indicated that there was a significant increase in the number of trials where there was an impact in the K-Sonar and Miniguide conditions compared to full vision ($p<.01$). There was no significant difference between number of impacts between the K-Sonar and Miniguide (*p*=0.30).

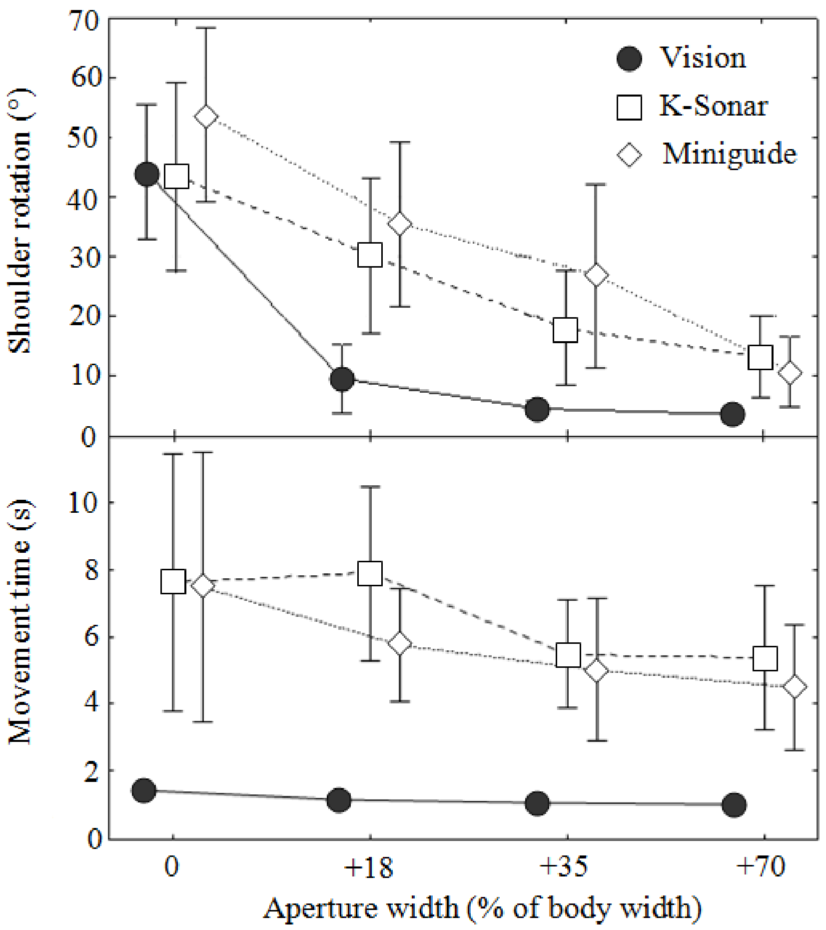

Fig. 3 Mean shoulder rotation (upper panel) and mean movement time to pass through apertures (lower panel) for full vision (closed circles joined by black lines), sensory substitution using the K-Sonar (open squares joined by dashed lines), or sensory substitution using the Miniguide (open diamonds joined by dotted lines). Error bars represent ±1 standard error, and are shown unless smaller than the symbol size

Figure 3 shows mean shoulder rotation and mean movement time to pass through each aperture width. In order to avoid symbols obscuring one another, a small amount of variation in the x dimension has been included in the data presented in the figure. In all conditions, shoulder rotation decreased as aperture width increased. Shoulder rotations were generally greater when using an SSD compared to when full vision was available. There was a main effect of condition ($F(6, 54) = 6.25$, $p=0.01$) aperture width ($F(6, 54) = 41.13$, $p=0.001$), and a significant interaction between condition and aperture size ($F(6, 54) = 2.57$, $p=0.029$). A main effect of repetition was not observed, suggesting there was no improvement over trials. Post-hoc analysis revealed that shoulder rotation in the full-vision condition was significantly lower for all but the smallest aperture size compared to both of the SSDs. With full vision, shoulder rotation at aperture widths of +18%, +35%, and +70% was less than at 0% body width. For the K-Sonar, shoulder rotation to pass through apertures of 0% body width were significantly greater than for apertures which were +35%, and +70% larger than body width. For the Miniguide, rotations made to pass through the 0% body width aperture were significantly greater than for all other aperture sizes, and participants rotated less for aperture widths of +70% compared to aperture widths of +18%. Very little shoulder rotation was observed in the full vision condition for all but the narrowest aperture (0% body width). Previous work has shown that participants visually generally judge apertures that are less than 1.3 times shoulder width as requiring rotation to allow passage without collision (Warren and Whang 1987), however our results indicate that the placement of the aperture directly in front of the participant allowed participants to walk through all but the narrowest aperture widths without rotating the shoulders. This is probably due to the use of a relatively close starting distance of 1.5 m from the aperture, compared to previous studies which used further starting distances (e.g. 7 m, Warren and Whang 1987). Under guidance using SSDs, participants rotated the shoulders significantly more than when using full vision for all aperture widths except the widest aperture.

For full vision, movement times were fastest and approximately equal for all aperture widths in this condition. Longer movement times were observed when an

SSD was utilized to pass through the aperture, and movement time generally increased as aperture width decreased. There was a main effect of condition (*F*(6, 54) = 17.37, *p*=0.001), aperture width (*F*(6, 54) = 7.01, *p*=0.001) and repetition (*F*(6, 54) = 3.68, *p*=0.013), and a significant interaction between condition and aperture size (*F*(6, 54) = 2.35, *p*=0.043). Post-hoc analysis showed that movement time was significantly faster for full vision for all aperture sizes compared to the two SSDs. For the K-Sonar, movement times to pass through apertures of 0% and +18% were significantly longer than the +35%, and +70%. For the Miniguide, movement time to pass through the 0% aperture was significantly longer than for aperture sizes of +35%, and +70%.

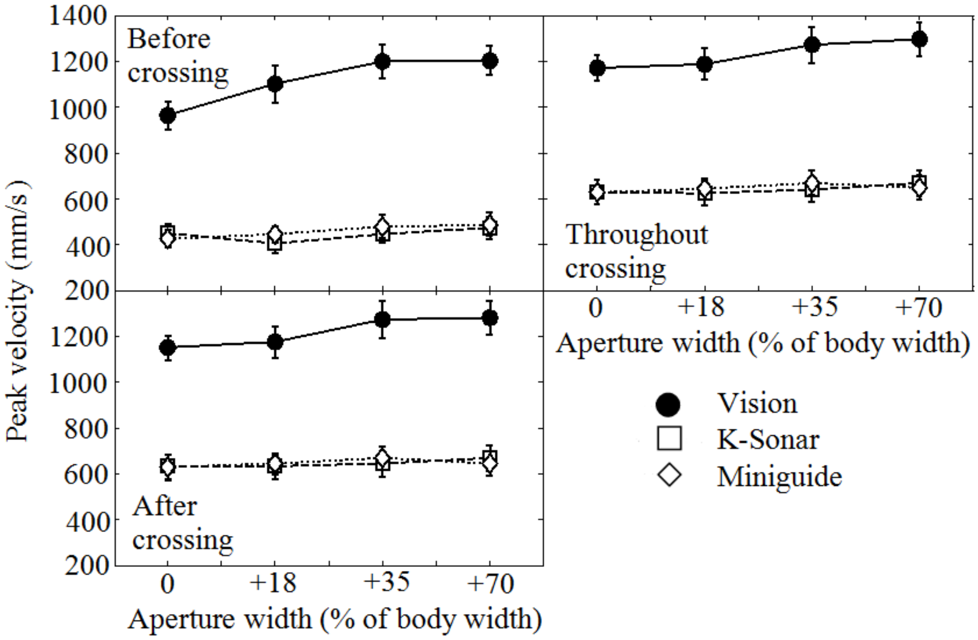

Fig. 4 Peak velocity before crossing through apertures (upper left panel), after crossing (bottom panel), and throughout (upper right panel) for full vision (closed circles joined by black lines), sensory substitution using the K-Sonar (open squares joined by dashed lines) or using the Miniguide (open diamonds joined by dotted lines). Error bars represent ±1 standard error, and are shown unless smaller than the symbol size

Figure 4 shows peak velocity before crossing, after crossing, and throughout movement through the apertures. Full vision data is shown by closed circles joined by solid lines, SSD data is shown by open squares joined by dashed lines for the K-Sonar and open diamonds joined by dotted lines for the Miniguide. In all cases, peak velocity was highest when participants had full vision available. For peak velocity before crossing, velocity increased under visual guidance as aperture size increased. For the SSD conditions, peak velocity was similar across aperture widths. There were main effects of condition ($F(6, 54) = 56.26$, $p=0.001$), aperture width ($F(6, 54) = 5.62$, $p=0.019$) and repetition ($F(6, 54) = 4.73$, $p=0.016$). No significant interactions were observed. Post-hoc tests showed that peak velocity before crossing was significantly higher for full vision for all aperture sizes compared to the SSD conditions. For peak velocity after crossing, there was a moderate increase in velocity as aperture size increased. For the SSD conditions, peak velocity was approximately equal across aperture widths. There was a main effect of condition only ($F(6, 54) = 18.69$, $p=0.003$), where peak velocity for full vision was significantly greater compared to both SSDs. For peak velocity throughout, there was a moderate increase in velocity as aperture size increased, and, peak velocity was approximately equal across aperture widths in the SSD conditions. There were main effects of condition ($F(6, 54) = 72.94$, $p=0.001$), aperture width ($F(6, 54) = 6.7$, $p=0.002$) and repetition ($F(6, 54) = 2.98$, $p=0.032$). A significant interaction between aperture width and repetition ($F(6, 54) = 2.9$, $p=0.002$) was also observed. In summary, peak velocities before crossing, after crossing and throughout moving through an aperture using an SSD were smaller, around 50% of that when under visual guidance, suggesting a more cautious approach.

An analysis of average velocity values showed a main effect of condition (*F*(2, 18) = 17.37, *p*=0.001) aperture width (*F*(1.55, 13.99) = 7.00, *p*=.011), and repetition (*F*(1.89, 17.01) = 2.36, *p*=0.049). Post-hoc analysis revealed that average velocity was higher with full vision compared to both SSDs, and that average velocity was higher in the widest aperture compared to the smallest two apertures. There were no significant interactions.

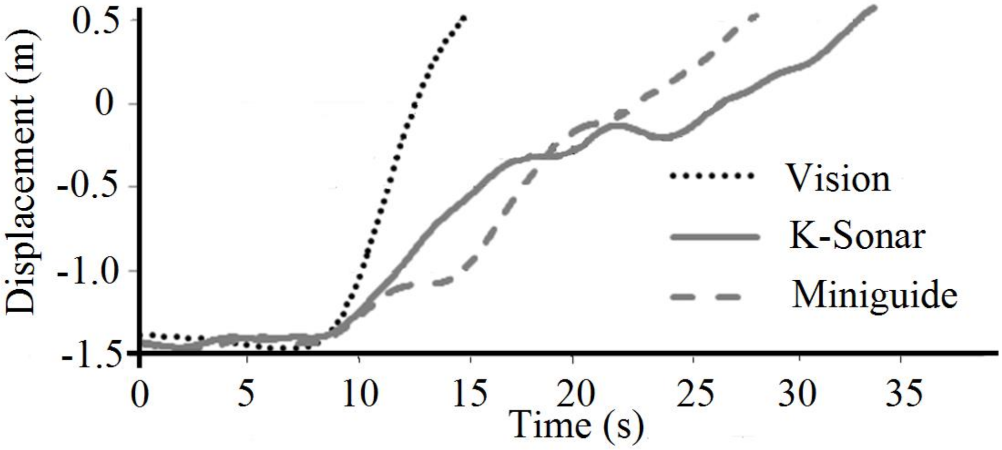

Fig. 5 Time course-displacement movement data for navigating through an aperture size of 0% body width for full vision (dotted line), sensory substitution using the K-Sonar (solid line), or using the Miniguide (dashed line)

The approach distance from initiating movement to passing through the aperture (1.5 m) was shorter than that utilized in other studies that have investigated walking through an aperture under visual guidance (typically 3-10 m). As a consequence, it should be noted that the time course of movement speed from initiation of walking under full vision is distinct from that of other studies. When the walking distance is greater than 3 m, a decrease in movement speed is observed, usually a few steps prior to crossing the aperture (see Higuchi et al. 2006a; Cowie et al. 2010). Figure 5 shows the representative time course for distance displacement over time. Flat lines indicate stationary movement, negative values denote starting behind the aperture, 0 m displacement denotes the point at which the participant passed through the aperture, and +0.5 m denotes the end of the trial. A steeper gradient indicates a higher movement speed, and the figure shows that, unlike other studies with greater approach distances, there is no decrease in speed when approaching the aperture under visual guidance. This suggests that the peak velocity before crossing under visual guidance (see top left panel of Fig. 4) may be greater than that observed in studies that utilize a greater approach distance. There was some reduction in speed under SSD guidance when approaching the aperture, and post-hoc tests showed that peak velocity before crossing was significantly higher for full vision for all aperture sizes compared to the SSD conditions (see above). In addition, Figure 5 shows the increased time taken for participants to navigate through an aperture size of 0% body width in the K-Sonar and Miniguide conditions, compared to the full vision condition.

Discussion

The findings of the current study showed that irrespective of sensory input, participants were able to negotiate the different aperture widths, albeit participants did sometimes impact the aperture when using echoic information from an SSD. In the SSD conditions, participants were able to use sensorimotor interactions with the surrounding environment in order to pass through apertures of various widths, using the available auditory spatial information from an SSD. Participants were able to use this information to scale their shoulder rotation according to the width of the aperture passed through, although not to the same fine degree as when performing the task with full vision. Participants tended to make larger shoulder rotations when using an SSD compared to full-vision conditions, especially for apertures at 0%, +18%, and +35% of body width, thus creating additional buffer space to avoid collisions. This demonstrates that the participants exercised greater caution to increase the likelihood of a safe passage due to uncertainty regarding the precise location of each panel, consistent with the findings of Hughes (2001), who reported lower accuracy for passability judgments under guidance using an SSD. Movement time was significantly greater for the narrower apertures compared to the wider apertures when using an SSD, suggesting that the participants were using spatial information to adapt their movements to pass more cautiously through narrower apertures. Participants sometimes impacted with the aperture panels when using an SSD (the average number of impacts was less than 2 for each aperture width), but not under full vision, demonstrating that they were not always successful at utilizing SSD information to pass through an aperture. This may be a contributory factor to the relatively low use of sensory substitution devices by those with visual impairment (Roentgen et al. 2009). It is possible that more extensive training may result in avoiding collisions, however, this was beyond the scope of the present study. Movement time to pass through apertures was significantly faster under conditions of full vision than with an SSD. Peak velocities before crossing, after crossing, and throughout were higher under conditions of full vision. Increased movement time and lower peak velocity indicate that when using an SSD, participants needed to explore the aperture to a greater extent compared to the visual condition, so that the CNS could gain a better representation of the external environment prior to passing through the aperture.

Previous studies have indicated that under conditions of full vision, the representation of space is relatively accurate in relation to locomotor action capabilities (see Higuchi et al., 2006b for a review). Higuchi et al. suggest that the CNS probably utilizes visual information beyond peri-personal space to avoid obstacles, in addition to optic flow information acquired during self-motion, indicating that the CNS controls locomotion in a feedforward as well as a feedback-based manner (Higuchi et al. 2006b). The current findings suggest that the CNS is able to utilize echoic spatial information from a sensory substitution device in the absence of a visual signal to control locomotor activity. This substituted information allows the position of the aperture panels to be represented relative to the participant during self-motion through an aperture, but not to the same extent as vision. This is most likely due to the loss of fine spatial detail conveyed by the SSDs, which is limited as a consequence of the wavelength of ultrasound (Easton 1992; Lee 1993). In addition, pilot work showed that blindfolded participants using an SSD would stop when nearing an aperture regardless of the approach distance. Hughes (2001) also reported that exploratory strategies adopted by participants consisted of approach ceasing and scanning of the aperture panels with an SSD. This unique characteristic may be one of strategies used by the CNS to compensate when using echoic information from an SSD, as stopping during approach to an aperture is generally not reported for normally sighted controls walking under visual guidance (Higuchi et al. 2006a; Cowie et al. 2010).

No significant differences were found between the two SSDs, suggesting that the two devices selected for the study had the necessary properties to achieve guidance when walking through apertures. Similar locomotor precision was achieved despite the differences in the two SSDs, suggesting that spatial layout information provided by the spatiotemporal flow fields of the two devices were approximately equally effective regardless of the methods of audification of distance information.

However, the results do not necessarily imply that any kind of SSD is useful, as a study by Davies et al. (2011) found that participants were not able to use audified ultrasound from their SSD to tailor shoulder rotations to aperture width. Procedural differences and less training with the SSD may also have contributed to differences between their findings and ours.

Previous research has shown that occipito-parietal and occipito-temporal areas are selectively activated in sighted blindfolded participants when using a visual-to-auditory substitution device in order to perceive depth (Renier et al. 2005). These findings suggest that brain areas that normally process visual depth may be multimodal in nature, and can be recruited for processing depth using substituted auditory information. Enhanced occipital cortex activity was observed in early blind participants whilst using auditory information from an SSD in a spatial distance and direction evaluation task (De Volder et al. 1999). It is probable that these brain areas are also involved in processing depth information while using substituted information to pass through apertures and perform shoulder rotations to avoid collision, however further work is needed to determine this.

It is important to ascertain whether the current findings would generalize to the vertical dimension as well as the horizontal. However the ability to utilize sensory substitution information for navigating vertical apertures remains to be investigated. Studies have indicated that individuals under visual guidance stoop down to successfully pass through vertical openings 1-1.04 times their height (van der Meer 1997; Stefanucci and Geuss 2010; Franchak et al. 2012). The greater space assigned for passing through horizontal apertures is likely to be related to differences in body movement to allow safe passage (Franchak et al. 2012). If the findings of the current study for horizontal apertures also apply to vertical apertures, then a greater buffer space (greater ducking or bending) should also be found when using a SSD. This work would be particularly relevant in determining control laws that direct the action choices of blind listeners who utilize SSDs in order to avoid collision with obstacles on the upper section of the body, which are not detected by use of a white cane (Farmer and Smith 1997).

Our findings show that SSDs inform locomotor adjustments among blindfolded normally sighted participants when walking through apertures, and hence will be of value to individuals who lack visual capabilities. Although these individuals were not tested in the current study, it has previously been shown that performance for navigation tasks among blindfolded and functionally blind participants is similar, and that ñthere is little indication that spatial competence depends strongly on prior visual experienceò (Loomis et al. 1993). Our approach of using blindfolded normally sighted participants is consistent with the majority of previous work in the sensory substitution literature, including investigations regarding perceived aperture width (Hughes 2001; Davies et al. 2011) and studies involving substituting sound for vision to perform localization, object recognition and identification tasks (Auvray et al. 2007; Kim and Zatorre 2008). Future work will investigate how SSDs can benefit partially sighted and blind individuals when navigating through apertures.

Our findings suggest that self-generated echoic information, such as that used by echolocators to detect obstacles, may also provide the CNS with information that allows shoulder rotations to be made proportional to aperture width. This remains to be determined. It is important to take into account the differences between human echolocation and using spatial information from an SSD; as pointed out by Thaler et al. (2011), human echolocation signals are comparatively weaker than SSD signals, and unlike SSD processing, human echolocation involves comparing the self-generated sound to the echoes. Nonetheless, the current findings raise the possibility that echolocation may be utilized to successfully navigate through apertures while avoiding collisions, potentially greatly increasing the spatial awareness and mobility of those who have lost their sight.

The current findings suggest that although for horizontal apertures substantially greater than body width (+35% and + 70%), SSD spatial information is sufficient to enable passage with minimal chances of collision, for narrower apertures (0% and 18%) SSD information is less effective. These results may be relevant to orientation and mobility programs designed to promote rehabilitation using SSDs following severe visual loss, and suggest that more training may be needed to utilize SSDs to traverse narrower apertures safely. In summary, the findings of the current study show for the first time that young adults are able to combine spatial information obtained by means of sensory substitution with body-scaled information to determine the degree of shoulder rotation that is necessary to pass through a narrow aperture, in the absence of a visual signal. However, the larger buffer associated with increased rotation when using an SSD implies that greater caution is being taken during locomotion, as the representation of external space is less accurate when using substituted information compared to vision.

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