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RESEARCH ARTICLE

Virtual auditory aperture passability

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Abstract

Two experiments investigated (1) the ability of individuals to perceive the passability of apertures that are constructed using two virtual sounds sources and (2) the nature of the perceptual information that is used when determining passability in such a way. In the first experiment, participants judged whether they could successfully walk between two sound sources, heard through headphones, without turning their shoulders. We hypothesized that judgements would be accurate and driven by the detection of a proposed informational variable that relates head rotation, forward locomotion and aperture width. To test this hypothesis, we used motion tracking and a gain manipulation to alter apparent head rotation relative to virtual sound source positions and evaluated the effect on performance. Participants were able to accurately judge aperture passability based only on acoustic information. However, the gain manipulation did not show a significant influence on perceptual reports. The unexpected significant influence of lateral head movement on perceptual accuracy, however, does suggest that an alternative informational variable, based on lateral movement, may have been used. In the second experiment, a group of participants with wide shoulders was compared to a group with narrow shoulders on a similar task. Significant differences in minimally acceptable aperture width were found between the wide and narrow groups. When these aperture widths were scaled to the participants' shoulder widths, however, the differences were no longer present. These findings are consistent with previous studies investigating perception of passability and offer promising applications of virtual reality technology in the study of auditory perceptual abilities.

Keywords Auditory · Aperture · Affordance · Perception

Introduction

Gibson (2014) proposed that an animal needs to only detect the information that specifies its relationship to the environment to perceive what possible actions it is afforded. An individual who is attempting to pick up a glass of water, for example, need to only detect a commensurate relationship (i.e., a fit) between her hand and the glass. Perception of this relationship requires that there be a pattern of energy—defined with respect to both the observer and the environment—reaching the perceiver (light, sound, etc.) that corresponds, in a one-to-one fashion, with the state of affairs. It requires, also, that the perceiver has the ability and the intention to detect such energy patterns. Under this theory, the ability to perceive affordances is what allows for prospective control (Turvey 1992), which is a hallmark of successful human behavior—one must know prior to engaging in most actions whether the action is possible to avoid adverse outcomes.

Affordance perception and the required specifying information have been primarily studied in the visual and haptic modalities. This is most likely due to the obvious involvement of these modalities in everyday activity. Visually and haptically perceived affordances such as sit-on-ability (Mark 1987; Mark et al. 1990), step-on-ability (Warren 1984; Wraga 1999), reachability (Carello et al. 1989), pass-through-ability (Davis et al. 2010; Fath and Fajen 2011; Wagman and Taylor 2005; Warren and Whang 1987), and many others have been thoroughly examined (see Richardson et al. 2009, for a review). There is, however, a dearth of research on auditory perception of affordances. Some work has been done but has focused on the auditory perception of certain object properties (Carello et al. 2005) such as length (Carello et al. 1998), size, and shape (Kunkler-Peck and Turvey 2000) as well as on the judgement of object reachability via audition (Rosenblum et al. 1996; Russell and

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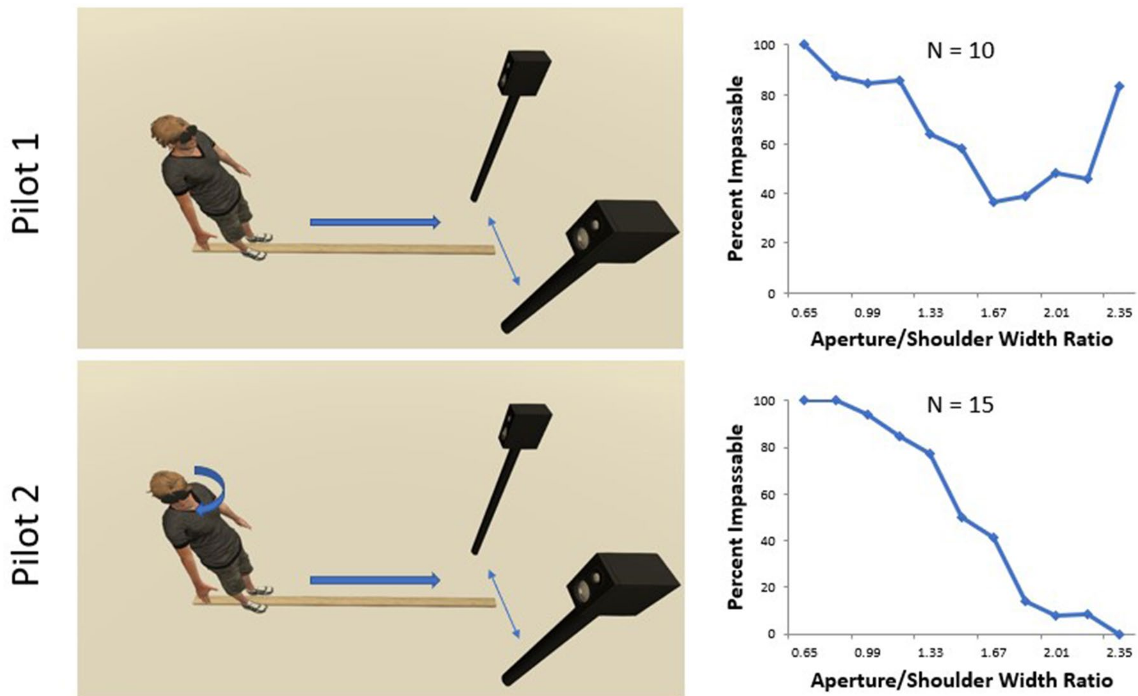

Fig. 1 Setup and results for both pilot studies. Participants in the first pilot study (top) were not encouraged to engage in head movement, but participants in the second pilot study (bottom) were. The average percent of apertures judged to be impassable as a function of shoulder scaled aperture width reflects greater accuracy in pilot 2 than in pilot 1

Turvey 1999). The general objective of the current studies is to extend this work by showing that audition can be used as a primary means of navigation. To achieve this objective, we utilized an aperture passability paradigm. Aperture passability provides stable ground for this work because it is one of the few affordance-related paradigms that have generated results pertaining to auditory perception (Gordon and Rosenblum 2004; Russell and Turvey 1999). Previous work has shown a strong evidence for the auditory perception of aperture passability but has failed to fully describe the underlying information. The aims of the current studies are to (1) demonstrate that aperture passability can be accurately judged for apertures constructed from two separated sound sources, (2) determine if passability judgements are scaled to a perceiver's shoulder width, and (3) evaluate a candidate acoustic informational variable that specifies pass-through-ability.

Two pilot studies concerning the auditory perception of passability of apertures defined by separated sound sources were conducted prior to the current studies. In both pilots, blindfolded participants were asked to approach the sound sources and make a series of judgments regarding passability. To ensure that participants stayed centered, participants were asked to straddle a wooden plank while walking. In the first pilot, most participants performed very poorly and seemed completely unable to perceive passability (see Fig. 1). Participant 10, however, was noticeably observed to adopt a strategy that involved exploratory head movements, specifically right–left head turning. This participant performed better than average, often successfully discriminating between passable and impassable openings. In the second pilot study, all participants were asked to turn their heads from side to side while approaching the aperture, prior to providing a passability judgement. Participants in this study performed markedly better than those in the first study who did not make head movements. Their pattern of judgements, on average, suggested a shift from passable to impassable at an aperture width that was 1.5 times their shoulder width (see Fig. 1, bottom right).

The results of the two pilot studies suggest that head movements may be an essential aspect of auditory perception of aperture passability and may underlie the detection of acoustic information that specifies that affordance. For example, as can be seen in Fig. 2, the head-turn angle (henceforth referred to as β) changes in a manner that is systematically related to the size of the aperture as the perceiver moves a certain distance (ΔD). The width of the aperture (referred to in Fig. 2 as w) has, therefore, an invariant relationship to β and ΔD (described in Fig. 3). Both β and ΔD are accessible to the participant through head rotation and forward locomotion, respectively. The ratio between β and ΔD, identified in the right side of the highlighted equation

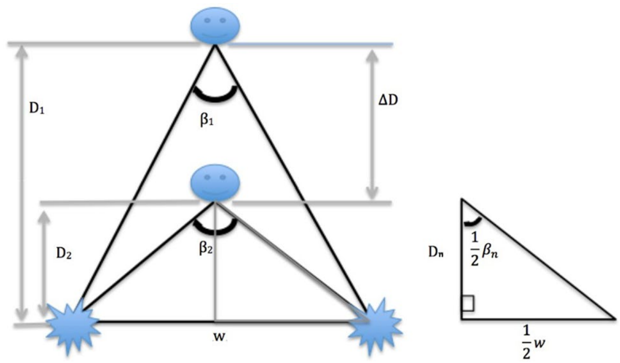

Fig. 2 A diagram of a perceiver approaching an auditory aperture and utilizing exploratory head movements

$$\Delta D = D_1 - D_2$$

$$\tan\frac{\beta_1}{2} = \frac{\frac{1}{2}w}{D_1} \Rightarrow h_1 = \frac{\frac{1}{2}w}{\tan\frac{1}{2}\beta_1}$$

$$\tan\frac{\beta_2}{2} = \frac{\frac{1}{2}w}{D_2} \Rightarrow h_2 = \frac{\frac{1}{2}w}{\tan\frac{1}{2}\beta_2}$$

$$\Delta D = D_1 - D_2 = \frac{1}{2}\frac{w}{\tan\frac{\beta_1}{2}} - \frac{1}{2}\frac{w}{\tan\frac{\beta_2}{2}}$$

$$\Delta D = \frac{1}{2}w\left(\cot\frac{1}{2}\beta_1 - \cot\frac{1}{2}\beta_2\right)$$

$$\boxed{w = \frac{2\Delta D}{\cot\frac{1}{2}\beta_1 - \cot\frac{1}{2}\beta_2}}$$

Fig. 3 The trigonometric relationship between β, ΔD and w

in Fig. 3, is, therefore, a candidate informational variable for perception of aperture passability. Also, as is the case with eye height and shoulder width (Warren and Whang 1987), there presumably exists a similar allometric relationship between stride length and shoulder width. The implication is that perceivers may detect the candidate information variable in body-scaled units to know the size of apertures relative to their shoulders, that is, to perceive the affordance of passability.

One detection strategy, consistent with the use of the candidate information variable, would be to turn the head so as to center one sound source (i.e., until its intensity is equal in both ears) and then turn to center the other source, both while approaching or receding from the aperture. In this case, the angle subtended by the head would represent the top angle of a triangle (shown in Fig. 2), the base and height of which would be the same as the distance between the sound sources and the distance from the head to the aperture, respectively. While this outlines one informative relationship that could be detected by individuals who intend to perceive passability, it should be noted that there may be any number of other, non-specifying relationships that they may use (Withagen 2004). According to the co-specificity hypothesis (Turvey 1988; Turvey et al. 1990) each of these relationships would be detected using exploratory movements that relate to the nature of the variables constituting the information. Therefore, noting the specific nature of exploratory movements that are used in completing the task will be essential in assessing the validity of claims relating to the information that is detected. Experiment 1 focused on the nature of the exploratory head movements that were hypothesized to underlie the ability of individuals to accurately judge the passability of apertures using sound.

Experiment 1

To investigate whether individuals used the proposed informational variable, outlined in Figs. 2 and 3, a gain manipulation of head rotation amplitude using auditory virtual reality was implemented. This manipulation, unbeknownst to the participants, increased or decreased the apparent amplitude of their head rotation relative to the sound sources, effectively manipulating β. This was achieved by implementing "virtual" sound sources (described in detail in the method section), heard through motion-tracked headphones. During the non-manipulated trials (gain = 1), the participant's head rotation produced a change in the sound that corresponded canonically with that which would be produced by head rotation relative to actual sound sources (such as those in the pilot studies 1 and 2). These trials make up one-third of the overall trials. The other two-thirds are made up of a gain that increases the apparent degree of head rotation (gain > 1) and a gain that decreases the apparent degree head rotation (gain < 1). We predicted that trials with altered head movement would exhibit differences in the perceived aperture width. Specifically, we predicted that a gain > 1 should result

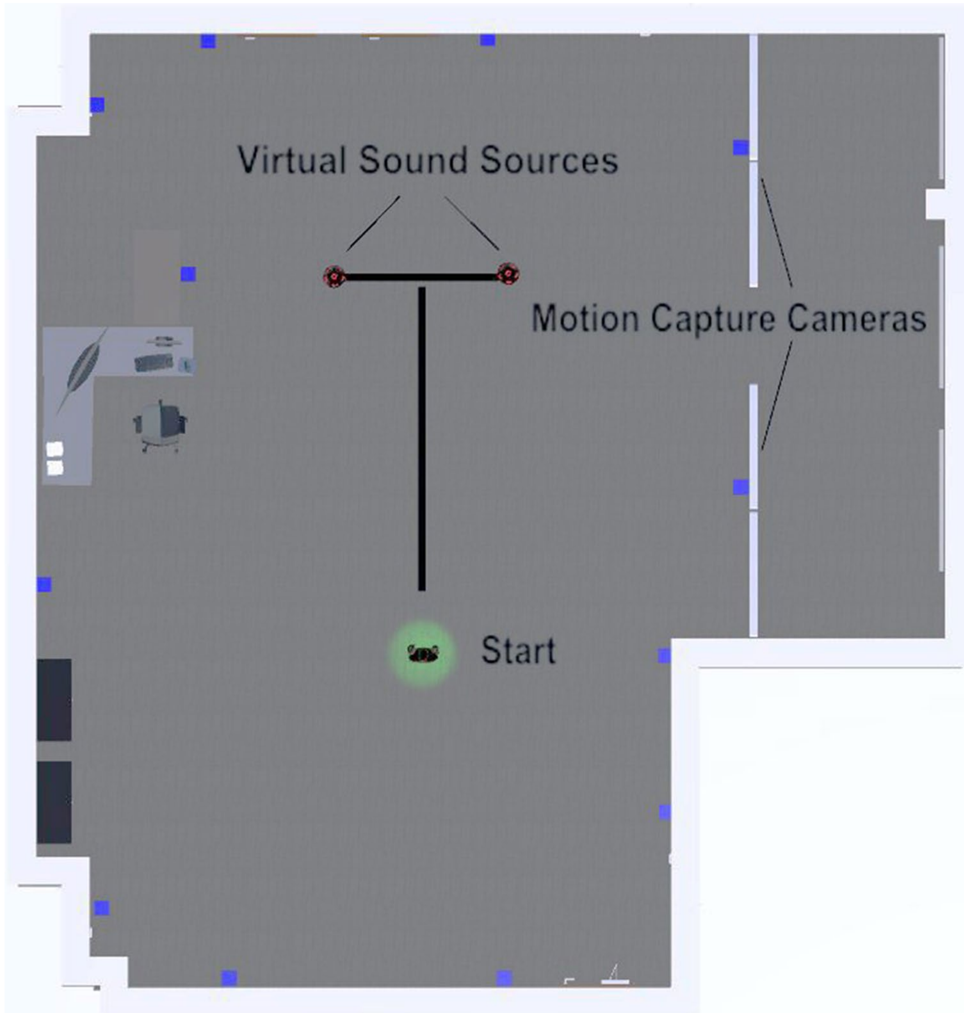

Fig. 4 A diagram of the experimental setup including the positions of the starting point, sound sources and motion capture cameras

in individuals judging wider apertures to be narrower and some passable apertures to not be passable. We predicted the reverse for a gain < 1. In effect, the application of a head gain was expected to yield a larger quantity of inaccurate passability judgements.

Participants

Forty-six[1] college students ranging from 18 to 27 years of age participated in this experiment. There were 18 male and 28 female participants who all reported normal hearing and vision. They participated on a voluntary basis from the University of Cincinnati Psychology Research Participation Pool and received class credit in exchange for participation.

Apparatus/materials

For the first experiment, a 12-camera Motion Analysis system as well as Cortex motion capture software (Motion Analysis, Santa Rosa, CA) was used to track the motion of each participant's head at a sampling rate of 50 Hz. The participant's head position and rotation were streamed into the Unity3d game engine (Unity Technologies, San Francisco, CA, USA) which, along with the 3Dception audio plugin (Facebook, Menlo Park, CA, USA), generated sounds, over a pair of Bluetooth headphones, which realistically sounded as if they were emitted by sources that were positioned in the experimentation room (Fig. 4). The 3Dception plugin achieves realistic sound spatialization using generalized head-related transfer functions (Zhong and Xie 2014) and a logarithmic distance attenuation function. Thus, as the blindfolded participants moved from the starting point towards the position of the virtual sources (Fig. 4), the apparent intensity and frequency content of each source would change in a physically appropriate manner. The "virtual" sources

[1] Streit, Shockley and Riley (2007) required only 17 participants to find a significant effect of a similar gain manipulation to the one used in Experiment 1.

were spaced at varying distances across trials, producing a range of aperture widths. Unity3d also handled the application of gain to the participant's head movement in the manipulated trials.

Procedure

After the system began tracking their motion, the participants were guided through an initial orientation wherein they could freely explore the room and become acquainted with a pair of virtual sound sources. During the orientation, participants were asked to make sure that they were able to (1) identify the positions of the sound sources by pointing, (2) center themselves between the sources, and (3) approach the sources from a distance and stop before passing between them.

After the orientation, participants were given a brief training session, during which they were blindfolded and asked to approach a randomized set of ten sound source pairs, spaced from 24 cm to 96 cm apart at 8-cm intervals. They were brought to a starting position (3 m in front of the center of the aperture) and asked to walk forward and stop when they were roughly arm's length away from the two sources. They were asked to then center themselves between the two sources and provide a verbal "yes or no" judgment of their ability to pass between the sources without hitting their shoulders and without having to turn sideways. After each judgment, the participants were asked to turn around and walk back to the starting position and then re-orient themselves towards the sound sources. The training session included ten trials but was extended until participants successfully judged the passability of ten consecutive apertures. This ensured that they were able to make passability judgments with acceptable accuracy (i.e., they could differentiate between apertures that were wider and narrower than their shoulders). After the training session was complete, participants were asked to, in the same manner, complete 90 consecutive trials (three randomized blocks of ten different aperture widths across three gain conditions: gain < 1, gain $= 1$, and gain > 1).

Data analysis

Perceptual reports were given a score of 1 if correct and 0 if incorrect. A judgment was counted as correct if it reflected the actual passability (aperture $>$ shoulder width) or impassability (aperture $\leq$ shoulder width) of the corresponding aperture for that individual. In this way, an average accuracy score was assigned for each condition for each participant (see Fig. 5a). Aperture widths were also coded in terms of the absolute value of their difference from an individual's shoulder width (see Fig. 5b). This allowed accuracy to be measured as a (unsigned) function of extremeness from the actual aperture boundary (i.e., between what could and could not be passed through by each participant). Finally, for each participant in each condition, a mean coefficient of variation for both lateral position and head rotation was calculated. This was done to better characterize the exploratory dynamics that participants employed during task performance.

A random coefficient, multilevel regression analysis was used to predict trial by trial accuracy scores based on aperture extremeness, gain, and exploratory dynamics. This type of analysis is ordinarily used to investigate relationships within nested data sets (e.g. student, school and state levels [Snijders 2011]), but were used here because unlike other, similar methods it does not require that each group has an equivalent number of observations, as this is not the case when parsing the judgment scores by aperture extremeness (given that participants were different sizes relative to each aperture).[2]

We took a step-wise approach to model building with comparisons of fit made between nested models through assessment of change in -2 log likelihood, which for nested models has a chi-square distribution with degrees of freedom equal to the difference in the number of parameters between compared models. Table 1 shows the progression from the base model (model 1) to model that included various other predictors. The final model (Model 3) is outlined in Table 2.

Results and discussion

Average accuracy scores across all participants and conditions were high [$M = 2.42$ (maximum $= 3$), SD $= 0.86$], indicating that participants correctly judged passability in most cases. The best fitting multilevel regression model, as determined by decreases in -2 Log Likelihood, indicated a significant main effect for Extremeness ($F(1,46.14) = 220.19$, $p < 0.01$). A coefficient of 0.20 for Extremeness indicated a positive relationship between judgment accuracy and extremeness. In other words, the more different an aperture width was from an individual's shoulder width the more accurate participants' judgments were. This is exactly the pattern that would be expected if participants are able to differentiate the aperture widths relative to their own shoulder

[2] The conventional method for analyzing binary (yes/no) perceptual judgments, as was followed by Russell and Turvey (1999), Warren and Whang (1987) and others, produces sets of critical perceptual boundaries—critical aperture to shoulder width ratios in this case—that can then be compared across conditions or groups, to reveal any perceptual differences generated by a given manipulation. This method could not, however, reliably pick boundaries for Experiment 1 because many participants produced judgments that were not sufficiently regular in their relationship to aperture width. Experiment 2, however did follow this method and was able to determine body scaled perceptual boundaries.

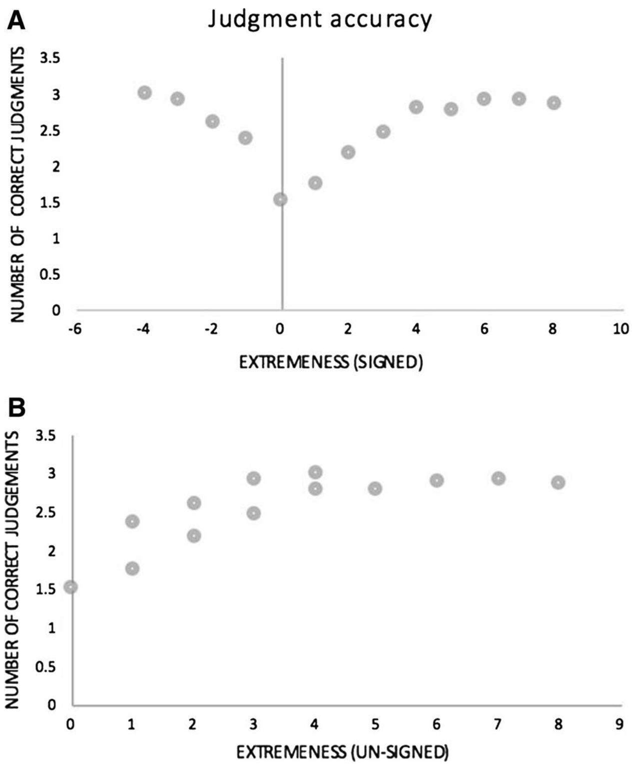

Fig. 5 Judgement accuracy of all participants across all levels of aperture extremeness, both signed (**a**) and unsigned (**b**). Positive values of extremeness indicate that the apertures were wider than the individual's shoulders and negative values indicate that they were narrower

width, suggesting that participants were indeed able to acoustically differentiate apertures for passing through.

No significant effect was found for Gain or for head rotation variability. A significant main effect was found for lateral head position variability ($F(1, 32.24) = 4.49$, $p < 0.05$). A coefficient of 0.58 for lateral head position variability indicated a positive relationship between the variability in lateral head movement and judgment accuracy (i.e., the more lateral head movement the more accurate participants' judgments were). This finding suggests that lateral head motion, rather than hypothesized head rotation, defined the relevant exploratory procedure for successful aperture perception. This is a surprising finding in light of our pilot data and will be discussed further in the general discussion.

In sum, Experiment 1 provided evidence that individuals are able to accurately judge the passability of acoustic apertures and identified a potential exploratory action that may underlie this ability. However, the results of this experiment are insufficient to conclude that individuals produce perceptual judgements that are scaled to their body dimensions in a particular way. This conclusion would require evidence that individuals of different shoulder width picked out the same shoulder-scaled aperture width as being minimally passable. Experiment 2 was specifically designed to address this issue.

Experiment 2

This experiment aimed to determine a shoulder-scaled critical boundary for auditory aperture passability. To accomplish this, a wide-shouldered group and a narrow-shouldered group were recruited so that their judgements of minimally passable aperture width could be compared. Those who have wider shoulders should judge wider apertures to be minimally pass-through-able while narrower individuals should judge more narrow apertures to be pass-through-able. If the two groups are using the same body-scaled boundary, then there should be no difference between judgments that are scaled to body size (cf. Warren and Whang 1987). There was no manipulation of the information involved in this experiment.

Participants

Twenty[3] female college students (age 18–23) with normal hearing and vision participated in this experiment. They participated on a voluntary basis from the University of Cincinnati Psychology Research Participation Pool and received class credit in exchange for participation. To ensure difference in affordance boundaries, half (ten) of the participants had shoulder widths that were in the uppermost population quartile[4] (> 46 cm; $M = 47.7$ cm) while the other half represented the lowermost quartile (< 43 cm; $M = 36.7$ cm). Females were used exclusively due to the difficulty of creating gender-balanced shoulder width groups.

Apparatus/materials

For the second experiment, an HTC Vive (HTC, New Taipei City, Taiwan) and integrated headphones were used to track the motion of each participant's head and to present the visual and auditory stimulus. As in Experiment 1, the participant's position and rotation were streamed into the Unity3d game engine (Unity Technologies, San Francisco, CA, USA). The Steam Audio plugin (Valve, Bellevue, WA, USA) was used for sound spatialization in Experiment 2. This produced very similar HRTF and distance-based filtering to the plugin used in Experiment 1 which had been discontinued.

[3] Warren and Whang (1987), in a similar experiment, found significant differences between groups of only 5 participants each (a total of 10 participants).

[4] Anthropometric data from the ANSUR II Database.

Table 1 Changes in − 2LL for inclusion of variables related to exploratory activity as predictors of perceptual performance

Model		− 2LL	Δ-2LL (dof)	p
1	Extremeness, Gain, Extremeness × Gain	3279		
2	Extremeness, Gain, HRV, Extremeness × Gain, Extremeness × HRV, Gain × HRV, Extremeness × Gain × HRV	3272	− 7 (8)	> 0.01
3	Extremeness, Gain, LMV, Extremeness × Gain, Extremeness × LMV, Gain × LMV, Extremeness × Gain × LMV	3225	− 54 (8)	< 0.01
4	Extremeness, Gain, LMV, Extremeness × Gain	3228	− 3 (5)	< 0.01

The comparisons reflected in the Δ-2LL column are as follows: Model 2 vs Model 1, Model 3 vs Model 1 and Model 4 vs Model 3

HRV head rotation variability, *LMV* lateral movement variability

Table 2 An outline of the effects from the final model (Model 4)

Predictor	Estimated β	SE	p
Intercept	1.41	0.07	< 0.01
Extremeness	0.18	0.01	< 0.01
Gain	− 0.07	0.04	> 0.01
LMV	1.11	0.15	< 0.01
Extremeness × gain	0.01	0.01	> 0.01

Procedure

Experiment 2 began with a training session, during which participants were placed in a virtual room containing a green start line and red stop line. They were asked to walk from the green line to the red line, behind which two invisible virtual sound sources were located. In half the trials, the sources were initially placed at 96 cm apart (wide initial aperture). In the other half, the sources were placed 24 cm apart (narrow initial aperture). Trials alternated between wide and narrow apertures. Participants were asked to indicate, during each trial, how the sources should be moved (inward or outward) so that they were just wide enough to be passed through without the participant turning their shoulders or colliding with either source. The sound sources were adjusted by the experimenter to accommodate the participant's requests. When the participant was satisfied with the source placement the sources were shown to her in the form of two small spheres in her virtual environment. This process was repeated eight times to familiarize the participant with the task and help them visualize what they should be doing. Subsequently, the participants were asked to complete eight more trials in the same manner, but without being shown the source positions visually. Again, in half the trials, the sources were initially placed at 96 cm apart (wide initial aperture). Alternatively, on every other trial the sources were placed 24 cm apart (narrow initial aperture). After each of these trials, the distance between the final positions of the sources was recorded, representing the participant's judgment of a minimally passable aperture width.

Results and discussion

The aperture width judgements for the narrow-shouldered and wide-shouldered groups were submitted to a repeated measures analysis of variance (ANOVA) with trial number and initial aperture width (wide [i.e., descending aperture sizes] or narrow [increasing aperture sizes]) as within-subjects factors. As illustrated in Fig. 6a, there was a significant main effect of group ($F(1,18) = 19.88$, $p < 0.001$, $\eta_p^2 = 0.53$), with the minimally passable aperture being larger for the wide-shouldered group than for the narrow-shouldered group. Aperture width judgements re-coded as a ratio of aperture width to shoulder width (judged aperture width/participant shoulder width) were submitted to the same ANOVA. The only notable difference in results is that the main effect of group was no longer statistically significant ($F(1,18) = 1.50$, $p = 0.24$, $\eta_p^2 = 0.08$). In other words, when the perceptual boundary of aperture pass-through-ability was scaled to the shoulder width of participants, the two groups were not statistically different in terms of their perceptual reports (see Fig. 6b). These findings suggest that the two groups successfully differentiated what was pass-through-able, and that their judgements were scaled to body size in a consistent fashion. For both groups, the average shoulder-scaled aperture width judgement was approximately 1.56 shoulder widths [95% CI (1.46, 1.67)] which is significantly higher than the more common findings of 1.3 shoulder widths (e.g., Warren and Whang 1987; though cf.; Franchak et al. 2012 who found 1.1). The difference in critical boundary from prior research may be due to the unfamiliarity of the participants with auditory navigation resulting in a lack of attunement to an appropriate, specifying variable (discussed further in the general discussion).

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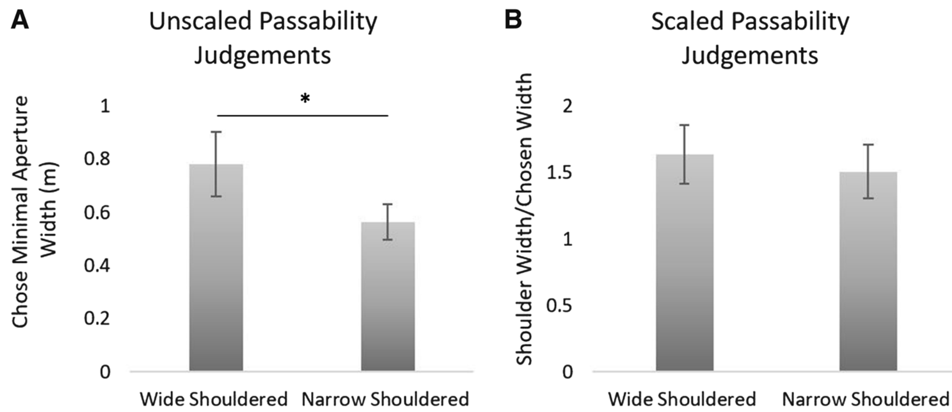
Fig. 6 **a** The mean minimally passable aperture width chosen by wide- and narrow-shouldered individuals and **b** the mean minimally passable aperture width chosen by wide and narrow shouldered individuals, scaled to their shoulder width. Error bars reflect 95% confidence intervals



General discussion

In the current study, the main goals were to (1) determine if individuals can perceive passability (using auditory information) and (2) test a candidate (acoustic) informational variable. Experiment 1 demonstrated the perceptual sensitivity of individuals to the passability of acoustic apertures. Consistent with previous aperture passability studies (e.g., Gordon and Rosenblum 2004; Russell and Turvey 1999), individuals were able to successfully differentiate passable and impassable apertures that had boundaries demarcated using sound. However, it was not clear if they were able to accurately perceive their own body-scaled critical boundaries of passability based on the data collected using the present method. In Experiment 2, the inclusion of wide/narrow-shouldered groups and a different report method (adjustment by the participant) allowed for the demonstration of a consistent body-scaled critical boundary.

The gain manipulation used in Experiment 1 to evaluate perceptual sensitivity to the candidate acoustic informational variable (Fig. 3) did not significantly influence perceptual reports. It thus appears unlikely that this variable was used to inform participants about aperture size in this study. Although gain and head rotation were not significantly related to performance, the significant relation between lateral movement and performance suggests that participants exploited a different variable, one that captures some relationship between lateral head position and aperture width. This variable, however, may only be useful in generating reasonably accurate estimates of aperture width while not providing the specific relationship between shoulder width and aperture width that would be needed for the direct perception of afforded passability.

We predicted the use of the informational variable described in Fig. 3 based on the results of the pilot which indicated that exploration through head turning was instrumental for adequate performance. One difference between the pilot study and Experiment 1 is the conditions of exploration. In the pilot study, participants were limited in their lateral movement by a plank positioned between their legs that guided them towards the aperture. It may be the case that these restricted circumstances facilitated discovery of the specifying variable related to head rotation (see Fig. 2). When individuals can freely explore an auditory aperture (as in Experiments 1 and 2), they pickup initially salient (van de Langenberg et al. 2006), though possibly not specifying, information that is implicated by their more natural lateral movements. Therefore, under less-restricted conditions, more experience might be needed to hone the exploratory patterns that implicate the use of specifying variable for perception of auditory passability. It is also important to consider that the proposed informational variable could be modulated by changes in distance or head rotation. Thus, experimental manipulation of the variable could have produced changes in perceived distance from the aperture rather than aperture size. Although we did not ask for distance reports and so cannot speak to this possibility in the present data, we see this as unlikely given other available perceptual information for distance changes (e.g., patterns of acoustic intensity change, kinesthetic information from walking) but may be useful to control for in future research. In any case, the lesson is that task constraints seem to be key for perception of environmental affordances regardless of the means by which such affordances are perceived.

The critical boundary identified in Experiment 2 was significantly larger than what has been found in work on visual aperture passability. This may be due to the use, by most participants, of information that did not specify passability. Jacobs and Michaels (2007) contend that perceivers in novel situations often use non-specifying variables and then, with proper feedback and instruction, progress to the use of specifying variables through a process of perceptual learning. Perception is thus related to an information space containing multiple variables that correlate in different ways, some more strongly than others, to a property (here the passability of an aperture). The structure of the errors in performance related to the use of a non-specifying variable generate information for learning—that is, information that specifies the direction of change in information space that will lead to the use of a specifying variable. For example, when perceiving wielded object width, initially, individuals are generally attuned to mass and then gradually towards using the third moment of inertia after consistently receiving appropriate feedback (Wagman et al. 2001).

It may have been the case that with proper feedback and number of experimental trials participants in Experiments 1 and 2 would have attuned to the specifying variable posited at the outset of this study and would, therefore, have been able to more accurately judge their critical boundaries. Future studies could test this conjecture by assessing whether different exploratory patterns predict perceptual reports and what exact conditions are necessary to guide individuals towards the proposed, specifying variable involving head rotation. In both Experiment 1 and 2, accuracy was emphasized in the initial training session, but participants were given no performance-related feedback during the later (experimental) trials. If participants were using a non-specifying informational variable they would not, due to a lack of feedback, be aware of any incorrect judgments later in the experiment and thus would not be able to adapt an exploratory strategy that allowed the detection of more useful information.

Alternatively, it may be possible that the informational variable accessed through lateral movement *is* specific to aperture passability, but participants were unable to properly calibrate the relevant values of the specified relation due to insufficient experience with the task. Improper calibration would explain the imprecise location of the action boundary even in light of yet-unseen evidence that participants were attuned to specifying information. As was demonstrated by Jacobs, Silva and Calvo (2009), individuals become increasingly calibrated as they gain experience with a task. If no shift in behavior from lateral movement to head turning was observed after participants had considerable experience with auditory apertures, but judgement accuracy increased significantly it could be concluded that the information related to lateral movement is likely specific to passability. We leave these questions to future investigations.

In summary, three conclusions can be drawn based on the present research. Participants were indeed able to acoustically differentiate two point-source auditory boundaries (Experiments 1 and 2). Participants of varying action capabilities were consistent in their identification of their action capabilities (suggesting consistent use of an acoustic informational variable) (Experiment 2). Exploration patterns involved in acoustic perception were distinct depending on the physical constraints of the task (which will almost certainly play an important role in understanding the underlying acoustic information that supports performance in this task) (Pilot data vs Experiment 2).

Applications/practical implications

An understanding of the acoustic information that is relevant to passability will allow for virtual environments to be constructed such that the auditory perception of passability within them can be actively manipulated. Additionally, the current study represents a step towards a general understanding of auditory perception and thus a step towards the creation of virtual auditory environments that may enhance acoustic navigation and behavioral control, which could be of profound significance to those with visual perceptual deficits. Individuals who have visual impairments, for instance, may find that virtual auditory environments are useful as a training tool that would tune their ability to navigate using sound. Many different acoustic situations, such as road crossing or building navigation, could be simulated and would allow for training to take place in a safe and controlled environment. Furthermore, future studies could investigate the optimal sound-source characteristics for auditory navigation so that real sound sources could be embedded in the environment to facilitate mobility for those with visual impairments.

Advancements in our understanding of action-relevant acoustic information would also potentially enrich theoretical understanding of other perceptual modalities as well as multi-modal perception, generally. As virtual environments become more complex and as control is shifted from hand-operated controllers to human body movement, a need to understand the relationships between human perception and action comes to the forefront. Most real human behaviors involve dynamic, full-body movement that is guided by rich perceptual information. Virtual environments will continue to be useful tools for understanding human perception, but only if the nature of perceptual information is considered during their construction. Realism should be sought, not in an artistic sense, but in a sense that is considerate of real physical relationships between individuals and their environments.

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