# University of Cincinnati

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**I, Christopher Riehm, hereby submit this original work as part of the requirements for the degree of Master of Arts in Psychology.**

It is entitled:

**Virtual Auditory Aperture Pass-ability**

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Virtual Auditory Aperture Passability

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**Abstract**

The current study 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 a virtual environment, participants were asked to judge whether they could walk through two (virtual) sound sources in front of them without hitting them with their shoulders and without turning their shoulders. In order to evaluated a specific informational variable that would involve head rotation to detect, a gain was applied to head movement in the virtual environment to determine if participants' perceptual judgments of passability were influenced by this manipulation. Although participations were able to differentiate aperture sizes based on acoustic information, though 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 an alternative informational variable, based on lateral movement, may have been used. The present findings are consistent with previous studies investigating auditory perception of passability. They also offer promise of the application of virtual reality technology in the study of auditory perceptual abilities in real-world situations.

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# CHAPTER 1

## Introduction

As human agents, we engage in a diverse set of actions each day. We deftly navigate cluttered rooms, precisely pilot speeding vehicles, and skillfully wield a variety of tools and devices. These and similar activities make up the bulk of our waking lives and are characterized by our continuous engagement with an ever changing world. Unlike activities that are, at least seemingly, purely mental (imagination, memory etc.), most require constant adaptation to evolving optical, acoustical, mechanical and chemical circumstances. We watch the roadway and fluidly switch lanes to avoid slow-moving cars; we actively locate ringing cell phones under couch cushions; we operate remote controls and keyboards with only touch. More generally, we *perceive* our relationship with the world and so are able to act effectively. The present study is designed to investigate perception by evaluating the human ability to navigate the environment using acoustic information.

Gibson (1979) proposed that perception, at its most basic level, is of affordances—opportunities for action. Affordances are defined as relations between the animal and its environment (Chemero, 2003). Gibson (1979) proposed that animals need only detect the information that specifies the animal-environment relationship in order to perceive the affordances that are available at any given time. An individual who is attempting to pick up a glass of water to drink, for example, need only detect a commensurate relationship, a fit, between her hand and the glass. Perception of this relationship requires that there be a pattern of energy 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. The ability to perceive affordances is what allows 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 in order to avoid (potential costly) adverse outcomes.

Affordance perception and the existence of the required specifying information have been primarily studied in visual and haptic perception. This is most likely due to the relatively obvious involvement of these two modalities in everyday activity. Visually and haptically perceived affordances such as sit-on-ability (Mark, 1987; Mark, Balliet, Craver, Douglas, & Fox, 1990), step-on-ability (Warren, 1984; Wraga, 1999)), reach-ability (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989) pass-through-ability (Davis, Riley, Shockley, & Cummins-Sebree, 2010; Fath & Fajen, 2011; Wagman & Taylor, 2005; Warren & Whang, 1987), and many others have been thoroughly examined (see Richardson, Shockley, Fajen, Riley, & Turvey, 2008, for a review).

For the purposes of the current study, passability, afforded by openings of different widths, is the focus. Given that the human capacity to determine passability has been demonstrated in a wide range of studies and contexts (Davis, Riley, Shockley, & Cummins-Sebree, 2010; Fath & Fajen, 2011; Wagman & Taylor, 2005; Warren & Whang, 1987), it provides a promising domain for an investigation into auditory perception. In the first empirical study on this ability, Warren and Whang (1987) investigated if individuals were able to visually perceive the pass-through-ability affordance and, if so, what visual information could support this activity. Importantly, Warren and Whang characterize affordances, here, in terms of the *critical point*s at which individuals switch between behavioral modes (e.g., can or cannot fit through) during a task, a method originally formulated by Warren (1984). For aperture passability, this critical point can be defined by a ratio that represents the relationship between the width of an aperture (A) and the width of an individual’s shoulders (S) (A/S ratio). This relationship is defined as the specific aperture width at which an individual begins turning their shoulders while attempting to pass through. The average critical point was found, experimentally, to lie at an A/S ratio of 1.3. It was also found, in a second experiment, that individuals with wide shoulders and those with narrow shoulders judged different aperture widths to be minimally passable. When their pass-ability judgments were expressed as A/S ratios, however, they were virtually identical.

An important component of Warren and Whang's (1987) investigation was their determination of the informational basis for the perception of aperture pass-ability. It was hypothesized that individuals used eye-height-scaled information as the basis for their perception of pass-ability. Sedgwick (1973) showed that perceivers can use exactly this type of visual information to know about the relationship between vertical size of an object and their own body size. Particularly, when looking straight ahead, an individual’s line of sight is parallel to the ground and divides the field of view in half. As a result, the position and extent of objects in the visual field have a specific geometrical relationship to height of the eyes—the center level of the visual field. Those objects that do not extend above the perceiver’s line of sight are shorter than that height by an amount proportional to the angle needed to tilt the head so that the eyes are pointed directly at the top edge of the object. Importantly, a similar, trigonometric relationship also allows for the horizontal dimensions of objects to be determined based on a relationship to eye height. Warren and Whang stated that because there is allometric scaling between a perceiver’s eye height and their shoulder width, the shoulder to aperture width ratio can be characterized as an invariant relationship to eye height and is thus directly available to the perceiver.

In a subsequent experiment, designed to test whether or not individuals were actually using eye height information, Warren and Whang (1987) manipulated eye height by artificially raising the floor, unbeknownst to participants. They hypothesized that this would significantly affect the critical point that was derived from their pass-ability judgments, which is, in fact, what they found. Those who had their eye heights raised produced judgments of pass-ability that were shifted so that narrower apertures were judged to be more readily passable than would have been expected under normal circumstances. The relationship between apparent eye height (normal or altered) and critical aperture width, however, remained stable. Sensitivity to this information has been found in a variety of studies in subsequent research (e.g., Mark, 1987; Wraga, 1999).

## The Current Study

There is a dearth of research on auditory affordances. Previous studies have focused on the auditory perception of certain object properties such as length (Carello, Anderson & Kunkler-Peck, 1998), size, and shape (Carello, Wagman & Turvey, 2005) but there is little research on auditory affordance perception, especially with a focus on the informational basis of such a perceptual ability. The general objective of the current study is to show that audition can be used as a primary means of navigation by way of the aperture pass-ability paradigm, established previously. The aims of the current study are to demonstrate that the critical point of pass-through-ability of an aperture can be perceived and to evaluate a candidate acoustic informational variable that specifies pass-through-ability.

The lack of focus on auditory perception of affordances related to navigation may stem from a seeming inability of humans to use of auditory information in this way. Navigation using sound is something normally attributed only to bats and other echolocating animals. Humans can, however, use sound to skillfully navigate (Loomis, Golledge, and Klatzky 2001; Walker & Lindsay, 2006), though, research into human auditory navigation is far less prevalent than research on visually guided navigation, especially with respect to affordance perception. Two prior studies, however, have made efforts in this regard.

Russell and Turvey (1999) devised an experiment to study if the pass-through-ability of an opening could be perceived using acoustic information. In that study, participants were asked to judge whether different width gaps between a speaker, playing a mallard vocalization at regular intervals, and a wall were passable. Russell and Turvey hypothesized that participants would be able to use the sound of the speaker and the resulting reflections off of the adjacent wall to perceive aperture pass-ability. The study produced a similar result (aperture/shoulder width = 1.11) to Warren and Whang's (1987) initial investigation into aperture pass-through-ability. Russell and Turvey mused, however, that the accuracy of pass-through-ability judgments in this experiment might have been due to the participants' prior knowledge of the wall's position and their ability to determine the distance of the speaker from their shoulder. If this were the case, they would not perceive pass-ability of an aperture, but simply notice differences in the single sound source's horizontal distance from their body. In efforts to further investigate the phenomenon they devised three more experiments in which they manipulated the position of the participant relative to the wall, the distance to the aperture at which the participant gave their judgment and the participants' exposure to the room prior to the experiment. The results of the first additional experiment returned significantly higher critical values (M = 2.04) than those seen in the first experiment from the same study. This suggests that, as was suspected, participants were not reporting about the aperture, but only the distance of the speaker from their body. That is, they were not picking up on the added distance from the wall and were underestimating the aperture width. The second study showed no influence of sound source distance on the critical boundary, suggesting that passability is not determined using interaural time differences—the difference in time that it takes for a sound to reach both ears—because these would vary with source distance. The third study resulted in a significant difference in critical boundary between those who saw the room prior to the study (M= 1.19) and those who did not (M = 1.36), suggesting that prior experience with a room provides some information that is later used in accomplishing the task. Overall, Russell and Turvey could not determine, specifically, what information was being used for auditory perception of passability. They noted, however, that, given the right configuration of constraints, it was certainly possible to guide action with auditory perception.

In a similar set of experiments, Gordon and Rosenblum (2004) showed that the pass-ability of an aperture could be perceived when a sound source was placed behind it, so that the sound was partially occluded by the aperture's sides. In the first experiment, a recording of crowd noise was played from behind an adjustable aperture while blindfolded participants faced it and actively explored (head turning, leaning etc.). They found that participants could successfully determine which apertures were wider than their shoulders and which were not. They also found that the critical A/S ratio was 1.16, similar to the findings of Warren and Whang (1987). They concluded that the auditory perception of occluded-sound-source type aperture pass-ability is indeed possible, but due to higher standard deviations than those produced by individuals in Warren and Whangs's (.48 vs .15) it is not as reliable as perception of visual aperture pass-ability. In a second experiment Gordon and Rosenblum investigated the possibility of acoustic perception of vertical apertures. They found that apertures with larger vertical openings were judged as passable significantly more often than those with smaller vertical openings. They also found, in a third experiment, that the absolute intensity of the sound source had a significant effect on the ratio at which participants switched from judging vertical apertures as passable to not passable. The reason for these differences is unclear, but it may point to a plurality of acoustic properties involved in the perception of auditory aperture pass-ability. In discussing their findings Gordon and Rosenblum assert that a similar metric to eye height, such as ear height or inter-aural distance, in relationship to the width of the aperture could provide information for direct auditory perception of aperture pass-ability. In the next sections, a similar acoustic structure is posited for evaluation in the present study.

Two pilot studies concerning the auditory perception of pass-ability of apertures made up of separated sound sources were conducted prior to the current study. In the first, participants were asked to approach the sound sources and make a series of judgments regarding passability while straddling a wooden plank, so as to stay aimed at the center of the opening. Most participants performed very poorly and seemed completely unable to perceive passability. A few participants, however, adopted a strategy of exploratory, horizontal head movements, specifically right-left head turning. These participants performed significantly better, successfully discriminating between wide and narrow openings. In the second pilot study, all participants were asked to actively listen by moving and turning their heads. All participants in this study performed significantly better than those in the first study who stayed still. This shift in accuracy suggested that head movements are an essential aspect of auditory perception of aperture pass-ability and may underlie the acoustic information that specifies that affordance. For example, basic trigonometry reveals that the amplitude of head rotation required to center the sound sources between the ears at each extreme is directly related to both their distance apart and their distance from the observer. Thus, one detection strategy would be to center one sound source (turn the head until its intensity is equal in both ears) and then turn in order to center the other source, both while approaching or receding from the aperture. The angle subtended by head, in this case would represent the top angle of a triangle, 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.

As can be seen in *Figure 1,* the previously described head-turn angle (henceforth referred to as $\beta$) changes in a manner that is systematically related to the size of the aperture as the perceiver moves a certain distance ($\Delta D$). The width (referred to in *Figure 1* as *w*) of the aperture, therefore, has an invariant relationship (described in *Figure 2*) to $\beta$ and $\Delta D$ (both of which are accessible to the participant through head movement and body movement, respectively). Presumably, as is the case with eye height and shoulder width (Warren & Whang, 1987), there exists a similar allometric relationship between stride length and shoulder width. Perceivers may detect this, along with the invariant relationship between w, $\beta$ and $\Delta D$ in order to know the size of an aperture relative to their shoulders. While these constitute one informational relationship that could be detected by individuals who intend to perceive passability, it should be noted that there may be any number of other higher-order relationships that they may be using. Each of these relationships, however, would be detected using different exploratory movements. Therefore, noting the specific nature of exploratory movements that are used in completing the task will be useful in assessing the validity about claims relating to the information detected.

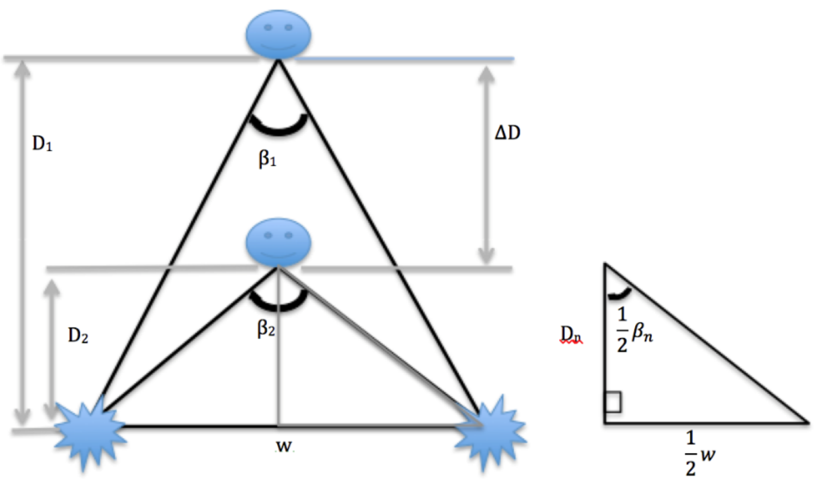


*Figure 1: A diagram of a perceiver approaching an auditory aperture and utilizing exploratory head movements.*

$$\Delta D = D_1 - D_2$$

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

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

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

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

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

*Figure 2: The trigonometric relationship between β, ΔD and w.*

In an effort to demonstrate that pass-ability can be perceived in a two sound-source arrangement, the current study aimed to evaluate critical A/S ratios. In order to evaluate perceptual sensitivity to the proposed informational variable described above, a gain manipulation on head rotation amplitude using auditory virtual reality was implemented. This manipulation, unbeknownst to the participants, virtually increased or decreased their lateral head rotation relative to the sound sources in order to artificially manipulate β. This was achieved by implementing a "virtual" head, driven, in real time, by the motion of the participant, and "virtual" sound sources (described in detail in the Method section), heard through motion-tracked headphones. During the non-manipulated trials (gain = 1) the virtual angle traversed by lateral head rotation corresponded canonically with actual lateral head rotation. These trials make up one third of the overall trials. The other two thirds are made up of a gain that increases lateral head movement (gain > 1) and a gain that decreases head movement (gain < 1). I predicted that trials with altered head movement would exhibit differences in the perceived A/S ratio critical boundary for pass-through-ability. Specifically, I predicted that a gain that is greater than 1 should produce higher critical A/S ratios because participants would need to turn their head less to center each sound source and would therefore judge wider apertures to be narrower and some passable apertures to not be passable. I predicted the reverse for a gain of less than 1.

## Method

### Participants

Forty-six college students 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.

### Apparatus/Materials

For this study, 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 50hz. The participant's position was streamed into the Unity game engine (Unity Technologies, San Francisco, CA), which was then used to generate spatially oriented sounds, over headphones, corresponding to two obstacles (sound sources) that were spaced at varying distances and positioned in the motion capture room (as seen in *Figure 3*). Both sound sources emitted the sound of a continuously bowed violin, but the sources were pitched six semitones apart so that the sources would be more easily differentiated. Figure 3 indicates the positions of the sound sources and motion capture cameras relative to the participant's starting point.

Unity also handled the application of gain to the participant's head movement in the manipulated trials. The spatialization of the sound sources was handled by the 3dception audio plugin (Facebook, Menlo Park, CA). This plugin uses head-related transfer functions (HRTFs) and a logarithmic attenuation function to realistically reproduce the acoustic spatialization of a sound source. A unique head-related filter was applied to the left and right sound signals depending on the relationship between the listener's head position and rotation and the desired sound source position. The sound sources were modeled as point emitters and so produced equivalent volumes in all directions, depending on their distance from the listener.

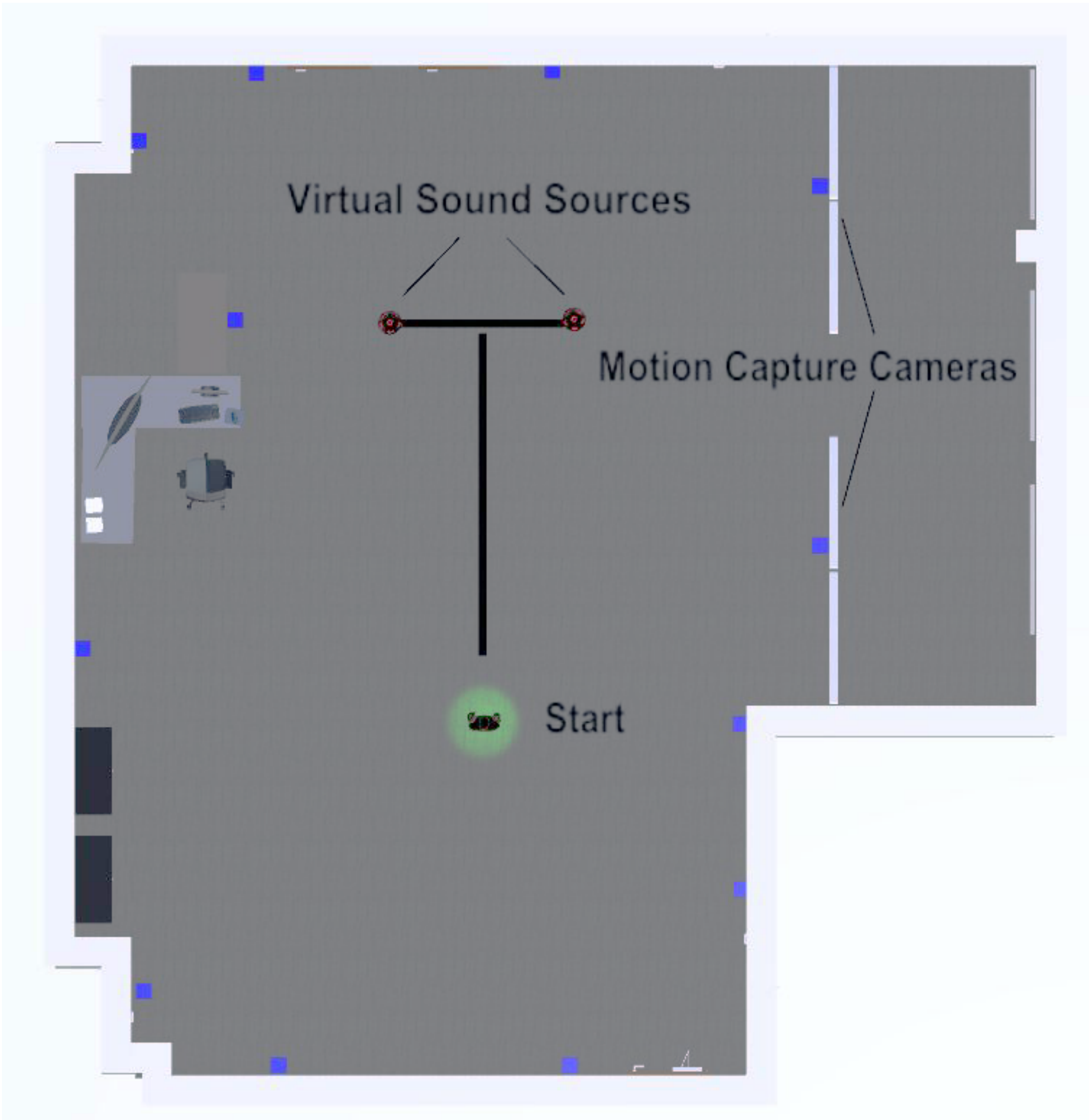


*Figure 3: A diagram of the experimental setup including the positions of the starting point, sound sources and motion capture cameras.*

**Procedure**

Participants provided informed consent to the Institutional Review Board-approved procedure after an overview of the experimental procedure. After informed consent was obtained, demographic information was collected and the participant's shoulder width was measured. Next, participants were outfitted with a pair of wireless headphones and a set of infrared reflective markers. The markers were placed on the center of the participant's foreheads and on the wireless headphones. The participants were then asked to stand in the center of the room so that the motion capture system could begin tracking their motion. After the motion tracking system was activated, the participants were guided through an initial orientation wherein they were allowed to 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, 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 10 sound source pairs, spaced from 24 cm to 96 cm apart at 8 cm intervals. They were brought to a starting position (3m in front of the center of the aperture) and asked to walk forward and stop before reaching 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 10 trials, but was extended if participants were unable to make pass-ability judgments with acceptable accuracy (i.e., they could not differentiate between apertures that were much wider and much narrower than their shoulders).

After the training session was complete, participants were asked to complete 90 trials (three randomized blocks of ten different aperture widths across three gain conditions (gain < 1,gain = 1, and gain > 1)). They were asked, after each block, if they would like to take a short break. After the completion of all 90 trials, participants were thanked and any questions were addressed.

**Data Analysis**

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, in order to reveal any perceptual differences generated by a given manipulation. First, however, the critical boundaries must be identified using the raw yes/no judgments. In order to determine critical boundaries for this experiment it was crucial that the transition from non-passable to passable aperture widths be clear (i.e., a sigmoid function delineating the transition from "no" to "yes") and identifiable for each participant. Ideally, each participant would say that *all* apertures under a certain width were not passable and *all* apertures greater than that width were passable.

The data were initially submitted to probit analysis in order to determine the perceptual critical boundary. In this type of analysis a sigmoid function is fit to the distribution of judgments and the 50%-yes point of the function is identified by the probit analysis as the critical boundary (e.g., Davis et al., 2010). This method could not, however, reliably pick boundaries because many participants produced judgments that were not sufficiently regular in their relationship to aperture width. That is, some apertures that were judged to be passable were subsequently judged not to be passable and vice versa. In many cases and partially due to the fact that each width/gain condition was only presented 3 times, a fit and critical boundary could not be determined using standard psychophysical methods.

For this reason, an alternative method of estimation, which was used by Warren and Whang (1983), was applied. This involved the use of a simple rule to determine critical boundaries. For each participant and each gain condition, the critical boundary was operationalized as the aperture width at which the participant always judged the aperture to be passable and did not judge any wider apertures not to be passable. Like the probit analysis, this method could not, however, reliably estimate critical boundaries for all participants and conditions. There were simply too many boundaries that could not be determined due to a mixture of passable and impassable judgments for the same aperture width. It is unclear precisely why the judgments were not sufficiently uniform, but this may be due to the novelty of the task. The training session may simply have not been long enough for individuals to develop a successful strategy.

Due to the abovementioned difficulties, I coded the perceptual reports relative to the actual boundary relative to each participant's shoulder width (see Figure 4A). A judgment was counted as correct if it corresponded to an aperture that was actually passable. For example, if the aperture was passable and the participant gave a "yes" judgment a point would be given. Concordantly, a "no" judgment when the aperture was not passable would also yield a point. In this way, an average accuracy score was assigned for each condition for each participant. Aperture widths were coded in terms of the absolute value of their difference from an individual's shoulder width (see Figure 4B). This allowed accuracy to be measured as a 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 were calculated. This was done in an effort to better characterize the exploratory dynamics that were exhibited. These data were submitted to a random coefficients, multilevel regression analysis. This type of model is ordinarily used to investigate relationships within nested data sets (e.g. student, school and state levels), but was used here because unlike other, similar methods it does not require that each group have an equivalent number of observations, as this is not the case when parsing the judgment scores by aperture extremeness.

## Results

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 accuracy scores were submitted to a random-coefficients, multilevel regression analysis. The factors used in the model were Extremeness and Gain. Factors for lateral head position variability and head rotation variability were also included so that exploratory movements engaged in by participants could be further investigated. The first The best fitting model, as determined by -2 Log Likelihood indicated a significant main effect for Extremeness ($F(1,46.14) = 220.19$, $p < .01$). 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. No significant effect was found for Gain or for head rotation variability. Surprisingly, considering previous predictions, a significant main effect was found for lateral head position variability ($F(1, 32.24) = 4.49$, $p < .05$ ). A coefficient of .58 for lateral head position variability indicated a positive relationship between lateral head movement and judgment accuracy (i.e., the more lateral head movement the more accurate participants' judgments were).

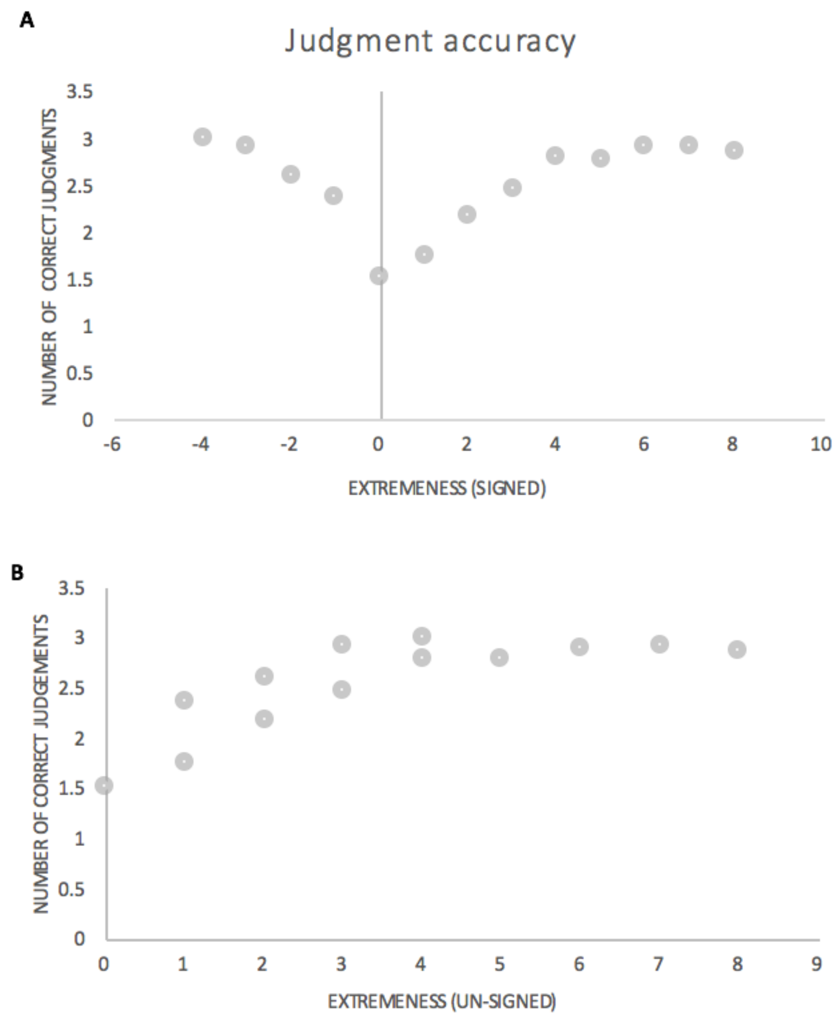


*Figure 4: Judgement accuracy of all participants across all levels of aperture extremeness, both signed (A) and unsigned (B). Positive values of extremeness indicate that the apertures were wider than the individual's shoulders and negative values indicate that they were more narrow.*

# CHAPTER III

## Discussion

This study investigated the perceptual sensitivity of individuals to acoustic apertures. It also evaluated a candidate acoustic informational variable as the basis for this ability. Consistent with previous aperture passability studies (e.g., Gordon & Rosenblum, 2004; Russell & Turvey, 1999), individuals were able to acoustically differentiate apertures whose boundaries were demarcated using sound. Although participants were able to differentiate aperture boundaries acoustically it was not clear if they were able to accurately perceive their own critical boundaries based on the data collected using the present method. The gain manipulation used to evaluate perceptual sensitivity to the candidate acoustic informational variable (Figure 2)) did not significantly influence perceptual reports. It thus appears unlikely that this particular variable was used to inform participants about aperture size in this study.

Although gain and head rotation were not significantly related to performance, suggesting that participants are not perceptually sensitive to the proposed informational variable, the significant relation between lateral movement and performance does suggest, however, the potential for an alternative informational variable that may have been used. This variable would capture the invariant relationship between lateral head position and sound source position over time. This sort of variable may not be the only useful variable, but may simply be preferred over less optimal variables when individuals are allowed to freely explore an auditory aperture. It should be noted that the second pilot study leading to the present research differs from the current study in that participants in the pilot were limited in their lateral movement by a plank positioned between their legs that guided them towards the aperture. In these restricted circumstances it may be that the proposed variable was being used, but only because the participant's access to a more optimal variable was limited. If they were allowed to freely explore they would likely have switched exploratory dynamics appropriately. Riley, Santana, Carello and Turvey (2002) define exploratory dynamics as a subclass of a given exploratory procedure, which, in turn, is defined by Lederman and Klatzky (1987, 1993) as stereotypical patterns of movement. General behaviors such as wielding are said to be single exploratory procedures but may take on different dynamics when performed under different circumstances.

Riley et al. (2002) describe differences in exploratory dynamics that are exhibited while engaging in exploratory wielding. They explain that, following from the co-specificity hypothesis (Turvey 1988, 1990; Turvey et al., 1990)—which relates perceived properties, attunement to information, and exploratory behaviors for detecting such information—it is to be expected that the intention to perceive different properties will yield varying exploratory dynamics because they require the detection of different information. Specifically, attempting to perceive properties such as length and width, which depend on different components of a wielded object's inertial characteristics, will require that exploratory dynamics be used that access the correct inertial component. Each style of wielding has a *specificity relationship* (Riley et al.,2002) with the intention to perceive the property that is uncovered by that wielding style. For example, forward-backward wielding will provide information about length, while side-to-side wielding will provide information about width. Both behaviors are examples of a single exploratory procedure (wielding), but exhibit different dynamics because they facilitate the detection of different information. Evidence for this specific relation was found by Michaels, Arzamarski, Isenhower, and Jacobs (2008).

For the current study it could be said that the general behavior that all participants engage in while determining passability constitutes exploration. All participants engage in some sort of active listening behavior that consists in changing the spatial relationship between their two ears and the two sound sources such that passability can be determined. Furthermore, the precise patterns of movement that are used on a trial-by-trial basis could constitute exploratory dynamics. While all participants engaged in some sort of active listening, many took on different exploratory dynamics. For example, some stepped or leaned side-to-side while others stood in place and turned their heads. It is not obvious why there may have been differences in exploratory dynamics. One explanation could be that the task requirements were not sufficiently constrained to entail exploratory dynamics that accessed the optimal variable. Lederman and Klatzky (1987, 1990, 1993) showed that exploratory behaviors are chosen so as to *optimally* access information that is relevant to the intended perceived property. This can only be expected to take place, however, when participants have been able to discover the optimal informational variable. This may not happen if they are not motivated to achieve high task accuracy. In the current study, accuracy was emphasized in the initial training session, but was not enforced during the later experimental trials. Participants who managed to perform sufficiently well during training could have used a non-optimal informational variable given that they were not aware, due to a lack of feedback, of any incorrect judgments later in the experiment. Feedback as well as stricter accuracy requirements could encourage participants to shift their exploratory dynamics so as to access the optimal variables. In effect, this would demonstrate perceptual learning (Gibson, 1969). Based on the findings of Arzamarski, Isenhower, Kay, Turvey, and Michaels (2010) it should be expected that a gradual, as opposed to sudden, shift in dynamics be observed as feedback guides an individual's attention towards the optimal information for passability. Such gradual shifts are linked to cases of perceptual learning while sudden shifts are seen when individuals change their intended perceptual object.

For this study it was not possible to observe such shifts in behavior due to the small number of observations made per condition and the fact that judgments were not recorded during the initial training session. In order to identify and qualify behavioral shifts, future studies would need to begin data collection before individuals had any experience with acoustic apertures. Also, subtle shifts in behavior would be more aptly characterized if the movement data that was recorded from each participant were analyzed using more fine-grained methods than those employed here. Possible methods include recurrence quantification analysis (cf. Riley et al., 2002) as well as detrended fluctuation analysis (Kelty-Stephen & Dixon, 2014).

In the current study the main goals were to 1) test to see if individuals can perceive passability [using auditory information] and 2) test a candidate [acoustic] informational variable. The measures that were initially used (perceptual judgments) allowed for many interesting observations, but were not ideal for a quantitative evaluation of the present goals. The verbal "yes/no" perceptual judgments, while potentially indicative of an individual's perceptual state, are very coarse (i.e., only 3 potential values of passability per condition) and relied heavily on a participant's interpretation of the particulars of a given task (e.g., squeezing through the aperture vs. walking through the aperture without touching; their understanding of what the sound sources meant functionally, etc.). While all potential participants should be familiar with passing through openings, it is unlikely that many had attempted to do so using only sound and so it may have been unrealistic to assume these sorts of perceptual reports would yield sufficiently sensitive data to achieve the goals of this project. One strategy to yield more refined data would be to use movement data as a primary measure. Fath and Fajen (2011), for example, studied aperture passability using behavioral data. Instead of recording and analyzing perceptual judgments, they looked at the shoulder angle adopted by individuals who were walking through apertures. This was done using motion capture markers on the head and both shoulders. Similar to the collection of perceptual judgments, this method allows for critical boundaries to be determined by looking for the maximum aperture that is passed through without any shoulder turning. Additionally, behavioral measures such as those used by Fath and Fajen would allow for feedback to be delivered precisely and continuously. For example, a participant whose shoulders come into contact with the sides of an aperture could be provided with auditory or visual information that would help guide their attention towards optimal information for passability.

**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 it very useful to use virtual auditory environments 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 different perceptual modalities as well as mutlimodal 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 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.

## Conclusion

In general, the results of this study provide evidence that humans are able to perceive action-relevant layouts in the environment via auditory perception and that these can be simulated acoustically in a virtual environment. Furthermore, the significant relationship between lateral motion and performance may point to a different informational variable that participants may be sensitive to that could be investigated in future studies.

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