2022

Visual Looming Cues Increases The Auditory Looming Bias

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Recommended Citation

McCracken, Maggie K., "Visual Looming Cues Increases The Auditory Looming Bias" (2022). *Senior Independent Study Theses.* Paper 9753.

The College of Wooster

Visual Looming Cues Increases the Auditory Looming Bias

by

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Presented in Partial Fulfillment of the Requirements of

Senior Independent Study Thesis

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2021-2022

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Abstract

Looming objects have been environmentally relevant cues throughout human evolution due to potential danger. Observers integrate both auditory and visual signals emitted by moving objects. While visual arrival time estimates are relatively more accurate, auditory estimates are anticipatory as observers perceive a moving sound source as arriving before it actually does. In the present study, participants made loudness change judgments of sounds presented unimodally or with visual motion. The sounds consisted of two intensity ranges and conditions included both looming and receding motion. The results showed that listeners perceived looming sounds as changing more in loudness than equivalent receding sounds. Sounds were also perceived to change more when presented with coincident visual stimuli. The influence of visual information on auditory perception was greater in the receding conditions. These findings demonstrate that the perception of auditory loudness change is susceptible to alterations in the visual domain. The present study also provides additional evidence supporting an adaptive bias in the perception and integration of looming objects.

Introduction

Motion perception is used in many ordinary situations to keep us safe. In events as simple as a pedestrian at a crosswalk, we rely on motion information to determine when it is safe to cross. Vision and audition have typically been treated separately by researchers, as much of motion perception research concerns only one or the other. Although studying each modality independently provides essential information about the nature of each sense, moving objects typically emit both auditory and visual information. Generally, humans use both these visual and auditory signals in navigation and making judgments about the surrounding environment. This makes it important to understand how these two modalities interact. Multisensory integration concerns how multiple senses are combined. Although audiovisual perception involves two senses, these modalities are not weighted equally as both modalities have their advantages and disadvantages. When combined, audition and vision create a perceptual representation that is not always accurate but allows us to be highly successful with interacting with approaching objects (Hoffman et al., 2015). For example, underestimating the arrival of an approaching object is an inaccurate perception, but this inaccuracy also gives an observer more time to prepare (Haselton & Nettle, 2006).

Some of the more well-known examples of multisensory integration are not in motion perception but are in speech perception. McGurk and MacDonald (1976) showed a powerful example of audition and vision combining by presenting participants with mismatched stimuli. When the auditory speech articulates a syllable and is dubbed with a face saying another syllable, observers report hearing a new syllable not present in either stimulus. This phenomenon has been referred to as the McGurk effect and remains one of the most famous multisensory illusions studied today. Audiovisual speech perception has also been studied in terms of spatialization. An illusion, referred to as the ventriloquist effect, occurs when observers perceive a voice as emanating from the location of the visual stimuli (Alais & Burr, 2004). These multisensory illusions reveal how perception does not always align with environmental information. Similar perceptual inaccuracies occur in motion perception, showing how observers use various sensory information (Glatz & Chuang, 2019; Gordon et al., 2013; Gray & Regan, 1999).

Auditory Motion Perception

Auditory looming bias

Recognizing a looming object is an important perceptual task because it can signal approaching danger. Auditory perception reflects this as listeners tend to underestimate the arrival time of approaching sounds. This perceptual bias is referred to as the auditory looming bias. By perceiving a sound as arriving sooner than the actual arrival, the listener receives more time than expected to prepare. A large body of research has been dedicated to further understanding the extent to which this systematic bias occurs, including perceptual, environmental, and individualistic factors (Gordon & Rosenblum, 2005; McBeath et al., 2019; McGuire et al., 2016; Neuhoff et al., 2009, 2014; Riskind et al., 2014).

The auditory looming bias has been replicated using a variety of experimental designs, including go/no-go detection tasks (Cappe et al., 2009, 2012), time-to-arrival judgments (Bach et al., 2008; Gordon et al., 2013; Gordon & Rosenblum, 2005; Rosenblum et al., 2000), and subjective duration (Grassi, 2010; Grassi & Darwin, 2006; Grassi & Pavan, 2012).

One criticism of the validity of looming research stems from the experimental conditions under which it has been previously studied (Canévet et al., 1999). Previous methods include presenting a non-moving sound source that changes in loudness through headphones and participants providing loudness change estimates on a scale unrelated to distance (Neuhoff, 1998; Neuhoff et al., 2014; Seifritz et al., 2002). In addition, sound sources that have been artificially simulated are often impoverished, focusing on one acoustic motion cue, such as intensity change and ignoring all others. This simplification is also seen in participants' judgments on an arbitrary scale, focusing on a specific physical dimension, including intensity.

Addressing this criticism, a study replicated the looming bias in an outdoor environment using a moving loudspeaker (Neuhoff, 2001). This stimulus produced all of the acoustic cues typically present in a real moving sound. Listeners perceived an approaching sound as stopping closer than equidistant receding sound. Sounds in approach were also perceived as starting closer than equivalent receding sounds.

The auditory looming bias is also studied using time-to-arrival judgments (Bach et al., 2008; Gordon & Rosenblum, 2005; Gordon et al., 2013; Rosenblum et al., 2000). However, if approaching sounds are considered a perceptual priority, the looming bias should not be limited to egocentric distance perception. Neuhoff (2016) examined this question by asking participants to estimate how fast a sound source traveled with looming and receding stimuli. Looming sounds were perceived to be moving more quickly than equivalent receding sounds. Additionally, Neuhoff (2016) found that closer sounds are perceived to be moving faster than distant sounds. Closer sound sources pose a greater potential threat due to proximity, consistent with the loudness change findings of Neuhoff (1998). Listeners also showed better speed discrimination for looming sounds. Because approaching sounds pose the greatest potential for danger, the ability to differentiate the speed would be advantageous to the listener. These findings show a bias in the perception of looming sounds without distance-related estimates.

Accuracy in auditory looming judgments can be determined through implicit or explicit feedback. Because listeners with normal sight are typically guided visually, auditory judgments may be more influenced by experience and learning, such as feedback. When listeners are given feedback on time-to-arrival estimates of looming sounds, the auditory looming bias is reduced but not eliminated (Rosenblum et al., 2000). Listeners also show sustained judgment improvements when feedback is withdrawn on repeated trials. Rosenblum et al. (2000) showed that conscious attention influences time-to-arrival estimates when estimating the same approaching sound. However, if the auditory looming bias was entirely under conscious control, performance after repeated feedback should diminish biased responses completely.

The effect of cognitive processing on an auditory looming bias has also been studied in other domains such as attention. McGuire et al. (2016) had participants make arrival time estimates under various levels of cognitive load. Cognitive load was induced by a memorization task where participants were asked to memorize two numbers in a low load condition and seven numbers in a high load condition. Between the initial presentation and recall of the numbers, participants completed arrival time estimates for looming sounds. Because attention is a limited resource, devoting more cognitive resources to memorizing more units puts a listener into a vulnerable mental state. The study results support this theory as a looming bias increases when the listener is under a higher cognitive demand. These results, together with the feedback withdrawal findings (Rosenblum et al., 2000), suggest an influence beyond conscious cognitive processes.

Introducing uncertainty to auditory sound sources does not necessarily influence anticipatory biases. For example, Rosenblum et al. (1993) explored how the anticipatory bias is influenced by the duration of an occluded period, between auditory signal offset and the actual time of passage. Listeners were presented with partial recordings and instructed to indicate when the approaching sound source would have reached them, assuming constant velocity. Without auditory information of the virtual time of passage, listeners underestimated arrival time. However, estimates did not significantly differ from making estimates to complete recordings. In other words, hearing the actual time of arrival does not increase listeners' accuracy in arrival time estimates.

The perceived urgency of environmental factors can influence the magnitude of the auditory looming bias. Neuhoff et al. (2014) examined how the presentation of auditory stimuli unrelated to looming sounds affects time-to-arrival estimates. When presented with looming sounds accompanied by negatively valenced infant cries, listeners exhibit a larger looming bias, showing more cautious estimates of arrival time. Conversely, listeners showed the opposite effect with looming sounds presented with positively valenced infant laughs, producing less cautious estimates and significantly reducing a looming bias. These results suggest that changing the semantic context of approaching sounds is not required to elicit differing magnitudes of an anticipatory bias. Rather, inducing listeners' positive or negative affective states through sounds unrelated to approaching sound sources is enough to modulate auditory motion perception.

The auditory looming bias studied through loudness change

Most motion perception research typically does not provide participants with physically moving sounds sources because of the constraints of the laboratory setting. Three-dimensional moving sounds provide several acoustic cues to listeners, including intensity change, interaural temporal differences, and the Doppler shift. Each cue can individually provide information regarding the movement of the sound source. For example, interaural temporal differences refer to how approaching sounds will reach one ear before reaching the other, and the time difference is specific to the trajectory of the sound source. The gradual decrease of frequency in sounds moving towards a listener is referred to as the Doppler shift. Intensity change refers to the physical change in decibels. When limited by collecting data within a laboratory, understanding how each motion cue contributes to motion perception allows for artificial simulation of auditory motion.

To determine the relative importance of auditory motion cues, Rosenblum et al. (1987) manipulated each cue so that the passage time differed. Motion cues were put into competition so that one motion cue indicated a different arrival time than the other two (pitch, intensity, interaural temporal differences). Participants then made arrival time estimates to the incongruent auditory stimuli. Intensity change was found to be the dominant cue over Doppler shift and interaural temporal differences. Listeners were most accurate in their arrival judgments when all three types of variables were available. However, even when all cue conditions are available, listeners still exhibited a bias to perceive the sound as arriving before it actually did.

If intensity change is the primary cue to egocentric auditory motion perception, then a disparity between rising and falling tones should mirror the disparity in looming versus receding sounds. Neuhoff (1998) supported this claim as listeners perceived rising sounds to change more than falling sounds, despite having equivalent changes in decibels (Neuhoff, 1998). Furthermore, the asymmetry between looming and receding tones increases with the louder intensity range, simulating closer sounds. This study suggests that the auditory looming bias shows perceptual priority for closer approaching sounds than more distant sounds. Furthermore, Neuhoff (1998) found that this looming bias occurs with tones but not with white noise, typically derived from multiple sound sources such as wind, noise from a crowd, or a rainstorm. These findings suggest that single dynamic sound sources have greater perceptual importance.

Although the auditory looming bias refers to arrival time and distance estimates, looming research uses intensity change to simulate sound moving in relation to a listener. Specifically, rising intensity sounds simulate looming sounds, and falling intensity simulates receding. This category of auditory stimuli has been used in previous motion research (Bach et al., 2008, 2015; McGuire et al., 2016; Neuhoff, 1998, 2001). Even though these are not 3-D looming sound sources, rising intensity sounds allow the auditory looming bias to be studied with more variability by not limiting data collection to a laboratory environment.

Physiological evidence for an auditory looming bias

Identifying physiological responses for an auditory looming bias further supports the hypothesis of this perceptual bias being the result of evolutionary adaptation. Seifritz et al. (2002) used functional MRI imaging to locate parts of the brain preferentially activated in response to looming versus receding sounds. Tones changing in intensity activate the superior temporal sulcus (STS) more than constant intensity sounds (Seifritz et al., 2002). Furthermore, rising intensity sounds activate the STS and premotor and motor cortices greater than equivalent falling intensity sounds. Consistent with the findings of Neuhoff (1998), another area within the temporal lobe, called the inferior temporal gyrus, tracks intensity change in complex noise but not broadband noise (Bach et al., 2015). These results suggest a distributed neural network that modulates space recognition processes, attention, and motor planning. The physiological signs of preparation for rising sounds, particularly in motor and premotor cortices, provide further evidence of an autonomic warning system for approaching sound sources.

Looming sounds also produce greater activation in the amygdala when compared to equivalent receding sounds (Bach et al., 2008). Specifically, amygdala activation in response to simple rises in intensity suggests that intensity change can be a primary warning cue. Rising sounds also activate autonomic processes, such as the orienting reflex. By responding to immediate changes in the environment, the orienting reflex uses automated motor actions to deal with potential danger, such as directing attention towards potentially significant events and an increase in heart rate. The amygdala activation and response in the distributed neural network outlined by Seifritz et al. (2002) are heightened automatic processes in response to rising intensity sounds, unique brain responses to approaching sounds. Together, these findings suggest that the auditory system acts as a warning system with special attention to looming sounds that signal potential approaching threats.

Bach et al. (2009) measured the conductive skin response of listeners to looming sounds with varying motion cues. The physiological loom/recede effect of full-motion 3-dimensional auditory cues is comparable to sounds with intensity change only. Looming sounds in both conditions elicited similar arousal and saliency responses. These results are consistent with the previous findings (Rosenblum et al., 1987) on the importance of intensity change (Rosenblum et al., 1987). They suggest that using rising intensity sounds to simulate looming motion activates similar neural mechanisms. However, sounds with full-motion cues generated a greater skin conductive response. This difference in the physiological reaction might be because of the mobilization of energetic resources when full-motion cues are available. This also suggests that looming sounds are not as salient when they lack relevant information, such as a Doppler shift and interaural temporal differences. Taken together with the findings from Bach et al. (2008), the autonomic response, including amygdala activation and skin conductance, provide evidence of the auditory system providing advance warning of the approach of potential threats.

Individual differences in an auditory looming bias

A wide range of behavioral and physiological evidence has shown that looming sounds are prioritized by the auditory system as listeners consistently underestimate arrival time and distance when presented with looming sounds (Bach et al., 2008, 2009; Cappe et al., 2009, 2012; Maier et al., 2004; Neuhoff, 1998, 2001). An emerging area of study within the auditory looming bias is differences between individuals and how traits affect how likely an individual exhibits a stronger looming bias. The auditory looming bias is likely adaptive, as the cost of making preparatory actions too early is much less than the cost of making the same actions too late in response to approaching danger (Haselton et al., 2009; Haselton & Nettle, 2006). Based on this evolutionary hypothesis, individuals who are less prepared to engage with a threat should exhibit the greatest auditory looming bias.

Because the evolutionary pressures vary by sex, men and women have evolved to have different behavioral adaptions (Byrd-Craven & Geary, 2007). One theory of sex differences proposes that these differences are due to sexual selection, initially proposed by Darwin (1871). The number of offspring women can propagate in their life span is limited because of their investment in gestation and childbearing (Eagly & Wood, 1999). Men's intraspecies competition increased as a result, and women developed preferences for a mate that could provide resources. This theory and conclusions drawn from it are often criticized because of challenges in distinguishing adaptive behaviors from other feasible products of evolution, such as random acquisition or behaviors that evolved for a particular function but subsequently fulfilled a new role (Buss et al., 1998). Regardless of the validity of the evolutionary origin theory, sex differences have been observed in the perceptual domain. For example, men perform better on visual tasks that involve visuospatial manipulation (Collaer & Nelson, 2002). However, women outperform men on visuospatial memorization tasks (Alexander et al., 2002), showing that each sex may have their own perceptual strengths and weaknesses.

Sex differences can provide evidence for behavioral adaptions, suggesting an evolutionary origin. In the auditory looming bias, a sex difference has been demonstrated in the perception of looming sounds, but not in the perception of receding sounds. Women perceive looming sounds as closer than men (Neuhoff et al., 2009). If these findings resulted from simple sex differences in spatial transformation abilities, similar differences should be observed for receding sounds. However, an evolutionary origin for the looming bias would predict these differences to occur only when moving objects pose the greatest threat to the observer- when they are approaching. Neuhoff et al. (2009) found that with receding sounds, men and women provided similar responses. Therefore, this observation in looming perception is likely not due to general differences in audio spatial ability and may be due to evolutionary pressures.

Sex differences have also been found in the subjective duration of rising and falling intensity sounds (Grassi, 2010). Listeners estimated the length of sound for both increasing and decreasing intensities. While both men and women underestimate looming sounds, the difference between looming and receding sounds was greater for women. These results expand the findings of Neuhoff et al. (2009) by demonstrating the sex difference in the looming bias beyond distance estimates. The sex difference in the looming bias may be because women could benefit from having more-than-anticipated time for preparation.

Further evidence to support this hypothesis, including the sex difference in a looming bias, comes from research in physical fitness. In a correlation study, Neuhoff et al. (2012) found that physical fitness was negatively correlated with the magnitude of the auditory looming bias. First, participants estimated the arrival time of moving sound sources. Then, participants' cardiovascular fitness was measured through a heart rate recovery test in which they performed simple aerobic exercise. A lower resting recovery heart rate afterward indicated a higher level of cardiovascular fitness. Grip strength was also taken as a measure of total muscle strength. Together, these two tests provide measures of physical strength and fitness. The results showed that individuals with better physical fitness exhibited a smaller auditory looming bias. Because having a higher recovery heart rate indicates poorer fitness, heart rate was positively correlated with the magnitude of a looming bias. Individuals who were more prepared to interact with dangerous looming sound sources showed less of a margin of safety. The results from Neuhoff et al. (2009) can be explained in the context of these findings. Sex differences in the auditory looming bias could have resulted from differences in strength rather than biological sex. Furthermore, significant within-sex correlations suggest that differences in strength and fitness may primarily account for the findings of a sex difference. This suggests that the limits of the moto system may regulate auditory perception. These findings provide more evidence of this anticipatory bias resulting from evolutionary adaptation, allowing a greater looming bias in individuals whose preparatory behaviors require more time.

However, auditory research is not limited to physical characteristics. Recent work has begun to explore the relationship between anticipatory biases and cognitive vulnerability. Anxiety and depression systems have been found to influence the magnitude of the looming bias (Riskind et al., 2014). Anxiety symptoms promote a stronger auditory looming bias than depression symptoms, which reduce the anticipatory bias. This study is the first to demonstrate individual differences that are not limited to physical characteristics but also by the cognitive-affective states of the listeners.

Visual Motion Perception

Visual looming perception

The anticipatory looming bias that occurs in audition is significantly diminished in vision. Observers make substantially more accurate time-to-arrival judgments in vision than equivalent auditory judgments (DeLucia et al., 2016). However, visual anticipatory judgments are still present as the implications of approaching danger still exist visually. Visual looming studies elicit an underestimation of arrival time by introducing uncertainty. By occluding the final approach of an object, observers judge when an approaching object would have reached them had it not disappeared before arrival (Manser & Hancock, 1996). This uncertainty produces anticipatory looming judgments in vision, while auditory looming bias still occurs even when listeners are provided the whole approach of the sound (Neuhoff et al., 2009, 2012, 2014).

Uncertainty can be induced without occlusion and distance judgments. If there are still evolutionary effects from approaching visual danger, disparities in looming and receding visual motion should occur. Lewis and McBeath (2004) used the presentation of repeating patterns that presented participants with ambiguous motion. The stimulus was presented on a screen and consisted of a tunnel with shapes moving repetitively. Participants wore stereo glasses that made the visual appear three-dimensional. This procedure caused the illusion of motion, but the direction of this particular motion was bi-stable. It could be perceived as either approaching or receding—the ambiguous motion results in an unambiguous perceptual experience. The observers showed a bias to experience approaching motion. These findings are consistent with the salience of looming motion, as caution in interpreting approaching motion increases the likelihood of a successful interaction than not being cautious enough.

When an object approaches an observer, the object produces optical expansion on the retina, which increases as the distance to the eye decreases. Like auditory intensity, the optical expansion rate initially is small but increasingly grows as the distance decreases, indicating an impending collision. Optical tau can be derived without velocity or distance information as it is only derived from the angular extent of the object's image (Lee, 1976; Schiff & Detwiler, 1979; Yan et al., 2011). This is appealing to visual researchers because optical expansion can be used to artificially simulate visual looming motion, which has been used extensively in the past because of observer sensitivity to changes in optical tau (DeLucia, 2015; Kaiser & Mowafy, 1993; Lee, 1976).

Binocular rivalry refers to a visual phenomenon in which two different images are simultaneously presented to each eye. The perception of the images alternates between the two eyes, perceiving one of the two images for a few seconds before switching to the other image. The time between alternatives, however, does not always allow for the equal perception of both images. Using binocular rivalry to measure perceptual dominance, Parker and Alais (2007) showed that expanding visual stimuli temporally dominated over contracting visuals. This further supports the idea of approaching objects as salient and that perceptual processes devote attentional resources to environmentally relevant events as a result. When concurrently presented with looming sounds, this looming bias is amplified by prolonging the temporal dominance of expanding stimuli (Parker & Alais, 2006). Collectively, these studies show that expanding stimuli are prioritized in vision and when motion information presented in both modalities are integrated into a perpetual advantage for looming signals.

Biases found in vision could have notable consequences for the observer. These perceptual "inaccuracies" lead to successful interactions with objects in the environment, whether that is avoidance behaviors or interacting in other ways. One of the most widespread applications of visual motion perception is motor vehicles. Subtle errors in driver judgment based on direction and speed information obtained in milliseconds could be the difference between success and failure to avoid a collision (Gray & Regan, 1999, 2000). Similar judgment errors of ball movement in games with high-speed balls could lead to mistakes made by players. Underestimation of ball speed by baseball batters leads to the rising fastball illusion, where the hitter perceives the ball as rising in height throughout its trajectory (McBeath, 1990). Regardless of professional careers in baseball, humans interact with moving objects daily. And it is in our best interest to have these interactions be successful and reduce bodily harm.

Adaptive Biases and the Error Management Theory

These perceptual biases can be explained through the lens of the error management theory (EMT). Social, cognitive, and perceptual biases have evolved because of how our ancestors reacted throughout human evolution. The auditory looming bias falls under a specific category in the EMT with other threat-relevant biases, including food aversions and the overestimation of height (Stefanucci & Proffitt, 2009). Although the looming bias may not be accurate, evidence suggests that it is an adaptation that should be considered a design feature rather than a flaw. EMT predicts human judgment biases that fit three criteria: (1) there are asymmetrical costs between false positives and false negatives, (2) they involve uncertainty, and (3) there are consequences to evolutionary fitness (Haselton et al., 2016).

When making cognitive or perceptual judgments, the observer can commit two types of errors: false positives and false negatives. When a bias is associated with asymmetrical costs, human judgment is likely to sway in the direction that results in survival. Bigger asymmetry leads to bigger biases (Haselton et al., 2016). In relation to the auditory looming bias, the cost of responding too early to a looming sound source (false positive) greatly outweighs the costs of potential death because of reacting too late (false negative). By perceiving a looming sound source as arriving sooner than it actually does, the brain and body are given more than expected time to prepare. The cost of this false positive is low because, by the time the sound source actually does arrive, the likelihood of a successful interaction does not decrease. On the flip side, an overestimate of arrival time results in a more costly false negative as the listener will be struck by the source.

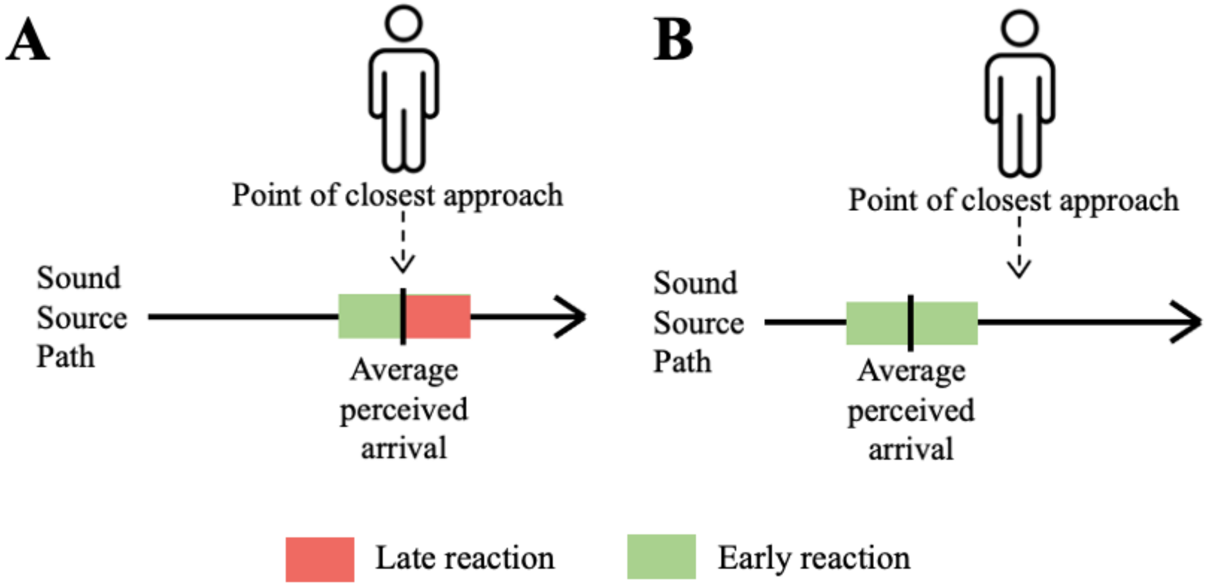
Although an optimal mechanism would result in no judgment errors, they can be induced under conditions of uncertainty, as seen in visual looming research where final approaches are occluded (Manser & Hancock, 1996). In general, perceptual judgments are made in conditions with uncertainty (Mathys et al., 2014). in the case of auditory looming, the presence of ambient noise, such as wind through trees or noises produced by traffic, likely produces some error.

Throughout evolutionary history, traits that aided in our ancestors' survival were also passed down to future generations. When a perceptual bias has life or death consequences, decisions that have led to successful results are beneficial. With the auditory looming bias, listeners who underestimated arrival time and reacted early were more likely to survive and successfully reproduce.

With the logic of Error Management Theory, individuals who are less prepared to interact with approaching danger successfully will exhibit a larger looming bias. This has been seen in previous auditory looming bias research that has shown sex differences, the effect of physical fitness, and cognitive vulnerability (McGuire et al., 2016; Neuhoff et al., 2009, 2012; Riskind et al., 2014). The underestimation of looming sounds leaves a margin of safety, where even a late response still creates enough time to respond appropriately. As with any reactions, humans exhibit variability in their responses. If humans perceive looming sound sources accurately, a portion of the expected arrival time will still fall after the actual arrival (Figure 1A). With a looming bias, the margin of safety cushions the variability of human responses, so even the later responses are before the actual arrival time (Figure 1B) (Neuhoff, 2018).

Figure 1

Reaction times to looming objects



Multisensory Integration

Moving objects typically emit both visual and auditory information. The brain takes this information from both senses and combines it into a single percept. Multisensory integration has evolved to solve different evolutionary problems in interactions with looming objects. Guski (1992) proposed a type of collaboration between the two senses. In this ecological perspective, audition is thought to be a warning system in which a categorical decision is made about reactive motor behaviors, such as moving the head to look at the source. If there is enough time to turn the head, vision can provide more accurate arrival time estimates, and final motor decisions can be made appropriately.

Auditory and visual signals, however, are not always integrated. Knowing when these senses are integrated provides vital information regarding what the perceptual system deems ecologically important. Cappe et al. (2009) used a go/no-go detection task in which participants were asked to respond when the stimuli contained moving signals, referred to as a go trial. Trials involved both visual, auditory, and multisensory conditions. No-go trials consisted of mismatched (i.e., looming visual and static sound) or unimodally static stimuli. The reaction times in looming go trials were significantly faster than all other audiovisual conditions. Furthermore, audiovisual conditions were significantly faster in reactions times than their unimodality counterparts, showing a multisensory advantage. This suggests a prioritization of integrating auditory and visual cues that signal looming motion. These results also demonstrate a behavioral advantage for multisensory integration because of enhanced perception of motion.

The adaptive ability to perceive motion in relation to oneself would be diminished without the ability to also correctly match auditory and visual signals to such motion. If the ability to integrate auditory and visual signals was a true advantageous and evolutionary phenomenon, newborns might receive similar benefits from the ability of multisensory integration. Orioli et al. (2018) explored human newborns' capacity for matching looming sounds to looming visual motion. Newborns were presented with two visuals, one looming and the other receding, simultaneously with a centrally located sound in both a rising-intensity and fall-intensity condition. Newborns showed a visual preference for congruent looming visual motion when the sound intensity also increased. But preference was at chance levels when presented with a receding sound. This study emphasizes the early multisensory competence that prepares newborns to perceive their new audiovisual environment.

Comparative work of audiovisual looming perception

If humans' auditory, visual, or multisensory looming biases evolved because they provide a selective advantage, then such biases should also be employed by closely related species. Comparative psychology primarily researches rhesus monkeys due to their cognitive, social complexity, and genetic similarities with humans (Phillips et al., 2014), has investigated this evolutionary theory. Previous work has shown that rhesus monkeys exhibit an auditory looming bias with a preference towards rising intensity sounds over falling intensity (Ghazanfar et al., 2002). The head orientation in rhesus monkeys was measured in response to hidden sound sources. They found that orienting responses to rising-intensity tones were longer in duration than the response to equivalent falling-intensity tones. There was not a significant difference in the orienting response to broadband noise. This study shows that a bias towards looming sounds is observed in a closely related species.

Rhesus monkeys also show similar preferences with audiovisual stimuli. By presenting two visual stimuli on a computer screen, one receding and one looming, monkeys' visual preference was measured when accompanied by a moving sound. When listening to a looming sound, rhesus monkeys prefer to look at a looming visual over a receding visual (Maier et al., 2004). However, when paired with a receding sound, there was no preferential looking. This study shows that closely related species to humans also demonstrate the capacity of multisensory integration of looming but not receding stimuli. Because the rhesus monkeys involved in this experiment had no prior experience with computer-generated expanding disks, their preference for visual expansion paired with a rising-intensity tone was still salient. This suggests that monkeys, and likely humans, have the evolved preference of bimodal looming stimuli of simulated motion.

Multisensory integration in audiovisual looming perception

When presented with auditory and visual information regarding an object's trajectory, observers rely primarily on visual information to make time-to-arrival estimates. Participants in previous research were asked to make arrival estimates in three conditions: auditory-only, visual-only, and audiovisual (DeLucia, 2016). Comparisons of the single modality conditions show that observers' estimates for approaching auditory objects are shorter than for approaching visual objects, consistent with the findings of an auditory looming bias (Neuhoff, 2001). Comparisons between all three conditions show that when both modalities are present, estimates more closely resemble visual-only estimates, suggesting that multisensory integration is visually dominated. However, further analysis of the multisensory condition showed that auditory information still influenced arrival estimates. So although both audition and vision provide arrival time information, the two modalities are not weighted equally. This visual dominance has also been demonstrated in arrival time estimates of ecologically valid stimuli, such as an approaching car (Zhou et al., 2007).

To study the integration of both modalities' arrival information, Gordon and Rosenblum (2005) examined how audiovisual time-to-arrival judgments differ when arrival information is interrupted in one modality. Audio and video signals were presented simultaneously, creating a normal condition. The alternating condition consisted of alternating the audio and video signals, so only information in one modality was available at any given time as the object approached. In the last condition, the intermittent condition, both signals were concurrently interrupted, resulting in segments of blank visuals and acoustic silence. In addition to most responses underestimating arrival times across conditions, arrival estimates were least accurate in the intermittent condition. However, the normal and alternating condition estimates were not significantly different, suggesting that arrival judgments are not swayed as long as the information is available in one modality. The authors suggest a modally flexible detection mechanism.

Audition affecting vision

If senses are integrated based on what humans have interacted with throughout evolutionary history, then the perceptual system should take into account the 3-D spatial consistency of objects. Particularly, integrating auditory and visual information should be more likely when both are presented in the front of the body than incongruent presentation (i.e., one sense presented from the rear and the other presented from the front). Yamasaki et al. (2018) explored how looming and receding sounds presented from the front and rear of the body influence the size perception of a moving visual object. Participants were asked to determine when the size of an expanding or contracting target disk reached the same size as a reference disk. This size matching task occurred while participants were presented with a looming or receding sound that played either in front of them or behind them. Participants overestimated the visual size of the looming visual disk only when they were presented with a looming sound in front. Although this study did not involve audiovisual estimates, it still showed how looming auditory stimuli result in inaccurate estimations in the visual domain.

Ambiguity in one sense can be swayed by certainty in the other. Although humans are a visually dominant species, auditory signals can dominate when signals are not clear in the visual domain. McBeath et al. (2019) asked observers to make directional motion judgments of ambiguous visuals presented concurrently with auditory stimuli stimulating sound sources approaching from the left, right, or equally from both sides. They found an overall leftward visual motion bias as visual motion was perceived to move leftward when the sound was presented equally from both sides. In a second experiment, they also showed this auditory capture of approaching visual motion. Specifically, the intensity change of the sound influenced visual perception as there was no effect of initial sound intensity. These findings reveal that information from the senses is proportionally weighted to its reliability. Because vision is typically more reliable in motion-related information, vision generally dominates auditory signals. But McBeath et al. (2019) found that when audition provides definitive cues, the perceptual system can change the dominant sense to audition, resulting in auditory capture of visual motion.

Vision affecting audition

Although audiovisual time-to-arrival estimates incorporate information from both modalities, vision has been shown to influence auditory estimates. For example, Maniglia et al. (2017) asked participants to determine which of two static sounds were louder, one of which was presented with a laterally moving disk with a constant diameter. It is important to note that all acoustic stimuli used in this experiment were broadband noise, which has been shown to lessen the magnitude of loudness estimations (Neuhoff, 1998). Regardless, sounds presented simultaneously with visuals were perceived to be louder than sounds presented unimodally.

Looming and receding sounds are also influenced by visual information. Varying the magnitude of visual change in expanding disks influences loudness and changes estimates of simultaneously presented sounds. McCracken and Neuhoff (2022) presented listeners with rising intensity sounds accompanied by expanding and contracting disks that had small or large changes and were asked to make loudness change estimates. In addition to replicating the auditory looming bias with concurrent visual accompaniments, sounds were perceived to change more in loudness when presented with a larger visual change. Furthermore, participants showed better change discrimination between receding sounds than looming sounds, inconsistent with previous unimodal research (Neuhoff, 2016). These results may be due to the alerting nature of looming sounds, shown through greater amygdala activation and phasic alertness (Bach et al., 2008; 2009). Differences in participant responses may also contribute to the differences in sound discriminations as McCracken and Neuhoff (2022) explored intensity change estimations where Neuhoff (2016) looked at direct speed estimations. The results of this study show the influence of visual information on auditory perception. Specifically, the amount of change in the visual domain influences the perceived amount of change in the auditory domain.

The Current Study

Previous research has shown that listeners judge broadband noise as louder when accompanied by an expanding disk than the same sound presented with no visual accompaniment (Maniglia et al., 2017). However, auditory motion disparities have been shown to occur with tones but not with broadband noise (Neuhoff, 1998). When auditory stimuli are combined with congruent visual information, both modalities are integrated into a single percept. When visual and auditory information are both available with respect to a moving object, motion perception relies primarily on vision (DeLucia et al., 2016), and audiovisual time-to-contact judgments more closely resemble visual judgments than auditory. In addition, sounds are perceived to change more in loudness when presented with a larger visual change in both looming and receding stimuli (McCracken & Neuhoff, 2022). However, the extent to which the visual looming stimuli influence these loudness judgments is unknown. I aim to investigate how intensity change is perceived with and without accompanying visual information and examine the influence of change direction and intensity range.

Here, participants were presented with looming and receding sounds in a high or low-intensity range. Furthermore, sounds were presented either unimodally or with a visual accompaniment. The visual accompaniment was an expanding or contracting disk, stimulating visual motion cues. Participants were asked to judge how much the sound in each condition changed in loudness. I hypothesized that looming sounds would be perceived to change more in loudness than receding sounds, replicating the auditory looming bias. Additionally, I expected that the sounds presented audiovisually would have larger loudness change estimations than equivalent unimodal sounds. Finally, I hypothesized sounds in the higher intensity range would be perceived to change more in loudness than equivalent changes in the lower intensity range.

Methods

Sample Size

I conducted an a priori power analysis to determine sample size using G*Power 3.1.9.2 (Faul et al., 2007). I subsequently set the sample size at N = 60. This yielded statistical power of .80, which was sufficient to detect an effect size of *f* = .125 at an alpha level of .05 for the repeated measures design.

Participants

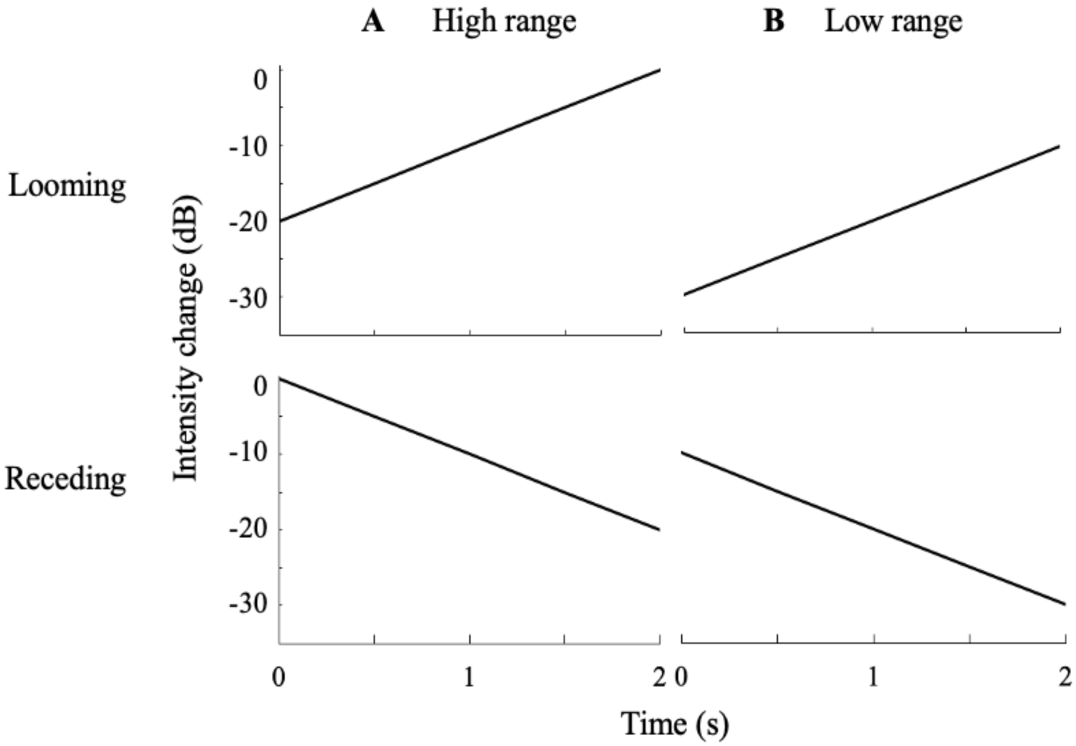
A total of 65 participants (40 female) between 27 and 77 years of age (*M* = 47.1, *SD* = 14.3) were recruited using Amazon Mechanical Turk (MTurk) through CloudResearch (Litman et al., 2017). All reported normal hearing and normal or corrected-to-normal vision. Participants were paid $0.35 for their participation. Five participants reported technology problems that resulted in the stimuli not being able to play to completion. These participants were replaced. All participants provided informed consent to the procedures approved by the College of Wooster's Human Subject Research Committee.

Stimuli

The auditory stimuli consisted of 440 Hz diotic sinusoids that increased or decreased by 20 dB (Figure 2). The stimulus duration of each sound was 2 seconds with a buffer of 1.5 seconds of silence played before and after to prevent any auditory clicks. Auditory stimuli were presented in two intensity ranges 10 dB apart, resulting in a high range sound (Figure 2A) and a low range sound (Figure 2B).

Figure 2

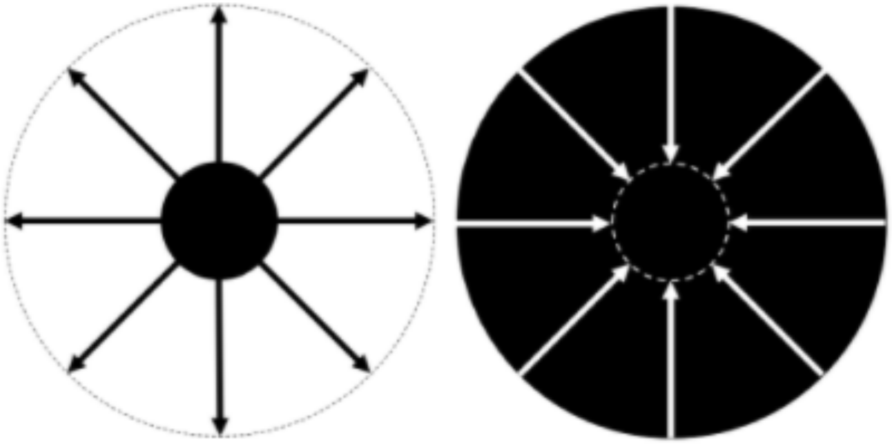
Auditory looming and receding stimuli in the high range (A) and low range (B)



The visual stimulus was a solid black disk centrally located on a white background (Figure 3). The disk expanded (looming condition) or contracted (receding condition) linearly at a constant speed over 2 seconds. The disk grew by 75% in size in the looming condition. The receding visual was the same as the looming visual but played backward. Because the experiment was conducted online, the visual angle cannot be calculated because the distance between participants' eyes and the screen presenting the stimuli is not controlled for.

Figure 3

Visual looming and receding stimuli



Design and Procedure

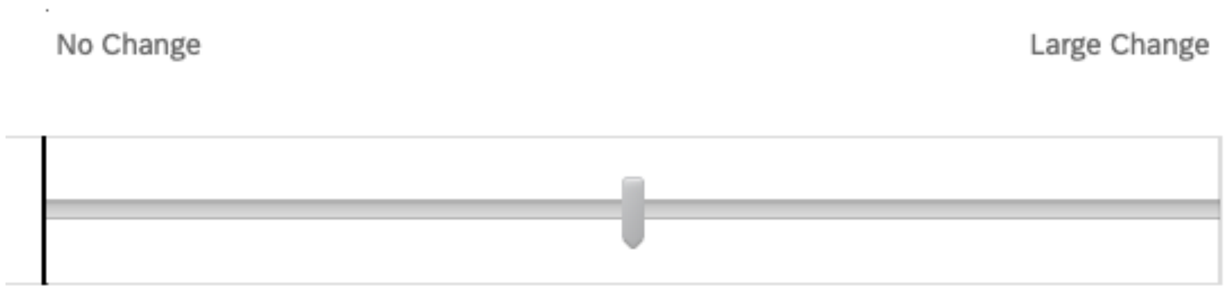
I conducted my survey online using Qualtrics. After providing informed consent, a recorded voice asked participants to adjust their volume to a comfortable listening level. Then, to verify that they could hear and see the stimuli, a recorded voice and a silent video asked participants to enter two codewords respectively into blank text boxes. Participants also indicated the model of headphones that they were using to verify that sounds were presented via headphones and not through speakers.

The experiment had a 2 x 2 x 2 repeated measures design. Each participant saw six videos in each condition (2 directions x 2 intensity range x 2 modality) for a total of 48 trials.

Stimuli were presented in completely random order. Participants were instructed to watch the video clips and estimate how much the sound changed in loudness using a visual analog scale after each video was played. The ends of the slider were labeled “No Change” and “Large Change” (Figure 4). Participants were able to move the cursor to any point on the slider to indicate their estimate of the change in loudness. Participants did not see the numerical value on the slider.

Figure 4

Response mechanism for recording loudness change estimates.



After playing the stimuli videos, the survey automatically advanced to the slider, preventing participants from relistening to a trial more than once. After completing the experimental conditions, participants reported demographics, including age, sex, and any hearing or vision impairments. Participants also reported any technical problems that prevented the stimuli videos from playing the entire duration intended.

Results

I conducted a 2 (direction) x (modality) x 2 (intensity range) repeated measures analysis of variance (ANOVA) on loudness change ratings. Data were analyzed using R statistics software (Version 1.4.1106) and are openly available at osf.io/kvb5y/. I found a main effect for direction that indicated looming sounds (*M* = 61.685, *SE* = 1.582) were perceived to change in loudness significantly more than receding stimuli (*M* = 48.940, *SE* = 1.746), *F*(1, 64) = 75.047, $p < .001$, $\eta_\rho{}^2 = .540$. I also found a main effect for intensity range of that indicated the higher intensity sounds (*M* = 65.831, *SE* = 1.598) were perceived to change more in loudness than the lower intensity sounds (*M* = 44.794, *SE* = 1.835), *F*(1, 64) = 152.479, $p < .001$, $\eta_\rho{}^2 = .704$. Importantly, the main effect for modality was also significant and showed that sounds presented audiovisually (*M* = 57.005, *SE* = 1.690) were perceived to change more in loudness than sounds presented unimodally (*M* = 53.621, *SE* = 1.637), *F*(1, 64) = 5.365, $p = .024$, $\eta_\rho{}^2 = .077$.

Table 1

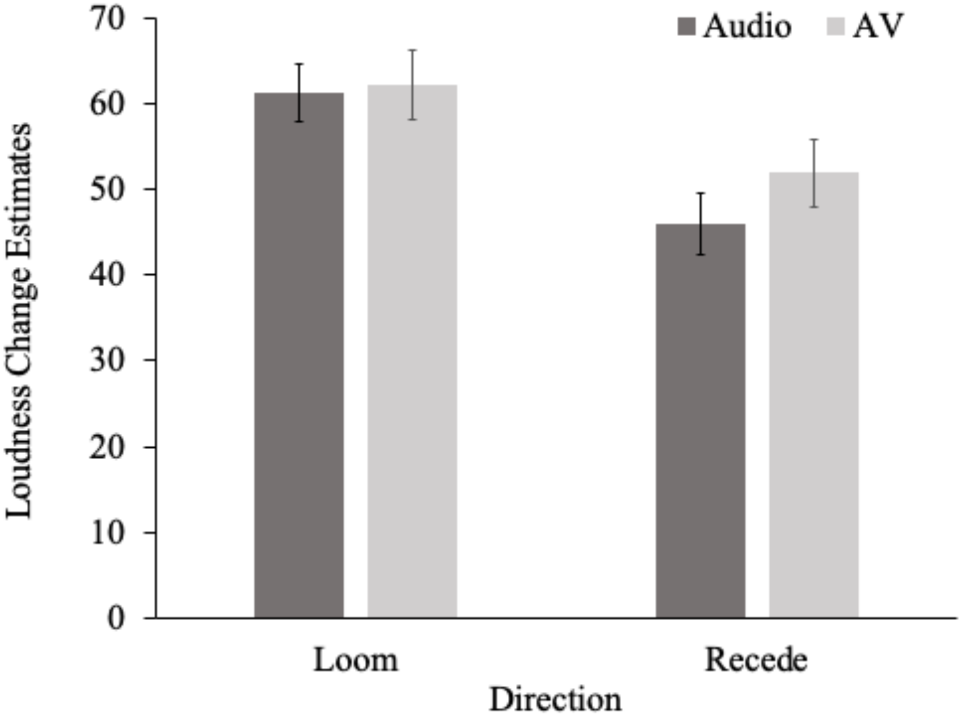
Three-way repeated measure ANOVA.

	F	***p***	$\eta_\rho{}^2$
Direction	75.047	<.001	.540
Modality	5.365	.024	.077
Range	152.475	<.001	.704
Direction * Modality	7.064	.010	.099
Direction * Range	28.289	<.001	.307
Modality * Range	3.536	.065	.052
Direction * Modality * Range	0.103	.750	.002

The ANOVA also showed a significant interaction between direction and modality *F*(1, 64) = 7.064, $p = .010$, $\eta_\rho{}^2 = .099$. Bonferroni corrected follow up t-tests showed that for receding stimuli, sounds that were presented audiovisually (*M* = 51.913, *SE* = 1.996) were perceived to change significantly more in loudness than sounds presented unimodally (*M* = 45.968, *SE* = 2.027), *t*(64) = 2.976, p = .002, *d* = 0.369 (Figure 5). However, for looming stimuli, there was no significant difference in loudness change ratings of sounds presented audiovisually (*M* = 62.097, *SE* = 1.760) and sounds presented unimodally (*M* = 61.273, *SE* = 1.725), *t*(64) = .564, *p* = .287, *d* = 0.070.

Figure 5

Estimated loudness change in each sound presentation condition and direction. Error bars represent 95% confidence intervals.

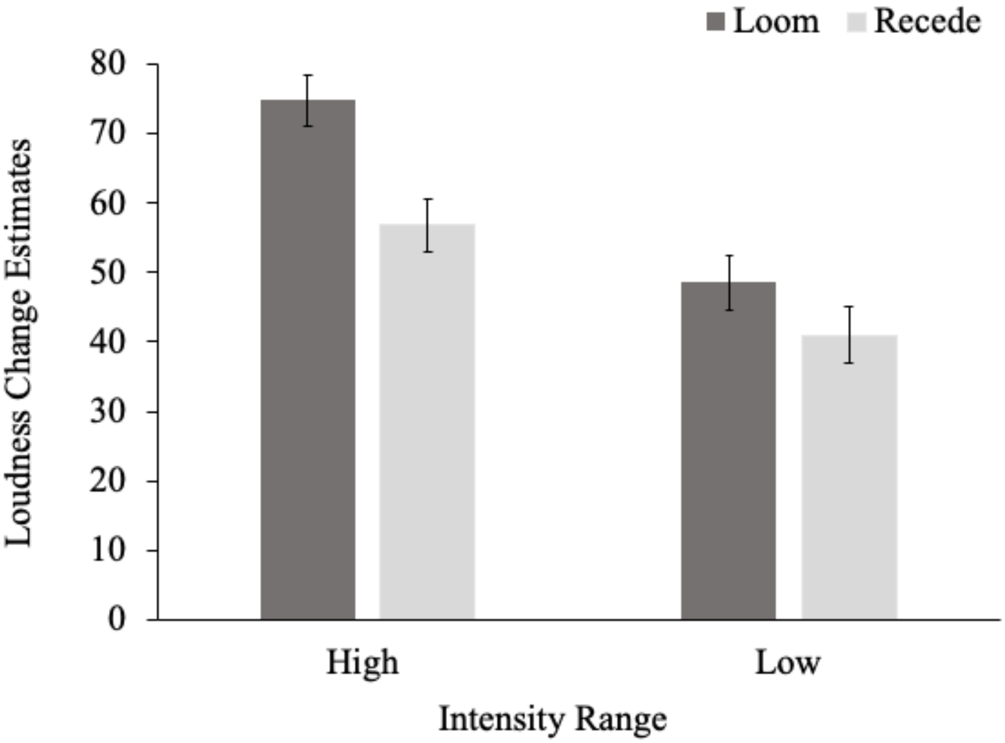


A significant interaction was also found between direction and range *F*(1, 64) = 28.291, $p < .001$, $\eta_\rho{}^2 = .052$. Bonferroni corrected follow up t-tests showed that for receding stimuli, sounds in the high range (*M* = 56.883, *SE* = 1.916) were perceived to change significantly more than sounds in the low range (*M* = 40.997, *SE* = 2.030), *t*(64) = 8.636, $p < .001$, *d* = 1.071. For looming stimuli, sounds in the high range (*M* = 74.780, *SE* = 1.825) were perceived to change significantly more than sounds in the low range (*M* = 48.591, *SE* = 1.956), *t*(64) = 12.634, $p < .001$, *d* = 1.567 (Figure 6). The interaction between modality and range *F*(1, 64) = 3.536, *p* =

.065, $\eta_{\rho}{}^{2} = .052$, and the three-way interaction $F(1, 64) = .103$, $p = .103$, $\eta_{\rho}{}^{2} = .002$, were not significant.

Figure 6

Estimated loudness change in each intensity range and direction. Error bars represent 95% confidence intervals.



To analyze the effect of a sex difference on a looming bias, I took the mean looming loudness change estimates and subtracted the mean receding estimates. Positive values indicate loudness change estimates being greater, suggesting a looming bias. I conducted an independent samples t-test with these bias values using sex as the between-subject factor. This showed marginally significant evidence for a sex difference as women had an approaching significantly greater looming bias (*M* = 14.425, *SE* = 2.169) than men (*M* = 10.057, *SE* = 1.510), *t*(64) = -1.457, *p* = .075.

Discussion

Auditory and visual motion perception have historically been studied separately. However, the current results show that the presence or absence of looming and receding visuals can influence the loudness change of coincident looming and receding sounds. Additionally, this effect depends on the direction of travel with respect to the listener as loudness change estimates of receding auditory stimuli differ more than equivalent looming conditions. These results show that auditory perception is susceptible to changes in the visual domain. These findings are consistent with evolutionary theories and that the auditory looming bias is adaptive to situations that have posed the greatest danger potential for our ancestors.

Auditory Motion Perception

Looming sounds were perceived to change more in loudness than equivalent changes in receding sounds. This study replicated the well-studied auditory looming bias as listeners showed a disparity in the perception between looming and receding sounds (Bach et al., 2008, 2009; DeLucia et al., 2016; Neuhoff, 1998, 2001; Neuhoff et al., 2009; Rosenblum et al., 2000; Seifritz et al., 2009). This disparity gives listeners more than expected time to prepare for approaching danger. Loudness change is just one way of measuring the auditory looming bias. This adaptive bias is also seen in perceived speed, as looming sounds are perceived as moving faster than equivalent receding sounds (Neuhoff, 2016). Looming sounds are also perceived as stopping closer than equidistant receding sounds (Neuhoff, 2001). With these studies taken together, the auditory looming bias has been empirically measured and has now also been shown to occur with coincident visual stimuli.

I also find support for previous work by showing that loud sounds were perceived to change more than soft sounds despite having the same amount of intensity change (Neuhoff, 1998). Previous research has also shown that listeners rely on intensity change to anticipate the arrival of sound source more than a change in pitch or interaural temporal differences (Rosenblum et al., 1987). In a natural environment, closer sounds are louder than equivalent sounds at a greater distance. These results taken together suggest a perceptual priority for closer sounds as nearer proximity poses a greater threat.

The direction fo motion exacerbates the effect of proximity for moving sounds. The louder range of intensity change showed a more significant perceptual disparity between looming and receding sounds. As loud sounds are perceived as closer to a listener than soft sounds, louder looming sounds would indicate the greatest potential danger compared to receding softer sounds. This interaction between looming and intensity was also seen in Neuhoff (2016), where closer sounds were perceived to be moving faster than distant sounds. Sounds that are close and approaching pose the greatest potential threats and adaptive biases, such as this display of the auditory looming bias, are seen as a result.

Previous research has shown sex differences in the auditory looming bias as women exhibit a greater margin of safety than men (Neuhoff et al., 2009). Similar research has also shown sex differences in subjective duration as women tend to overestimate the duration of looming sounds more than men (Grassi, 2010). The current study showed a sex difference that was approaching significance. However, key differences in methodology could contribute to this pattern of results observed in the present study. For example, sex differences have been shown when observers make distance estimates of looming sounds that stopped before reaching them (Neuhoff et al., 2009). In contrast, the current study has observers focus on the particular physical dimension of intensity. It has also been suggested that previous finding of a sex difference is due to differences in physical strength rather than biological sex (Neuhoff et al., 2012).

Multisensory Integration

Moving sound sources produce both auditory and visual cues integrated by the observer (Gordon & Rosenblum, 2005). Previous research has shown that changes in one modality influence how changes in another are perceived (Ben-Artzi & Marks, 1995; Schifferstein & Frijters, 1992; Spence, 2020). The current study shows that sounds were perceived to change more in the loudness when presented with coincident visual stimuli than equivalent sounds presented unimodally. This expands the results from McCracken and Neuhoff (2022) where greater loudness changes were perceived when sounds were presented with a larger visual change. Moreover, the current results show that this effect occurs irrespective of the magnitude of visual change as there was an effect with just the presence of accompanying visuals.

With looming objects that emit both auditory and visual information, previous work has shown that observers integrate both modalities when estimating arrival time (DeLucia et al., 2016). Although, audition and vision are not weighted equally as vision typically dominates multisensory motion judgments (DeLucia et al., 2016; Maniglia et al., 2017; Zhou et al., 2017). The current study shows that this integration is directional as visual information influences loudness change judgments in the receding condition but not in looming. Physiological work has shown looming sounds increase the sympathetic nervous system response and activate relevant neural mechanisms (Bach et al., 2008, 2009, 2015; Seifritz et al., 2002). The results of the current study may be due to the autonomic response to looming sounds with audition acting as a warning system, becoming dominant over the visual information when potential danger is greatest.

A large body of research has been dedicated to studying how the human brain combines information obtained from multiple senses. A coherent representation of the surrounding environment is created through multisensory integration (Spence, 2007). This process also includes sensory modalities having the ability to alter each other’s processing. Traditionally, vision has been viewed as the dominant modality (Welch et al., 1986). In the realm of motion perception, various findings from previous research have supported this idea (DeLucia et al., 2016; McCracken & Neuhoff, 2022). This interaction between vision and audition is also shown in the present study. However, McBeath et al. (2019) found that sound significantly influenced the perception of ambiguous visual motion. The two directions of influence, however, are not mutually exclusive. A possible explanation is that audition influences typically dominant vision when the optical information is ambiguous.

Limitations and Future Considerations

The online nature of my data collection introduces variability. Specifically, considerable interindividual variability is introduced as equipment and listening environment vary between participants, unlike more controlled laboratory conditions. For example, participants had control over the auditory stimuli's volume as they listened to the stimuli as embedded videos or mp3 files on their own devices. Unique listening environments also introduced varying amounts of background noise. However, these factors introducing variability would make it less likely to reject the null hypothesis as statistical power is decreased. Finding significant results despite the interindividual variability increases the external validity and generalizability of these findings.

The stimuli used in the current study were impoverished as they contain little ecological validity. Although previous research has used intensity change to simulate looming sounds (Seifritz et al., 2002), sound sources moving in the environment also emit changes in pitch and interaural temporal differences (Rosenblum et al., 1987). In the visual domain, impoverished optical stimuli such as an expanding disk (Cappe et al., 2009, 2012; Maier et al., 2004; Maniglia et al., 2017; Orioli et al., 2018). There are benefits, however, to using more realistic stimuli. Previous research shows that more realistic acoustic cues enhance a perceptual response from the observer (Bach et al., 2009). While we would expect a similar relationship with the present audiovisual stimuli, future research should examine how more realistic ecological cues influence the integration of audiovisual information.

One limitation in the current study is that participants focused on a particular acoustic dimension (e.g., loudness change). Although intensity is not the only acoustic cue with moving sound sources, previous research has shown that intensity change is the most dominant cue in the perception of approaching sounds (Rosenblum et al., 1987). Furthermore, intensity activates a similar, yet not as extreme, physiological and perceptual response (Bach et al., 2009). However, perception in a natural environment is not focusing on a particular dimension. Because of this, future research may consider a more holistic perception of change rather than focusing on one perceptual dimension, such as loudness change.

The direction of future research may also consider how auditory information influences visual size change estimates. Yamasaki et al. (2018) found that spatial location of sound presentation affects dynamic visual size perception. Sound and visuals were only integrated when the sound was presented in front of the observers. When the sound is presented from behind the observer and the sensory information is not integrated, the perceptual system does not assume the stimuli to be a unified event. It would be interesting to examine the differences between auditory and visual change estimates using a similar methodology from the current study.

Future research could explore more ecologically accurate situations by considering different judgments from observers. Although loudness judgments have been used to study auditory perception in the past (Bach et al., 2009; Maniglia et al., 2017; McCracken & Neuhoff, 2022; Neuhoff, 1998), practical perception would include how an observer will interact with an approaching object. These perceptual estimates include arrival time or speed judgments used in audiovisual research (DeLucia et al., 2016; Gordon & Rosenblum, 2005; Zhou et al., 2017). In the ecological approach, motion perception allows an observer to plan and execute motor behaviors to successfully interact with the object, which would require a different methodology than presented in the current study.

Conclusions

The current results show that the presence of accompanying visual information influences the perception of auditory stimuli. They provide evidence for an evolved auditory looming bias, supported by evidence from converging research. First, physiological evidence has been found in neuroimaging studies where looming sounds are preferentially processed by specific neural mechanisms (Bach et al., 2008, 2009, 2015; Seifritz et al., 2002). Comparative research has shown that rhesus monkeys selectively integrate looming audiovisual stimuli (Maier et al., 2004). Unimodal auditory experiments have found listeners to underestimate the arrival time of an approaching sound, erring on the side of caution (Gordon & Rosenblum, 2005; Neuhoff, 1998, 2001; Rosenblum et al., 1993, 2000). Finally, previous multisensory work has shown that although observers rely on both auditory and visual information, vision dominates over audition (DeLucia et al., 2016; Maniglia et al., 2017; Zhou et al., 2017). Taken together, these results provide support for an adaptive bias in the perception and integration of looming objects.

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