# Human Sensitivity to Differences in the Rate of Auditory Cue Change

By

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To my incredibly supportive parents, Dr. Stephen and Joan Maloff, and my sister, Kerstin

And to my beloved, Jaron Christianson for his unending patience and love

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# CHAPTER I

# INTRODUCTION

In our daily lives we experience an abundance of auditory events that change in some dimension to provide information about our frequently changing environment. In general, a meaningful change in cues over time along one or more dimensions contributes to our ability to perceive changing acoustic events. This thesis is in part concerned with how humans perceive changes in the rates of auditory cues and, in particular rates of spatial change. A real-life example of this would be a scenario where a pedestrian is waiting to cross a busy intersection. Passing vehicles at different speeds provide auditory cues that change systematically depending on vehicle speed and motion path. In an ideal situation, the pedestrian considers these auditory cues before making a decision to cross the street. The experiments in this study were designed to contribute to the current knowledge about how sensitive humans are to differences between rates of changing auditory cues, and to lay groundwork about how combinations of auditory cues may influence perception.

Chapter 1 begins by providing neural physiological evidence from previous literature reports and from work in our own laboratory about how humans are capable of processing auditory cue changes, such as those for motion perception. There is also a review of the pertinent literature that is focused on human perception and sensitivity to auditory directional or distance cues, such as interaural time differences, interaural level differences, Doppler shift, and intensity information, as well as the possible underlying perceptual mechanisms that are responsible for auditory motion detection.

There is evidence in previous literature reports that human sensitivity to different types of cues varies. It has also been shown that certain aspects of the signal, such as velocity or intensity may alter these perceptions. Chapter 2 introduces the literature that describes how humans weigh auditory cues in terms of importance for discrimination tasks, and in addition provides some evidence that there may be perceptual benefit when auditory signals include multiple changing cues. The literature pertaining to the combination of salient auditory cues and the impact on overall perception is limited, although there is some evidence that aspects of certain auditory cues are enhanced by including additional information. For example, when multiple directional and distance cues are available about a moving sound source, say an approaching vehicle, it may be easier to make a decision about how to avoid a collision than if only one motion-related cue (direction cue *or* distance cue) were available. Furthermore, it is possible that humans are perhaps more sensitive to changes in certain auditory cues compared to others. In this example, consider the possibility that the pedestrian is more sensitive to directional rather than distance motion-related cues. In this scenario, the pedestrian would have a better chance of avoiding a collision if at least directional cues were available and maybe easily avoid this disaster if both motion-related cues were available.

Generally, higher velocity is associated with shorter signal duration and greater extent of change (i.e., displacement). If duration is held constant for two signals with different velocities, then the faster one will change in position. If extent of change is held constant, then the faster cue will be shorter in duration. A traditional experimental approach to measure sensitivity to rate of extent of cue change involves jittering the signal duration or displacement, thereby making this cue unavailable to the listener. Other methods have been proposed in the literature that address this issue and have suggested a novel approach to measuring the sensitivity to differences between the rates of auditory cue changes over time. This method allows confounding cues of signal duration and velocity to co-vary together while sensitivity to auditory cue changes are measured through an enhanced perception in a duration discrimination task. For example, it has been suggested that duration discrimination performance is enhanced when the compared signals contain an additional auditory cue, such as rate of intensity change, as opposed to when the compared signals do not have this additional auditory cue. This proposed method thus indicates that human sensitivity to rates of changing auditory cues may be measured through the enhanced duration discrimination performance. This novel method has been applied in listening situations in which auditory cues, such as intensity or frequency, change in a stationary signal but have not been explored for events that change in spatial position. The last section of this chapter addresses the problem of confounding signal duration and velocity cues in measurements of human sensitivity to rates of auditory cue change. Also, this proposed psychometric "tool" is discussed in terms of how it may be useful to measure sensitivity to spatially changing auditory cues. The current study methods, discussion and conclusions are included in Chapter 3.

### *Underlying mechanisms for auditory spatial and temporal processing*

The experiments in the current study use behavioral measures that are in part focused on how humans perceive individual or multiple auditory cues that change in rate.

The following section is intended to provide a background that describes physiological evidence that the auditory system has the ability to process auditory signals that exhibit spatial and temporal changes over time. In particular there is recent work in the literature and from our own laboratory that demonstrates how certain brain regions and latency periods are specifically sensitive to auditory cue rate of change. Moreover, the work from our laboratory in part initiated some of the discussion regarding the current experimental designs, which is described in more detail below.

Investigators have used electrophysiology and neuro-imaging methods in animal models and in humans to explore the underlying mechanisms for auditory spatial and temporal processing. Several studies have shown that neural activity related to auditory signals that change over time and space, such as moving signals, likely evoke unique activation patterns (e.g., Brunetti, Della Penna, Ferretti, Del Gratta, Cianflone, Belardinelli, Caulo, Pizzella, Belardinelli, and Romani, 2008; Harrington, Stecker, Macpherson, and Middlebrooks, 2008; Krumbholz, Eickhoff, and Fink, 2007; Miller and Recanzone, 2009). These activation patterns are typically associated with more robust activity in specific brain regions, but are also associated with total neural activations that likely occur via distributed networks throughout the cortex (e.g., Brunetti, et al., 2008; Ivry and Schlerf, 2008; Middlebrooks, 2002; Middlebrooks, Xu, Eddins, and Green, 1998). For example, Brunetti et al. (2008) showed evidence of underlying mechanisms for processing cues that change spatially and temporally. In this study, functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) were used to provide information related to spatial and temporal aspects that pertained to the perception of the changes in auditory object location. Results from this study suggested that auditory localization activity begins bilaterally in the auditory cortex and then activates areas in the right posterior superior temporal gyrus (PSTG), right inferior frontal regions and right inferior parietal cortex (Brunetti et al., 2008). In our own effort to explore how humans respond to changing auditory cues, such as those that change in frequency or in spatial position, we have used event-related potentials in our laboratory to show that brain activation patterns are significantly different in response to signals that are moving or not moving in latency periods longer than 350 ms (Figure 1).

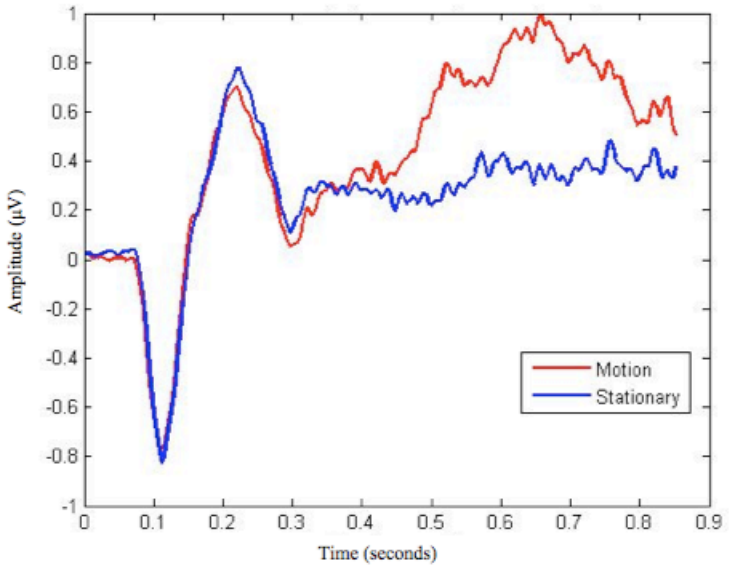

Figure 1. Event-related potential principle component analysis grand waveform results based on three spatial and four temporal factors from N = 12. The red tracing represents responses evoked by moving auditory signals and the blue tracing represents responses evoked by auditory signals that were stationary.

In addition, preliminary results from a follow-up study to this suggest that there may be a consistent pattern in response to conditions that contain changes in spatial position as opposed to a frequency change. Collectively, this research provides evidence that underlying neural mechanisms in humans demonstrate the ability to process auditory events with cues that exhibit spatial and temporal changes.

The event-related potential work from our laboratory led to discussions about the possibility that humans may be differentially sensitive to individual or multiple auditory cues that change across certain dimensions. In particular, discussions focused on the possibility that humans may respond differently to auditory cues related to motion perception than to auditory cues that change in another dimension, such as frequency. In our experiments we were able to show that physiological responses to moving signals were different than responses to signals that changed in frequency; therefore, we were able to demonstrate that the auditory system may respond specifically to moving auditory signals compared to general changes in the listening environment. There have been several psychoacoustic reports that have investigated how certain auditory cues and the rate at which they change contribute to the perception of motion. There has been a considerable effort to study how auditory cues that relate to motion perception are detected. Also, several psychoacoustic reports have focused on measuring human sensitivity to the smallest amount of cue change that can be detected, which has led to descriptions of the possible underlying processing mechanisms for motion perception. The next section provides a review of this literature.

### *Auditory cues for motion perception and underlying processing mechanisms*

There are several auditory cues that contribute to the perception of spatial location. Auditory cues for direction are based largely on interaural differences of arrival time and intensity as well as spectral variations arising from the shapes of the head and ears. Localization with respect to distance is based largely on overall sound level, the ratio of direct to reverberant sound, and Doppler shift if rapid motion is involved (Grantham, 1995; Rosenblum, Carello, and Pastore, 1987). The duplex theory may partially explain how humans localize sound sources with complex frequency spectra. Simply stated, this theory indicates that low frequency signals are localized by interaural time differences (ITDs) and high frequency signals are localized by interaural level differences (ILDs), however this cannot explain all aspects of directional hearing (Grantham, 1995). Spectral cues, which describe the shape of one's pinnae, may provide additional information (Grantham, 1995). Successful sound source localization and motion perception in real-life instances requires use of a combination of interaural time differences, interaural level differences, and spectral cues (Grantham, 1995). In daily life there are numerous instances, such as detecting a moving vehicle, when these auditory cues exhibit subtle changes that contribute to our perception of changes in the environment. Several investigations have focused on how changes in these auditory cues underlie the ability to discriminate location changes. These studies have provided important information about human sensitivity to differences in spatially separate auditory signals with respect to discrete or continuous changes. Presumably, motion perception is based on the same types of cues that underlie spatial localization when there is no relative motion between the sound source and listener. However, whether motion perception is "pure" or is derived from stationary localization has been a topic of debate.

Behavioral studies in adult humans have used the minimum audible angle (MAA) and the minimum audible movement angle (MAMA) to learn how humans discriminate location changes. The MAA describes the minimum angle needed to discriminate the differences in location between two stationary auditory signals (Harris and Sergeant, 1971; Mills, 1958). Auditory motion perception in humans has been measured by determining the minimum angular motion required to discriminate between a moving auditory stimulus and a stationary one (Grantham, 1986; Perrott and Musicant, 1977). Under optimal conditions (long interstimulus intervals or slow-velocity targets), MAAs are about 1° to 3° and MAMAs range from about 1° to 5°, depending on the velocity and stimulus frequency (Harris and Sergeant, 1971; Grantham, 1986; Grantham, 1995).

The underlying mechanisms for processing auditory events are based on continuous motion that have been extensively debated in the literature. Two theories have been proposed to account for this perception. The snapshot hypothesis suggests that humans take spatial samples or snapshots of the signal's onset and offset and compare these positions (Grantham, 1986, 1995). In a series of experiments, Grantham (1986) measured MAMAs in four participants when 1) duration was held constant and velocity was varied or when 2) duration was varied and velocity was held constant. He also did a third experiment where the velocity threshold was measured for a given duration (Grantham, 1986). Results from these experiments showed that participant performance depended more on the duration of the signal than the velocity (i.e., participant performance improved with increased signal duration while velocity was constant) (Grantham, 1986). These results suggest that participants may have performed these tasks by listening to the distance traversed rather than making use of velocity per se (Grantham, 1986). Therefore, Grantham (1986) concluded that auditory motion is perceived by interpreting a spatial difference between the onset and offset of auditory targets since the displacement between two signals is a more salient cue than the speed of the signals.

In contrast, the motion-sensitive mechanism or specialized motion detector hypothesis generally suggests that the auditory system can respond directly to the velocity of auditory signals in addition to being sensitive to the onset and offset positions of the auditory event (Perrott, Costantino, and Ball, 1993; Perrott and Marlborough, 1989). Perrott and Marlborough (1989) compared behavioral responses from four participants in two moving conditions with constant angular velocity (20°/s). One condition contained continuously moving noise and the other condition consisted of 10 ms noise bursts at the onset and offset with a silent interval between (Perrott and Marlborough, 1989). Results from this study showed that the thresholds for the condition with continuously moving noise were significantly lower than the condition with noise bursts at the onset and offset with a silent interval in between. Thus, the authors concluded that auditory information arriving after the onset and before the offset contributes to motion perception (Perrott and Marlborough, 1989).

Recent reports (Grantham, 1997) indicate that it is likely that aspects of both mechanisms are true under certain conditions. In a series of experiments Grantham (1997) re-examined the possibility that humans are able to use continuous motion information as opposed to detecting onset and offset cues to perceive moving signals. Grantham (1997) compared MAA, MAMA, and marked end point (ME) responses at two constant velocities (20°/s and 60°/s). For the slower velocity (20°/s), mean MAA threshold = 3.4°, mean MAMA threshold = 4.8°, and mean ME threshold = 5.6°. For the faster velocity (60°/s), mean MAA threshold = 5.9°, mean MAMA threshold = 7.8°, and mean ME threshold = 8.0°. These results show that when velocity is slower (20°/s), humans perform better when information is presented in the mid-portion of a horizontally moving target compared to two spatially separated end points (i.e., MAMA thresholds were lower than ME thresholds), which supports a motion-sensitive mechanism. Also, the results show that when velocity is faster (60°/s), performance is similar when either information is available at two spatially end points or when it is presented in the mid-portion of a horizontally moving target (i.e., ME thresholds were lower than MAMA thresholds), which supports a snapshot mechanism. Although these mechanisms are fundamentally different, it seems that they can both be used to describe how auditory motion perception is achieved by detecting changes in acoustic cues over time.

In summary, spatially changing information to localize an auditory signal includes direction and distance cues. Minimum audible angle (MAA) and minimum audible movement angle (MAMA) experiments have demonstrated how changing direction and distance cues influence the perception of changing auditory signals whether they are stationary or in motion. Taking into account the auditory cues that are used to detect spatially changing cues, the next section shifts the focus to consider the importance of certain auditory cues over others. The following chapter includes a literature review of this issue and also includes a discussion of how sensitivity to the rates of changing auditory cues may be measured and possibly influenced when these cues are combined.

# CHAPTER II

# PROCESSING OF MULTIPLE AUDITORY CUES

This chapter contains a review of the pertinent literature focused on how humans rank or “weigh” auditory cues in terms of importance for discrimination between two signals. Another goal of this chapter is to discuss how combinations of these cues may be useful to enhance overall perceptual differences between changing auditory events. In addition, the difficulty in measuring auditory cue change sensitivity with respect to confounding factors (between duration, rate, and extent) is addressed. A novel approach for measuring auditory cue sensitivity that addresses this confound is also discussed and was the impetus for the study design of the first and second experiments in this study.

## *Perception of auditory cues and their “weight”*

Previous reports suggest that humans can perceive changing auditory events more accurately for some classes of cues than others. For example Rosenblum et al. (1987) investigated the relative importance of individual cues about distance or approach time, such as interaural time differences, Doppler effect (frequency change) cues, and amplitude (intensity) changes, for accurately judging the arrival time of an approaching sound source that traveled on a straight indirect path relative to the listener (simulated ambulance traveling at 48.28 km/hr along a line 15.24 m in front of the plane of the listener). Participants (N = 13) listened to five different types of conditions. In the first condition (control) all three cues were available to the participant. In the second condition each cue was presented in isolation and the other two cues were held constant. In the third, fourth, and fifth conditions the timing of the cues was varied. The participants were told that they would hear an ambulance-type siren and to press a button when it sounded like it was just passing them. In the detection task, participants showed the best accuracy when the available cues were amplitude changes (intensity) and then interaural time differences, and finally Doppler effect (frequency change) cues.

In another study, Lutfi and Wang (1999) also explored the salience of overall sound pressure level (intensity), interaural time differences, and Doppler effect cues in terms of their influence on performance in a discrimination task. In addition they investigated if the order of importance among these cues was altered with differences in velocity, intensity, or frequency. To obtain cue weights, they used discrimination tasks involving judgments of displacement, velocity, or acceleration. For all conditions the standard source started at a fixed point and for each trial traveled the same duration (1 s) at a fixed velocity (10 or 50 m/s) and acceleration (0 m/s$^2$) along a straight path going in front of the listener. The comparison source had the same duration as the standard but varied in starting point, velocity and acceleration. Participants (N = 11) were asked to discriminate between two sounds that traveled left to right in terms of which signal moved further to the right, traveled with greater velocity or traveled with greater acceleration. This study concluded that some cues are more salient than others, depending on the velocity of the signal. At a moderate velocity (10 m/s), overall sound pressure levels and interaural time differences are preferred to discriminate displacement differences and Doppler effect cues are preferred to discriminate velocity and acceleration differences. At a higher velocity (50 m/s), the Doppler effect cues are generally preferred in all discrimination tasks. In an effort to replicate and extend this work, Kaczmarek (2005) used a velocity discrimination task to determine the differential velocity thresholds and the magnitudes of the same three auditory cues for motion (change in overall sound pressure level, Doppler effect cues, and change in interaural time differences) for a range of reference velocities (10, 20, 30, and 40 meters per second). This investigation also focused on how listeners assigned "weight" to potential auditory cues to perform the velocity discrimination task. Kaczmarek (2005) concluded that the rate of change for certain auditory motion cues, specifically the Doppler effect cues and change in overall sound pressure level, are useful to participants and are assigned the greatest "weight" for velocity discrimination tasks.

In general, previous literature reports have shown that the changes in the rate of intensity (described in previous studies as signal amplitude or overall sound pressure level cues) and possibly changes in the rate of frequency (described as Doppler effect cues) are most important to discriminate distance-related moving auditory signals (Kaczmarek, 2005; Lutfi and Wang, 1999; Rosenblum et al., 1987). It has also been shown that some cues (e.g., frequency rate of change) may be perceived as more important at particular velocity rates. Based on these reports it may be that humans are more sensitive to the rate of auditory cue change when the most important auditory cues are combined in a signal.

### *Influence of auditory cue combinations*

In addition to understanding the perceived weight of these cues, it behooves investigators to explore how combinations of these cues influence signal perception since this more accurately represents natural listening environments. Rosenblum et al. (1987) included three conditions where cues were combined in various ways. The authors noted that participants were most accurate in their judgments when the three cues were combined as opposed to when of one or more of the cues was isolated (Rosenblum et al., 1987). Thus, it is possible that the results of this study are not due to the isolated acoustic structure at the exact moment when the signal is "passing" the participant. Instead, participants could be responding to the rate of change in the combination of cues during a trial (Rosenblum et al., 1987).

Carlile and Best (2002) investigated the response to directionally changing cues when one aspect is enhanced to contain additional information. Specifically, they investigated how humans responded to differences between a pair of moving signals based on velocity information alone or velocity plus additional displacement cues. The signals for this study traveled along a circular path, thus direction cues were available to the listener but not distance cues. In this study, participants (N = 6) listened to two successive signals and were asked to choose which signal moved faster. In the first condition, velocity was the only reliable information available to participants; the magnitude of displacement was randomized in such a way to make it an unavailable cue. Displacement cues (angular extent, thus duration as well) were available in the second experiment and were even more salient in the third experiment (angular extent with common start position). Although participants were able to use velocity to perform the task when it was the only information available, the best performance for all participants was recorded when onset and offset cues were available. Furthermore, participants' performance improved according to the magnitude of the resulting displacement cue. It is clear from these results that humans use available displacement cues instead of motion cues if they are available.

Taken together, the results of these experiments suggest that humans may experience perceptual benefit when more than one auditory cue is combined in a changing dimension. Specifically, previous work has shown that additional cues related to auditory motion perception are beneficial. The results from these literature reports naturally give rise to the question of whether humans simply combine non-speech auditory cues or if the benefit of additional information in a changing signal yields an enhanced perceptual benefit acquired through somehow integrating these cues.

### *Auditory cue integration*

In the previous section, several literature reports were described that suggest humans are sensitive to changing auditory cues for motion and may be even more sensitive to combinations of changing cues. It may be possible that humans have the ability to integrate certain combinations of auditory cues as they change over time to yield an enhanced perception of a particular auditory event. For example, humans are sensitive to changes in rates of auditory motion cues that are distance and direction information. However, it is possible that when both types of cues are available, compared to situations where only one type of cue is available, humans may demonstrate enhanced sensitivity to a moving auditory signal, which may in part be because of auditory cue integration. Unfortunately, the literature is void of any research or proposed models that describe the perceptual response to simultaneously combined moving or stationary (non-speech) cues that are restricted to the auditory modality that may be integrated over time.

However, there are numerous multisensory reports that generally suggest that multiple sensory cue perception is accomplished through the so-called visual capture model or the maximum-likelihood estimation model (Battaglia, Jacobs, and Aslin, 2003; Lalanne and Lorenceau, 2004). Although these models are not used to describe sensory cues isolated to the auditory modality, it is conceivable that they may be applied in some way to auditory cue sensitivity and how combinations of these cues influence the perception of auditory events. The visual capture model describes a scenario where the more reliable cue (in multisensory experiments, this is usually vision) dominates in a "winner-takes-all" method so that participant judgments are based exclusively on that dominate cue (Battaglia et al., 2003; Lalanne and Lorenceau, 2004). The ventriloquism effect is an example of how this model is demonstrated. The maximum likelihood estimation model is also dictated by the reliability of a sound source. This model suggests that a sensory cue is reliable if the distribution of the cue source has a relatively small variance. If the cue source has a large variance the source is considered unreliable. In the maximum likelihood estimation model more reliable cues are assigned a larger weight and less reliable cues are assigned a smaller weight when linearly combined with other cues. There are currently no models to describe sensory cue integration that are restricted to the auditory modality. However, it may be plausible that a version of one or both of these models may describe the perception of combinations of multiple auditory cues that change over time. The previous section described several studies that showed that individuals perceived that certain auditory cues carry more weight than others for auditory discrimination tasks. It is possible then that the maximum likelihood estimation model may be more accurate to describe how multiple auditory cues are combined and possibly integrated to detect differences in these cues over time. In other words, the auditory cues that carry more weight may be more reliable than others. The measurement method by which humans are sensitive to auditory cue rate of change may influence the reliability of one or more cues. The next section addresses issues related to the measurement of auditory cue change.

### *Measurements of auditory cue changes*

In any study that aims to determine sensitivity to the rate of change in some dimension there is a natural confound or correlation between velocity, duration, and displacement. Figure 2 is an illustration of this relationship. In both panels of the figure, time is represented along the x-axis and stimulus value (could be any dimension, such as intensity or spatial position) is represented along the y-axis. In the top panel, the faster and slower functions have the same durations creating a scenario where the difference in the displacement of the stimulus value provides a cue about the difference in the rate of change. In the bottom panel, the faster and slower functions have the same amount of change in stimulus value, so the difference in duration provides a cue about difference in the rate of change.

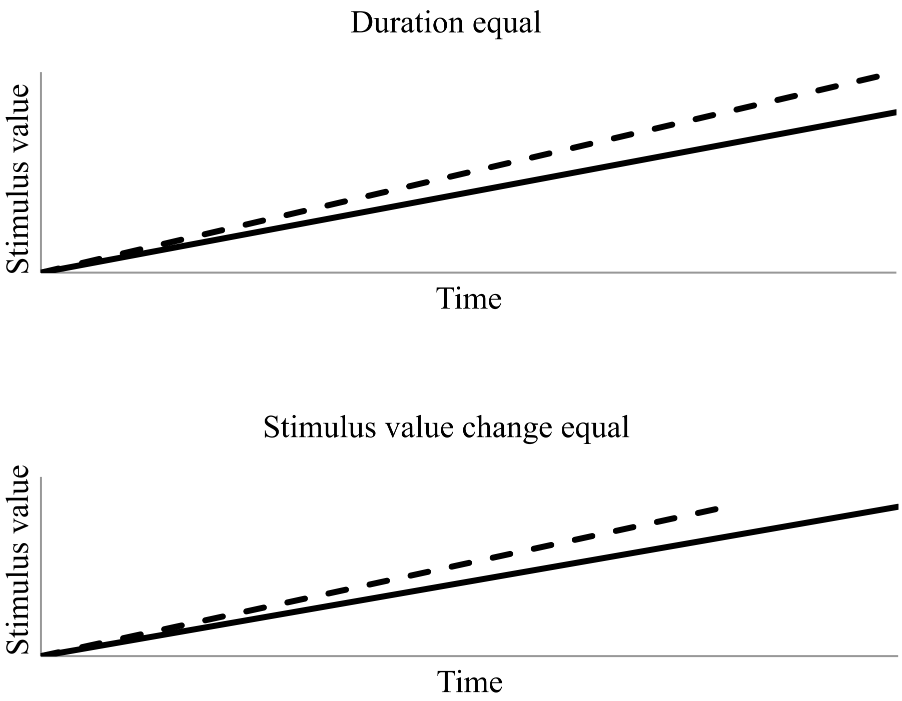

Figure 2. Illustration of the problematic confound between signal duration and changing stimulus values over time. The top panel shows how differences in the changing stimulus value may be a cue when signal duration is kept constant. The bottom panel shows how differences in the signal duration may be a cue when the stimulus value for the compared signals is kept constant.

In an effort to sidestep this problematic confound, Dooley and Moore (1988) proposed a psychoacoustic method aimed to measure the sensitivity to differences in auditory cue rates of change while allowing duration and velocity to co-vary together. This study involved the ability to discriminate differences in the durations of acoustic events with and without additional velocity cues. The intriguing finding reported in this study was that duration discrimination was enhanced by making the stimuli change in intensity, frequency, or both in such a way that a longer-lasting stimulus had a slower rate of change. The psychometric approach provided the impetus for development of the set of studies in the current study.

Dooley and Moore (1988) presented participants (N = 4) with a pair of 2000 Hz sinusoidal tones of different durations and asked them to indicate which signal lasted longer. This study examined the duration difference thresholds for 11 conditions that included additional cues for duration based on intensity, frequency, or both (Dooley and Moore, 1988) (Table 1). During the signal presentation, the intensity either ascended or descended by 5 or 10 dB and frequency ascended or descended by 100 Hz; the rate of change in these cues was allowed to co-vary with the duration of the signals (Dooley and Moore, 1988).

Table 1. List of conditions tested in Dooley and Moore (1988).

| **Dooley & Moore (1988) Conditions** | **Level (dB SPL)** | **Frequency (Hz)** |
|---|---|---|
| 1 | 65 | 2000 |
| 2 | 60-65 | 2000 |
| 3 | 65-60 | 2000 |
| 4 | 55-65 | 2000 |
| 5 | 65-55 | 2000 |
| 6 | 65 | 1900-2000 |
| 7 | 65 | 2000-1900 |
| 8 | 55-65 | 1900-2000 |
| 9 | 65-55 | 1900-2000 |
| 10 | 55-65 | 2000-1900 |
| 11 | 65-55 | 2000-1900 |

Thus, when two stimuli differing in duration contain the same amount of change in intensity (or frequency, or both), the longer lasting stimulus has the lower rate of change in intensity (or frequency, or both). So the rate of change in one or two dimensions of the stimulus is an additional piece of information that could be used to perform the task of discriminating between shorter and longer lasting events. On average the duration difference threshold for the baseline steady tone condition (no additional cues present) was 47 ms (Weber fraction = 0.063) (Dooley and Moore, 1988). These results are similar to previously reported duration discrimination thresholds for signals with comparable durations that had no additional cues present (Abel, 1971). On average these participants had the smallest duration discrimination threshold (28.5 ms) when there were both frequency and intensity cues (Dooley and Moore, 1988). In other words, participants demonstrated significantly better duration discrimination task performance for conditions with signals that had additional auditory cues compared to conditions with signals that did not have these additional cues. This result suggests that when additional auditory cues are available in the compared signals, participant performance will improve compared to conditions without these additional cues.

One way to evaluate how sensitive humans are to rates of auditory cue change is to calculate the Weber fraction for each condition. In general the results of Dooley and Moore (1988) showed that humans are sensitive to an average rate of frequency change of approximately 5.5 Hz/s and the calculated average Weber fraction is equal to 0.058. Also, the results of this study showed that humans are sensitive to an average rate of intensity change of approximately 0.54 dB/s for 10 dB of change and 0.28 dB/s for 5 dB of change and the calculated Weber fractions are equal to 0.056 (for the 10 dB and 5 dB amounts of change). The results of this study are summarized in Table 2.

Table 2. Summary of results from Dooley and Moore (1988).

| **Summary of results from Dooley and Moore (1988)** | **Average Threshold** | **Cue Change** | **Average Weber Fraction** |
|---|---|---|---|
| Frequency cues only (conditions 6 & 7) | 32.5 ms | 5.5 Hz/s | 0.058 |
| Frequency + Intensity cues (conditions 8-11) | 28.5 ms | 4.85 Hz/s<br>0.49 dB/s | 0.047 |
| 5 dB Intensity cue (conditions 2 & 3) | 32 ms | 0.28 dB/s | 0.056 |
| 10 dB Intensity cue (conditions 4 & 5) | 32 ms | 0.54 dB/s | 0.056 |

The results of the conditions that had additional cues in the compared signals are not consistent with other literature reports that describe human sensitivity to rate of changing auditory cues. For example, Strybel and Perrott (1984) showed that sensitivity to differences in the rate of intensity change for shorter distances (e.g., 1.5 meters) resulted in Weber fractions of approximately 0.1, which is nearly twice of that reported by Dooley and Moore (1988).

A possible caveat in this study relates to the listening experience of the participants. Given the arbitrary connection between signal dimensions, it is possible that task experience is particularly important to achieve the high level of performance reported in this study. It is possible that humans are naturally more sensitive to changes in the extent of an auditory signal as opposed to changes in the rate of cues. If this is the case then performance in a duration discrimination task should be good. Since humans may be less sensitive to changes in the rate of auditory cues it is possible that this information could be distracting. However, it is possible that humans with extensive listening experience may be conditioned to listen for and respond to changes in the *rate* as opposed to the *extent* of auditory cues. All four participants reportedly had extensive experience listening to these signals, thus it is possible that these results reflect expertise in listening for the rates of change in cues instead of the duration or extent of the auditory cue. Across all four participants, duration discrimination thresholds for conditions with additional cues were low and ranged from approximately 45 to 18 ms. Interestingly, the difference between the baseline condition and the conditions with additional cues was larger for the first author compared to the other participants. For example, the difference between the baseline and the fourth condition (10 dB ascending intensity cue) for the first author was 35ms and ranged from 3-18ms for the other participants. It is possible that the first author showed the largest perceptual benefit of additional cues compared to the other participants. This result may be in part due to extensive listening experience and an emphasis on auditory cues that change in their rates instead of attending to the differences in duration.

Nonetheless, Dooley and Moore (1988) concluded that participant performance in a duration discrimination task is improved when additional auditory cues are available. Based on this report, it is reasonable to suggest that a similar pattern of improved performance could be shown in conditions in which the additional auditory cue consists of motion of the sound source. Also, this study only included participants that were experienced with this task, thus it is not clear how naïve listeners would perform with and with out additional cues available.

The overarching goals of the current study were to 1) to learn if the psychometric “tool” that Dooley and Moore (1988) proposed could be replicated to measure sensitivity to differences in the rate of changing auditory cues and extended to include additional auditory cues that change in spatial position and 2) to determine if individuals experience enhanced sensitivity to auditory events that have more than one changing cue dimension compared to conditions with one available cue. Experiment 1 partially replicated the study by Dooley and Moore (1988) by re-examining the performance in duration discrimination tasks when the auditory signal was paired with an additional rate of change in intensity cue.

It was hypothesized that the results of Experiment 1 would replicate Dooley and Moore (1988), such that performance in conditions with moving auditory signals would be better than in conditions where the signal was not moving. The rationale for this hypothesis stems from the notion posed in previous work (Dooley and Moore, 1988) that when additional cues, such as changes in rate of intensity, are included in a signal, duration discrimination performance is improved. Since a moving signal includes velocity information that is not present in a stationary signal, it stands to reason that performance may be better in conditions that contain a moving signal. On the other hand, it is possible that the motion information could be a source of distraction in a task that does not emphasize attention to spatial attributes of the events.

The study design of the first experiment was based on the methods described in Dooley and Moore (1988). In that study and in the first experiment the differences between the rates of change in auditory cues were very small. Previous literature reports have indicated that humans require larger rates of auditory cue changes to be perceptually salient (Carlile and Best, 2002; Grantham, 1986; Lutfi and Wang, 1999). Therefore, it is possible that the information about changes in rate of intensity or directional velocity in the first experiment were not perceptually salient. In consideration of this possibility, Experiment 2 investigated whether duration discrimination performance was influenced when additional auditory cues are perhaps more salient to the participant, that is by increasing the duration of the signals, which in effect causes a slower rate of cue change.

The first two experiments were concerned with the possibility that sensitivity to rates of changing auditory cues may be measured through enhanced performance in a duration discrimination task. The aim of the third experiment was to determine if changes in auditory spatial position perception was influenced more by 1) direction or distance auditory cues, 2) combinations of direction and distance cues, and 3) a combination of direction and distance cues that were weighted for individual sensitivity to create an optimal listening environment.

# CHAPTER III

# EXPERIMENTAL FINDINGS

### *Environment, equipment, and stimuli*

All stimuli were presented from a horizontal circular array of 64 fixed loudspeakers, spanning a full 360° in an illuminated anechoic chamber. The loudspeakers were 1.95 meters from the center of the circle and separated by 5.6°. All stimuli were generated using Tucker Davis 3 hardware and custom Matlab routines. The signals were Gaussian noises that were band-pass filtered from 300 to 1000 Hz and presented at an average level of 65 dB sound pressure level (SPL), as measured by a microphone at the position of the participant's head. Motion paths of sound source were simulated by setting the direction and sound level of the signal, with a motion update at a sampling rate of 244 Hz. Direction was set by selecting two loudspeakers that spanned the current simulated direction, and used a panning algorithm to further specify the exact azimuth.

## *Experiment 1*

The purpose of this experiment was to investigate whether participant performance could be enhanced in a duration discrimination task with additional cues consisting of rate of intensity change (partial replication of Dooley and Moore, 1988), rate of spatial position change, or both cues. The rationale was that the occurrence and extent of enhancement would provide a measure of sensitivity to differences in the rate of change (of intensity, spatial position, or both).

### *Participants*

Participants for this experiment were six young adults (mean age = 26, age range = 22 to 30 years), three females and three males, with normal hearing who were recruited from the Vanderbilt University community. Normal hearing was defined as thresholds less than or equal to 20 dB HL at octave frequencies 250-8000 Hz. This hearing threshold criteria was used for all experiments. Informed consent was obtained from each participant prior to testing for all experiments.

### *Procedure*

The task was duration discrimination. A two-interval forced-choice task was employed, in which participants heard a standard signal and a comparison signal (both signals had 20 ms cosine-squared rise/fall times). The standard signal was always shorter in duration than the comparison signal and the order of presentation was randomized across trials. Participants were asked to indicate which signal lasted longer by pressing a corresponding button (see Appendix A for the instructions provided to the participants). Feedback that indicated the correct response using lights on the response box was provided for every trial. Duration discrimination thresholds were determined using an adaptive 3-down, 1-up staircase procedure, which reaches the 79% correct level. At the start of each threshold run, the duration difference between the standard and comparison signals was always 100 ms. Following every three consecutive correct responses, duration difference was decreased by dividing by 1.2. After every incorrect response, the duration difference was increased by multiplying by 1.2. Testing included 10 turnarounds (increasing to decreasing duration difference and vice versa). The threshold for each threshold run was determined as the geometric mean of the duration difference values from the last six turnarounds.

There were four conditions for Experiment 1: 1) no motion, no intensity change; 2) no motion, +10 dB intensity change; 3) motion, no intensity change; 4) motion, +10 dB intensity change. Conditions one and two were a partial replication of Dooley and Moore (1988), and conditions three and four extended the work of their design to include motion, that is, change in location across time. The order of conditions was randomized across participants. The conditions with no motion began and ended directly in front of the participant. The conditions with motion began at +20° and ended at -20° for a total span of 40° in front of the participant. The duration of the standard signal was jittered between 700 and 750 ms. The duration of the comparison signal on a given trial was set to the duration of the standard signal on that trial plus the current value of the difference in duration. The onset location of the signals was jittered by ±5° and the onset intensity was jittered by ±0.625 dB to prevent participants from potentially using onset or offset information as a cue. Testing included two practice sessions prior to the test session in which duration discrimination thresholds were determined. Each practice session and the actual test session were held on three separate days within one week to eliminate fatigue and boredom. Participants were allowed to take breaks at any time during the test sessions.

During the actual test session, three threshold runs were completed for each of the four conditions. To minimize fatigue, a five-minute break was given after each condition block of four threshold runs. After all 12 runs were completed, the mean threshold value and its standard deviation were determined for each condition. If the standard deviation for any condition was greater than 1/3 of the mean, additional runs were completed for that condition until this criterion was met. All participants met this criterion in no more than six threshold runs for each condition. Total testing time across all sessions for each participant was approximately 2.5 hours.

### *Results*

For each participant the mean thresholds across three to six threshold runs were calculated for all four conditions rounded to the millisecond. Also, the mean thresholds, standard deviations, and standard errors were computed across participants (Table 3, Figure 3).

Table 3. Experiment 1 descriptive results, thresholds in milliseconds.

| Participant | No Motion No Intensity Change (ms) | No Motion Intensity Change (ms) | Motion No Intensity Change (ms) | Motion Intensity Change (ms) |
|---|---|---|---|---|
| S 1 | 85 | 112 | 86 | 113 |
| S 2 | 81 | 88 | 75 | 100 |
| S 3 | 65 | 92 | 70 | 81 |
| S 4 | 41 | 68 | 47 | 47 |
| S 5 | 51 | 68 | 68 | 90 |
| S 6 | 47 | 72 | 82 | 82 |
| Mean | 62 | 83 | 71 | 86 |
| Standard deviation | 18 | 17 | 14 | 22 |
| Standard error | 7 | 7 | 6 | 9 |

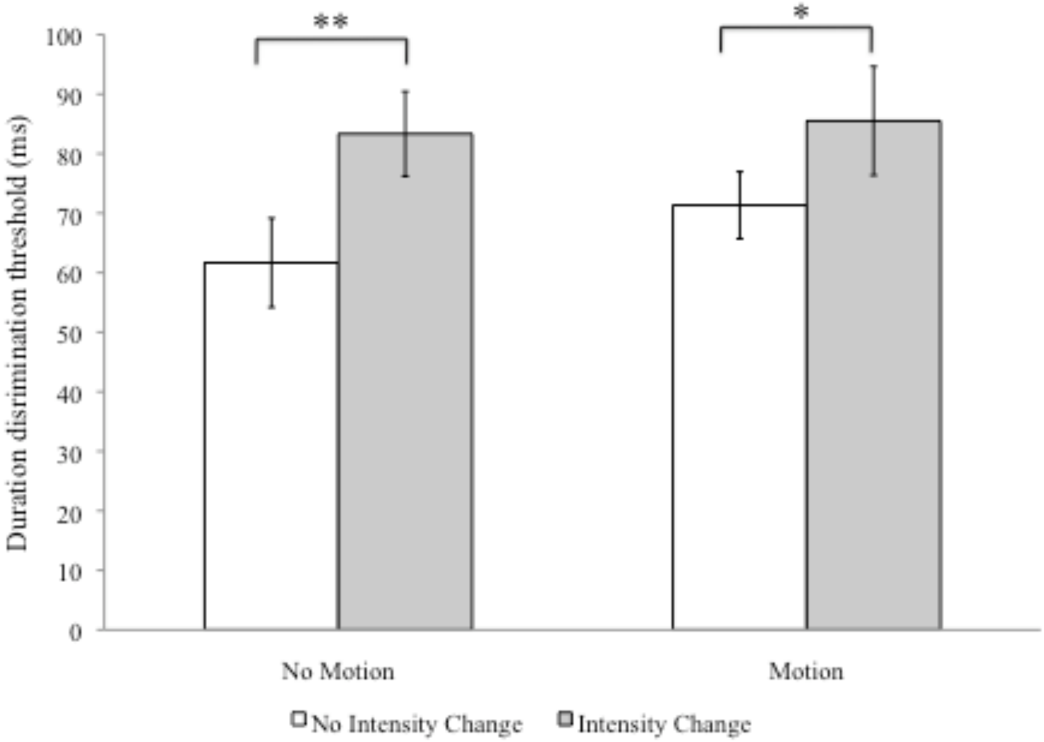

Figure 3. Experiment 1 grand average result from n = 6. Error bars are equal to the standard error of the mean. A significant finding of $p < 0.05$ is represented by * and a significant finding of $p < 0.001$ is represented by **.

An analysis of variance (ANOVA) was carried out on the threshold estimates with motion (yes, no) and intensity change (yes, no) as independent variables. The main effect of intensity change was significant, $F_{(1,5)} = 69.43$, $p < 0.001$, $\eta^2 = 0.93$. As shown in Figure 3, duration discrimination thresholds were approximately 15 to 20 ms higher when the stimuli contained intensity change. There was not a significant main effect for motion, nor was the interaction between intensity and motion significant.

Planned linear contrasts were done between the mean duration discrimination thresholds of certain conditions, as follows. The mean duration discrimination threshold for the no motion condition with +10 dB intensity change was significantly higher than the mean duration discrimination threshold for the no motion condition without an intensity change, $F_{(1,5)} = 42.25$, $p < 0.001$, $\eta^2 = 0.89$. The mean duration discrimination threshold for the motion condition with +10 dB intensity change was significantly higher than the mean duration discrimination threshold for the motion condition without an intensity change, $F_{(1,5)} = 7.976$, $p < 0.05$, $\eta^2 = 0.62$. Considering both of these contrasts, it was found that regardless of whether there was motion, listeners did worse at duration discrimination when there was an intensity change. This finding differs from that of Dooley and Moore (1988), who reported better duration discrimination when there was an accompanying intensity change. There was not a significant difference between the mean duration discrimination thresholds for the no motion and motion conditions, either with or without +10 dB intensity change.

### *Discussion*

Dooley and Moore (1988) proposed an interesting procedure by which a duration discrimination task could be used to measure sensitivity to rate of change on another dimension (for their study, intensity and frequency were used). By using the duration discrimination task, they avoided the usual confound that for the same net amount of change, a slower-changing stimulus lasts longer than a faster-changing stimulus. In their procedure, sensitivity to rate of change in intensity (or frequency) is indicated by enhanced duration discrimination due to the additional cue of rate of change. We were interested in whether their approach might be applied to the study of motion perception, that is, sensitivity to rate of change in location. However, the results of Experiment 1 did not show enhanced duration discrimination when a rate of change cue was present. In fact, duration discrimination was worse in the presence of rate of change cues, and this was statistically significant when the change was on the intensity dimension.

In the current study, for the +10 dB intensity change conditions, the average rate of intensity change at the beginning of a threshold run for the standard signal was 13.3 dB/s based on an average starting duration of 750 ms. The rate of intensity change for the comparison signal with a starting duration of 850 ms was 11.76 dB/s. Therefore, the difference in rate of intensity change averaged 1.54 dB/s at the beginning of a threshold run. By similar logic, the average duration discrimination threshold for the no motion, +10 dB intensity change condition was 83 ms, so the difference in rate of change of intensity between the standard and comparison signals was on average 1.30 dB/s which corresponds to a Weber fraction of 0.098 (the Weber fraction is calculated using the following equation: (standard velocity – comparison velocity) / standard velocity). The average duration discrimination threshold for the motion, +10 dB intensity change condition was 85 ms, so the difference in intensity rate of change between the standard and comparison signals was on average 1.32 dB/s, which corresponds to a Weber fraction of 0.099. These values of 1.30 and 1.32 dB/s are much larger than the value of 0.54 dB/s reported by Dooley and Moore (1988) for their condition with an ascending 10 dB intensity change, based on their duration discrimination threshold of 32 ms. Likewise, the Weber fraction calculated from a similar condition reported in Dooley and Moore (1988) was 0.056 which is smaller than the Weber fractions determined in the current study.

Whereas the findings from Dooley and Moore suggested an enhancement of duration discrimination based on exquisite sensitivity to differences in rates of intensity change, the findings from the present study suggested no such enhancement.

Previous work has been reported with regards to sensitivity to differences in intensity change between two successive sound sources. Strybel and Perrott (1984) performed a series of measurements with the intention of measuring the limits of the loudness discrimination model described by Coleman (1963). The loudness discrimination model employs the following mathematical expression:

$$\Delta I = 20 \log (r/r_o) \qquad (\textit{eq. 1})$$

Where ΔI is the change in intensity in decibels (dB) and r is the distance from the signal to listener. From this equation, the Weber fraction, or ratio, can be determined:

$$\Delta r/r_o = 10^{(\Delta I/20)} - 1 \qquad (\textit{eq. 2})$$

Strybel and Perrott (1984) reported that when sounds are presented to naïve listeners at distances from the listener in free field of approximately 6 to 50 meters, the predicted Weber fractions showed little variation and were between 0.035 and 0.060 (see their Figure 1). However, when listeners discriminated signals that were within a closer range, for example 1.5 meters, the Weber fractions increased to a range of 0.1 to 0.14 and had more variability. In the current study, the source of the auditory signals was approximately 1.96 meters from the listener. The Weber fractions for the current study were generally in agreement, but slightly lower than the results reported by Strybel and Perrott (1984); however this may be because their measurements were made in the outdoors with ambient noise and the current study measurements were made in an anechoic chamber. Thus, it is possible that participants may be sensitive to these rates of intensity change, but the results may have considerable variability. In other words, this may not be a reliable acoustic cue until the distance traveled by the signal is extended beyond approximately 6 meters or so. Since Dooley and Moore (1988) reported results from conditions that were tested under headphones, a direct comparison of rate of intensity change that takes into account the distance of the signal to the listener is more difficult. However, it is possible that Dooley and Moore (1988) showed lower Weber fractions compared to the current study and other previous work (Strybel and Perrott, 1984) because of differences in the signal characteristics and/or the listening experience of the participants (this issue is discussed in more detail below).

Certain characteristics of the signals may have contributed to the differences in outcomes between the current study and the results reported by Dooley and Moore (1988). Dooley and Moore (1988) used a pure tone signal with a rise-fall time of 10 ms. The current study used a band-pass filtered noise signal with a rise-fall time of 20 ms. It may be that the difference in the rate of change of the ascending intensity cue was not as salient for band-pass noise signals versus for pure tone signals. Neuhoff (1998) showed that human behavioral responses to white noise, a 1000 Hz sinusoidal tone, and complex (synthetic vowel) signals that had either a rising (or falling) intensity change were different from each other. Among other results, Neuhoff (1998) reported that performance was best for complex tones, followed by sinusoids and then white noise signals. Based on the results of Neuhoff (1998) it is possible that the ascending intensity cue in the current study would have been more salient had a pure tone signal been employed as it was in Dooley and Moore (1988). Another possibility for our failure to replicate the Dooley and Moore (1988) findings is that we used a 20 ms rise/fall time, whereas they used 10 ms. Our use of 20 ms was based on an unintended equipment issue that was not discovered until after the data for Experiment 1 were collected.

To investigate these possibilities, another replication of Dooley and Moore (1988) was conducted. Three participants, 1 female and 2 males, (mean age = 51 years, range = 32 to 64 years) performed a duration discrimination task as described in Experiment 1 in which 1000 Hz pure tone signals with a rise/fall time of 10 ms were used. Participants were tested in two conditions: 1) no motion, no intensity change, and 2) no motion, +10 dB intensity change. For each of the three participants the mean thresholds across three to four runs were calculated for the no motion, no intensity change and the no motion, +10 dB intensity change conditions. Also, the mean thresholds, standard deviations, and standard errors were computed across participants (Table 4, Figure 4).

Table 4. Experiment 1a descriptive results, thresholds in milliseconds.

| Participant | No Motion No Intensity Change (ms) | No Motion Intensity Change (ms) |
|---|---|---|
| S10 | 53 | 66 |
| S11 | 64 | 87 |
| S12 | 97 | 114 |
| Mean | 71 | 89 |
| Standard deviation | 23 | 24 |
| Standard error | 13 | 14 |

Results for all three participants showed higher duration discrimination thresholds for the condition with the +10 dB intensity change compared to the condition without an intensity change (Figure 4). A paired samples t-test was carried out on the threshold estimates for each condition.

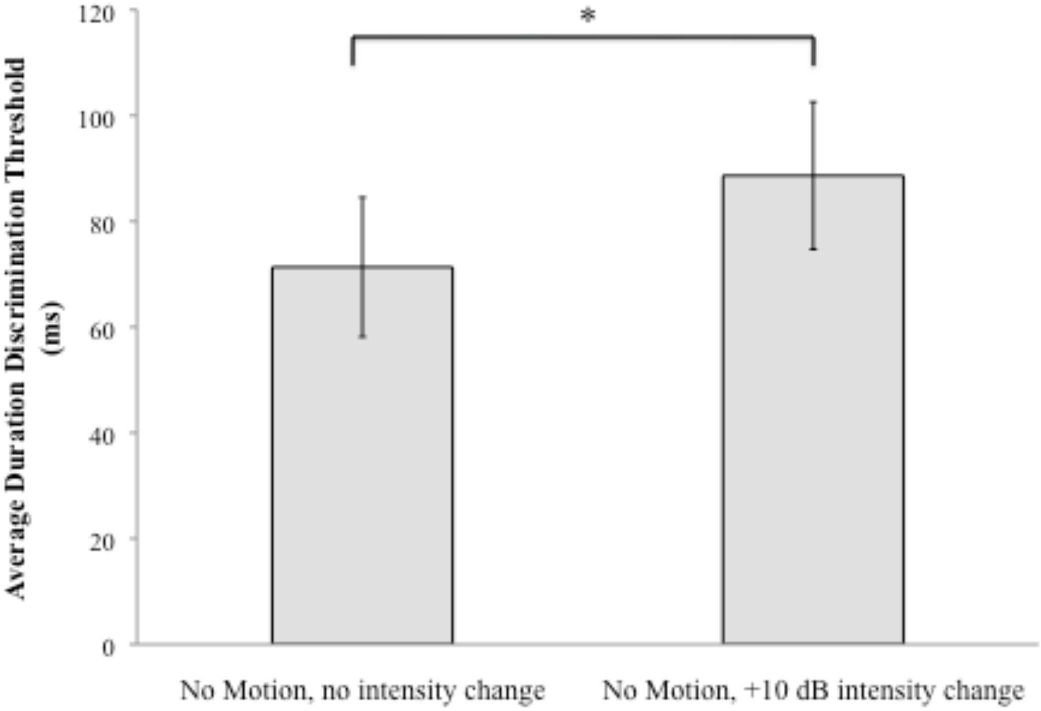

Figure 4. Experiment 1a, second replication of Dooley and Moore (1988) grand average result from n = 3. Error bars are equal to the standard error of the mean. A significant finding of $p < 0.05$ is represented by *.

There was a significant difference between these conditions, $t_{(2)} = 6.08$, $p < 0.05$ (two-tailed). This result suggests that when listeners perform a duration discrimination task using auditory signals that are very similar to those used by the listeners in the Dooley and Moore (1988) study, performance is worse in the condition with the additional intensity information.

This finding agrees with the results from Experiment 1, and similarly does not replicate the report by Dooley and Moore (1988). However, a pattern showing higher duration discrimination thresholds for signals with a +10 dB intensity change compared to signals without this additional intensity cue resulted whether the signal was a pure tone or a broadband noise. In addition, this overall pattern of results was the same whether the rise/fall time was 10 ms or 20 ms.

Another difference between the current study and the Dooley and Moore (1988) report relates to the participants that were included. The first part of Experiment 1 included naïve participants with limited experience listening to the auditory signals. In the Dooley and Moore (1988) study, the participants had considerable experience listening (at least four hours of practice as noted in their report) to these types of auditory events. It is possible that after considerable listening experience, one would demonstrate markedly improved performance over a relatively naïve listener and perhaps better identify known cues in each trial. Therefore, it is conceivable that the results reported in Dooley and Moore (1988), which showed enhanced duration discrimination performance for conditions with a rate of change cue were at least in part due to their participant's listening experience. It is also possible that additional experience with the duration discrimination task may also yield overall better thresholds. However, the three participants in the second part of Experiment 1 did have considerable listening experience with the signals and were familiar with the duration discrimination task and yet these results did not replicate the report by Dooley and Moore (1988).

The design of Experiment 1 introduced a deliberate confound in the duration discrimination task. Since the span of the motion signal was constant at 40°, the difference in duration between the standard and comparison signals was always accompanied by a difference in velocity. Dooley and Moore (1988) suggested in their report that this confound may be used as a tool to measure the rate of change of an aspect in the auditory signal. In the current study, we tested the application of this tool to determine if it could be extended to measurements about the rate of change in auditory motion. For example, assume that at the beginning of a trial the standard signal was 750 ms over a 40° span which has a velocity of 53.3°/s. For a comparison signal 100 ms longer than the standard signal the velocity would be 47.0°/s. Thus the difference in velocity between the two signals for this trial would be 6.3°/s. The average duration discrimination threshold for the motion, no intensity change condition was 71 ms, so the difference in velocity between the standard and comparison signals was on average 4.58°/s. The average duration discrimination threshold for the motion, +10 dB intensity change condition was 85 ms, so the difference in velocity between the standard and the comparison signals was on average 5.45°/s. To understand if the method described by Dooley and Moore (1988) can be applied here, it is imperative to know whether participants are sensitive to this difference in rate of change in motion. It stands to reason that if humans were sensitive to such small motion velocity differences, then duration discrimination thresholds for the moving conditions might be lower than the thresholds for the non-moving conditions. To determine if humans are sensitive to small differences in rates of change in velocity the Weber fractions of the current study results were compared to those from previous studies. In the current study, the Weber fraction based on the mean threshold for the motion, no intensity change condition was 0.086. Motion velocity discrimination results and the corresponding Weber fractions were evaluated from several literature reports. For example, Grantham (1986, Experiment III) reported that velocity discrimination results were approximately 8°/s for moving auditory signals with duration of 600 ms with reference angular velocity of 40°/s; thus the calculated Weber fraction was 0.2. Compared to the current study results, this Weber fraction is higher and therefore suggests that in Experiment 1 listeners were not likely to be able to take advantage of the velocity confound when performing the duration discrimination task. Similarly, a recent report by Carlile and Best (2002) reported that the median angular velocity discrimination threshold was 14.8°/s when the velocity of the standard signal was 60°/s, so the Weber fraction was 0.25. Other studies have reported velocity discrimination thresholds using signals that traversed with a constant linear velocity (Kaczmarek, 2005; Lutfi and Wang, 1999). Among other findings, Lutfi and Wang (1999, Experiment I) reported that average angular thresholds were 11° when the reference velocity was 10 m/s. In order to make a direct comparison to the current findings, these results were converted from constant linear velocity to changing angular velocity. A custom Matlab routine was used to convert constant linear velocity into changing angular velocity. This routine was used to estimate the average angular velocity as well as the maximum and minimum values. This type of signal travels past the listener in a straight path. So, the location where velocity discrimination is more likely is just as the signal approaches and passes the participant. The end points of this trajectory are not as likely to contribute to velocity discrimination per se, thus only the mean angular velocities for these studies are reported in the text. Based on the results of Lutfi and Wang (1999) the mean angular velocity was 90°/s, so the Weber fraction was on average 0.12. Recently, Kaczmarek (2005) reported similar results that replicated and extended the work of Lutfi and Wang (1999). They reported average angular thresholds that were 13° when the reference velocity was 10 m/s and mean angular velocity was 90°/s, so the Weber fraction was 0.14. In general, these results from previous studies suggest that humans are sensitive to rates of change in motion when velocity discrimination thresholds are associated with Weber fractions greater than approximately 0.12. Since the Weber fractions from the current study are lower than this, it is not likely that these discrimination thresholds are reflective of the perception of velocity differences in the signals. Therefore, the thresholds from the motion conditions in this experiment are likely due to the perception of the differences between signal durations, not velocity discrimination per se. In other words, the velocity and the duration of the signal confound was not useful in this experiment for determining sensitivity to rate of change in motion. However, it may be possible to measure sensitivity to rate of change in velocity with the method Dooley and Moore (1988) proposed if there were a larger rate of change difference between the compared signals.

The results of this experiment showed that conditions with intensity changes had significantly poorer duration discrimination thresholds than conditions without intensity changes. Although comparisons between conditions with and without motion cues were not significantly different, the results showed that conditions with additional motion cues tended to have worse thresholds than conditions without these additional cues. Based on previous work (Carlile and Best, 2002; Grantham, 1986; Kaczmarek, 2005; Lutfi and Wang, 1999; Strybel and Perrott, 1984) it is unlikely that participants in the current study were sensitive to auditory cue rate of change differences. If this were the case then these additional cues were not salient enough to the listeners to be beneficial as predicted. It is conceivable that if these cues were more obvious to the listener, they could be used to improve discrimination performance. If this was the case, the signal duration and rate of change confound may be a potentially useful tool for assessing sensitivity to rate of change as proposed by Dooley and Moore (1988).

The Dooley and Moore (1988) findings were interpreted as evidence that listeners utilized subtle differences between rates of change, resulting in enhanced duration discrimination performance. In contrast, the present findings were that listeners actually did worse in the duration discrimination task when the “added cue” was presented. Why would listeners do worse as opposed to just showing no difference, when there is a change on a dimension such as intensity, frequency, or spatial position? One possibility is that listening to the change engaged attentional resources, detracting from performance on the duration discrimination aspect of the task. The changes were very salient in our experience, +10 dB of intensity or 40° of spatial position, over the course of less than one second. Typically a change of that magnitude would carry meaningful information about whatever caused the change, so it would be reasonable for a listener to attend to the changing dimension. This might take away from performance on a duration discrimination task, particularly as the task progressed and the duration differences between the standard and comparison stimuli became smaller. The present experiments were not focused on dual attention issues, but there is an extensive research literature indicating that there are robust attentional responses to changing or unexpected acoustic events (e.g., Parmentier and Andres, 2010).

Another consideration, somewhat aside from the dual or divided attention issue, is that when the stimuli in our experiment included change in intensity or spatial position, listeners might have focused on the overall amount of change as a clue to duration. There is probably a tendency, for many events that involve acoustic change, for duration to be strongly correlated with overall amount of change. In our experiment, responding on the basis of this correlation would not have been a useful strategy, because the standard and comparison stimuli always had the same amount of change. If a listener nonetheless focused on the overall amount of change, this could have drawn on attentional resources, without providing any benefit for the duration discrimination judgments.

### *Summary*

In Experiment 1, we investigated whether the signal duration and rate of change confound in a duration discrimination task could be used as a method for measuring sensitivity to changes in intensity and motion. In contrast to previous reports, this experiment showed that this method was not successful to determine sensitivity to the rate of intensity or spatial velocity changes between the duration of two broadband signals and in fact resulted in poorer performance compared to duration discrimination of similar signals without changes in intensity. It is possible that in naïve listeners, if the rate of intensity change between the compared signals were larger, then the benefit of this additional cue would be more salient to participants. One way to accomplish this would be to increase the difficulty of the duration discrimination task, thus increasing the signals. This would result in greater differences between their rates of change and may allow the listener to use other available cues, such as rate of spatial or intensity change in the signals to perform the task. This approach was explored in Experiment 2.

## *Experiment 2*

The purpose of Experiment 2 was to further investigate if the signal duration task, with a rate of change confound, could be used as a method to measure sensitivity to changes in intensity and motion. In this experiment, the rate of change between these additional velocity-based cues was larger based on the assumption that a larger rate of auditory cue change would be more salient to the listener. In order to accomplish this goal, there were three modifications to the method described for Experiment 1. First, the duration of the standard signal was increased from 750 ms to 1500 ms. By increasing the overall duration of the compared signals, the duration difference thresholds are expected to be larger (see Abel, 1972), which in turn would introduce greater differences in velocity between the standard and comparison stimuli, and might be more salient to listeners. Second, the standard and comparison signals were independently selected from separate Gaussian distributions with considerable variability (standard deviation = 500 ms), rather than from specific point values (Figure 5). On each trial the duration of the standard stimulus was chosen from a distribution with a mean of 1500 ms, and the duration of the comparison signal came from a distribution with a higher mean value, with difference between the mean values of the two distributions changing over the course of the session depending on the tracking rules. Third, the dynamic, or velocity-related information was based on the means of the duration distributions (regardless of which specific duration values had been chosen from the distributions), to ensure that the velocity cue was always reliable. For example, if the comparison stimulus came from a distribution with a mean duration of 1800 ms, the calculation of velocities for the standard and comparison stimuli was nevertheless always based on 1500 and 1800 ms, regardless of the specific values that were randomly selected for the durations of the stimuli.

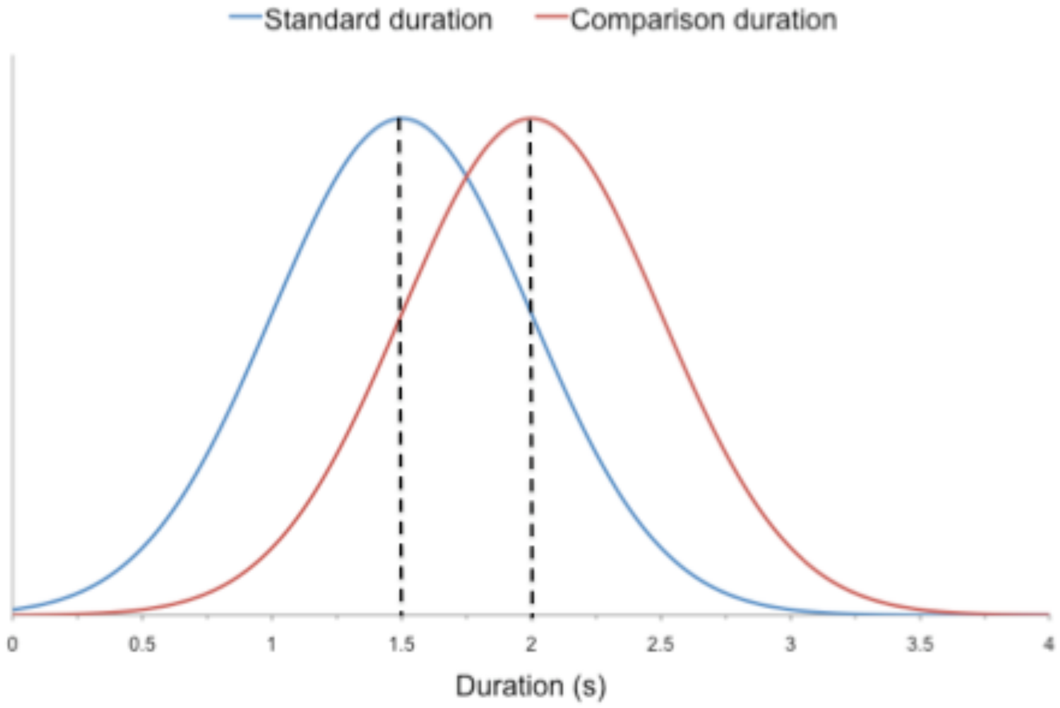

Figure 5. Standard and comparison independent signal distributions for Experiment 2. The blue line represents the distribution for the standard signal and the red line represents the distribution for the comparison signal. The black dashed vertical lines represent the means of each distribution at the beginning of a threshold run.

The net effect was that the velocity cue was always reliable, even when the actual durations were not reliable. When the means of the duration distributions are close together, the task will be difficult, and will even produce some trials on which the objectively longer duration comes from the distribution with the shorter mean. These method changes were expected to result in greater velocity differences between the standard and comparison stimuli as well as to emphasize velocity as a reliable basis for performance on the duration discrimination task.

### *Participants*

Participants for this experiment were six young adults (mean age = 30.7, range = 24 to 44 years), three females and three males, with normal hearing who were recruited from the Vanderbilt University community. Three individuals, one female, two males had also participated in Experiment 1. The other three individuals, two females, one male had not previously participated in experiments related to this study.

### *Procedure*

The experimental procedures were the same as in Experiment 1 except that all signals in this experiment had a 10 ms, rather than 20 ms, cosine-squared rise-fall time. There were four conditions: 1) no motion, no intensity change, standard deviation of duration distributions = 0 ms; 2) no motion, no intensity change, standard deviation of duration distributions = 500 ms; 3) no motion, +10 dB intensity change, standard deviation of duration distributions = 500 ms; 4) motion, no intensity change, standard deviation of duration distributions = 500 ms. As in Experiment 1, the motion began at +20° and ended at -20° for a total span of 40° for the durations that corresponded to the mean values of the standard and comparison deviations. The location onset was jittered by ±5° and the onset intensity was jittered by ±0.625 dB. These four conditions were counterbalanced across subjects and were tested separately on different days to minimize fatigue and boredom. For the first test condition, the standard deviation of the duration distributions was 0 ms (essentially this corresponds to using point values, and it would never lead to an incorrect response based on objective durations). The standard deviations were 500 ms for the second, third, and fourth test conditions. This allowed for a comparison to be made of responses obtained with a standard deviation of 0 ms and 500 ms. It was expected that duration discrimination thresholds for signals selected from a distribution with a standard deviation of 0 ms would be lower than the duration discrimination thresholds for signals selected from a distribution with a standard deviation of 500 ms.

For each test session, a total of three to six threshold runs were collected. After three threshold runs were taken, the mean and standard deviation values were determined. If the standard deviation for a given condition was greater than 1/3 of the mean, additional threshold runs, not to exceed six threshold runs, were completed for that condition until this criterion was met. Based on the results from Dooley and Moore (1988) and the method modifications to increase the salience of the velocity-based cues, it was predicted that duration discrimination thresholds would be lower for the no motion, +10 dB intensity change and motion, no intensity change conditions than the no motion, no intensity change condition.

At the beginning of a given threshold run, the mean duration of the comparison signal was set to the mean duration of the standard signal plus 500 ms in duration. For a given trial, the durations of the standard and comparison signals were randomly selected from independent normalized (Gaussian) distributions (Figure 5). The velocity of the standard signal was always determined by the span (40°) for the moving conditions or the intensity change (+10 dB) for the intensity change conditions divided by the mean duration, 1500 ms, not the actual duration of a given trial. Therefore, the velocity of the standard signal for the moving condition was always 26.7°/s and the velocity of the intensity change condition was always 6.67 dB/s. The velocity of the comparison signal was drawn from the second distribution, whose mean remained constant up to each reversal and then was increased or decreased depending on the tracking rules. Similar to the velocity of the standard signal, the velocity of the comparison signal was determined by the span or intensity divided by the mean of the comparison signal distribution as of that trial. This procedure allowed for velocity to be a reliable cue and directly addressed whether duration discrimination responses were influenced by the availability of this cue. In other words, a response based on velocity would always be correct, even on trials in which a response based on the objective durations would be incorrect.

At the start of each threshold run, the duration difference between the standard and comparison signal distribution means was always 500 ms. After every 3 consecutive correct responses the duration difference was decreased by a factor of 1.2, and it was increased by a factor of 1.2 after every incorrect response. Testing included 10 turnarounds (increasing to decreasing duration difference and vice versa). The threshold for each run was determined as the geometric mean of the mean differences between the standard and comparison duration distributions values from the last six turnarounds within a condition.

*Results*

For each participant the mean thresholds across three to six runs were calculated for all four conditions. Also, the mean thresholds, standard deviations, and standard errors were computed across participants (Table 5, Figure 6).

Table 5. Experiment 2 descriptive results, thresholds in milliseconds.

| Participant | No Motion No Intensity Change SD = 0 ms (ms) | No Motion No Intensity Change SD = 500 ms (ms) | No Motion Intensity Change SD = 500 ms (ms) | Motion No Intensity Change SD = 500 ms (ms) |
|---|---|---|---|---|
| S 2 | 205 | 546 | 632 | 960 |
| S 5 | 168 | 861 | 806 | 890 |
| S 6 | 119 | 686 | 850 | 549 |
| S 7 | 174 | 615 | 662 | 721 |
| S 8 | 134 | 758 | 808 | 744 |
| S 9 | 99 | 682 | 619 | 597 |
| Mean (ms) | 150 | 691 | 730 | 744 |
| Standard deviation | 40 | 110 | 103 | 160 |
| Standard error | 16 | 45 | 42 | 65 |

An analysis of variance was carried out on the threshold estimates for all four conditions. There was a significant difference between conditions, $F_{(3,15)} = 20.18$, $p < 0.001$, $\eta^2 = 0.80$. This result was primarily due to the fact that there were three conditions tested with signals that had a standard deviation of 500 ms around the distribution means, which resulted in a more difficult task than the condition with signals presented with a standard deviation of 0 ms. To further explore this, an analysis of variance was carried out on the threshold estimates for the three conditions with a standard deviation of 500 ms around the distribution means. This analysis did not show a significant difference between these three conditions.

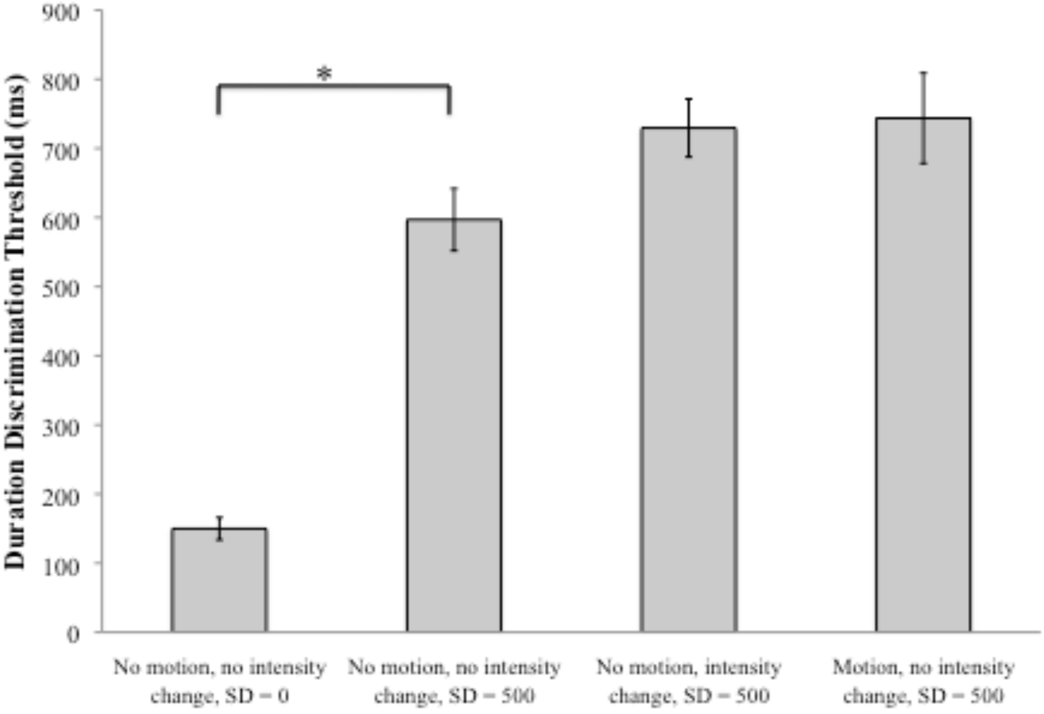

Figure 6. Experiment 2, grand average result from n = 6. Error bars are equal to the standard error of the mean. A significant finding of p < 0.05 is represented by *.

Planned linear contrasts were done between the mean duration discrimination thresholds of the four conditions, as follows. The mean duration discrimination threshold for the no motion, no intensity change, SD = 500 ms condition was significantly higher than that for the no motion, no intensity change, SD = 0 ms condition, $F_{(1,5)} = 18.63$, $p <$

0.05, $\eta^2 = 0.79$. This finding is not surprising because it was intended for there to be a large effect due to the increased variability in the condition with SD = 500 ms. Linear contrast comparisons showed no significant differences between all possible pairs of the conditions tested with signals that had a standard deviation of 500 ms around the distribution means. These results suggest that in this experiment when the standard and comparison signal velocity differences were a reliable cue (in Experiment 2 it was 8.9°/s or 2.19 dB/s compared to 4.6°/s or 1.3 dB/s in Experiment 1; see Tables 6 and 7), then participants did not perform better or worse compared to a condition without these changing dimensions. Moreover, the results of this experiment failed to replicate the findings reported by Dooley and Moore (1988), which suggested that sensitivity to the rate of auditory change could be estimated in a duration discrimination task.

Table 6. Calculated Weber fractions for individual participants in Experiment 1.

| | **Experiment 1 (Weber Fractions)** | | | | |
|---|---|---|---|---|---|
| | **No Motion** | **No Motion** | **Motion** | **Motion** | |
| **Participant** | **No Intensity Change** | **Intensity Change** | **No Intensity Change** | **Intensity Change, SD = 0 ms** | |
| **Experiment 1** | **SD = 0 ms** | **SD = 0 ms** | **SD = 0 ms** | **Motion** | **Intensity** |
| S 1 | 0.113 | 0.128 | 0.102 | 0.130 | 0.129 |
| S 2 | 0.108 | 0.103 | 0.090 | 0.117 | 0.115 |
| S 3 | 0.087 | 0.107 | 0.085 | 0.097 | 0.095 |
| S 4 | 0.055 | 0.081 | 0.058 | 0.058 | 0.057 |
| S 5 | 0.068 | 0.081 | 0.083 | 0.107 | 0.105 |
| S 6 | 0.063 | 0.085 | 0.098 | 0.098 | 0.096 |
| Weber Fraction Mean | 0.082 | 0.097 | 0.086 | 0.101 | 0.100 |
| Standard signal velocity | 750 ms | 13.3 dB/s | 53.3°/s | 53.3°/s | 13.3 dB/s |
| Mean velocity difference based on the threshold | 62 ms | 1.3 dB/s | 4.6°/s | 5.8°/s | 1.3 dB/s |

Table 7. Calculated Weber fractions for individual participants in Experiment 2.

| | **Experiment 2 (Weber Fractions)** | | | |
|---|---|---|---|---|
| | **No Motion** | **No Motion** | **No Motion** | **Motion** |
| **Participant** | **No Intensity Change** | **No Intensity Change** | **Intensity Change** | **No Intensity Change** |
| **Experiment 2** | **SD = 0 ms** | **SD = 500 ms** | **SD = 500 ms** | **SD = 500 ms** |
| S 2 | 0.137 | 0.364 | 0.297 | 0.391 |
| S 5 | 0.112 | 0.574 | 0.350 | 0.373 |
| S 6 | 0.079 | 0.457 | 0.362 | 0.269 |
| S 7 | 0.116 | 0.410 | 0.306 | 0.326 |
| S 8 | 0.089 | 0.505 | 0.350 | 0.332 |
| S 9 | 0.066 | 0.455 | 0.292 | 0.286 |
| Weber Fraction Mean | 0.100 | 0.461 | 0.326 | 0.329 |
| Standard signal velocity | 1500 ms | 1500 ms | 6.67 dB/s | 26.7°/s |
| Mean velocity difference based on the threshold | 150 ms | 691 ms | 2.19 dB/s | 8.9°/s |

*Discussion*

The results of Experiment 1 did not show that additional intensity- or motion-based velocity cues were perceptually beneficial in the duration discrimination task. However it is possible that these cues were not salient enough to participants to be useful. Therefore, the duration discrimination task for Experiment 2 was purposefully designed to be more difficult than the task in Experiment 1, such that participants could benefit from relying on additional cues other than signal duration to perform the task. The aim of Experiment 2 was to determine whether stronger velocity-based cues are perceptually useful in a duration discrimination task when characteristics of the signals (i.e., intensity or motion) have a larger velocity difference between the compared signals. Hence, if participants could achieve improved duration discrimination task performance, it would suggest that sensitivity of the rate of change for velocity-based cues may be measured as long as there was a large enough velocity difference between the signals. As discussed earlier, several method modifications were made to Experiment 2 to achieve a more difficult listening task. To determine if these modifications were successful in a duration discrimination task to estimate rate of change sensitivity, as described by Dooley and Moore (1988), results from Experiments 1 and 2 are compared.

For Experiments 1 and 2, the velocity difference between the compared signals at threshold and the Weber fraction were calculated for all comparable conditions (Tables 6 and 7; the standard signal velocity is also provided as a reference). For the no motion, +10 dB intensity change condition, the mean velocity difference for Experiment 1 was 1.3 dB/s which was smaller than that for Experiment 2, which was 2.19 dB/s. Likewise, for the motion, no intensity change condition, the mean velocity difference was 4.6°/s for Experiment 1 which was smaller than that for Experiment 2 which was 8.9°/s. The aim of Experiment 2 was to determine if these increases in velocity differences could be useful cues and thus improve duration discrimination task performance. Since the findings of Experiment 2 showed that overall duration discrimination task performance did not improve as Dooley and Moore (1988) reported when additional intensity or motion cues were available to the listener, statistical analyses were completed to be certain that these velocity differences were larger compared to Experiment 1.

To determine that the velocity differences between the compared signals were statistically larger for Experiment 2 than they were for Experiment 1, linear contrast comparisons were carried out using the Weber fractions calculated for each individual participant based on their duration discrimination thresholds for certain conditions in each experiment. First, the no motion, no intensity change, SD = 0 ms conditions for Experiments 1 and 2 were compared. There was no significant difference between these conditions, which suggests that, relative to the duration of the standard signal, threshold is not significantly better or worse for shorter or longer signal durations. This analysis revealed that the velocity differences were significantly larger between the compared signals for the no motion, no intensity change, SD = 500 ms condition (Experiment 2) compared to the no motion, no intensity change, SD = 0 ms condition (Experiment 1), $F_{(1,5)} = 152.72$, $p < 0.001$, $\eta^2 = 0.968$. Also, the no motion, +10 dB intensity change, SD = 500 ms condition (Experiment 2) had significantly larger velocity differences between the compared signals than the no motion, +10 dB intensity change, SD = 0 ms condition (Experiment 1), $F_{(1,5)} = 234.15$, $p < 0.001$, $\eta^2 = 0.978$. Similarly, the motion, no intensity change, SD = 0 ms condition (Experiment 2) had significantly larger velocity differences between the compared signals than the motion, no intensity change, SD = 500 ms condition (Experiment 1), $F_{(1,5)} = 163.47$, $p < 0.001$, $\eta^2 = 0.970$. These analyses demonstrate that the velocity difference between the standard and comparison signals for each of the conditions in Experiment 2 with a standard deviation of 500 ms was larger than for comparable conditions in Experiment 1 with a standard deviation of 0 ms. In addition, the Weber fractions calculated for the conditions in Experiment 2 were considerably larger than those reported in the literature. This suggests that the difference in the rates of auditory cue change between the two experiments was significant and were perhaps salient enough to participants to be detected. Thus, it can be assumed that even when the velocity differences between the compared signals in Experiment 2 were significantly larger than in Experiment 1, the sensitivity to rate of change cannot be measured in a duration discrimination task as proposed by Dooley and Moore (1988).

### *Summary*

Despite the modifications made in Experiment 2, the results showed that overall duration discrimination task performance did not improve, as Dooley and Moore (1988) reported, when additional intensity or motion cues were available to naïve listeners. In contrast to Experiment 1, these results did not show that performance was significantly worse for conditions with additional cues, although the tendency was for worse performance. The outcomes from these experiments show that additional cues with a smaller velocity difference between the compared signals generally result in poorer duration discrimination task performance. When the velocity difference between the compared signals was larger, these additional cues still did not enhance duration discrimination task performance. In summary, additional auditory cues (i.e., motion and intensity) were not found to be perceptually beneficial for this duration discrimination task despite efforts to enhance their usefulness to participants.

The goals of Experiments 1 and 2 were centered on the possibility that sensitivity to the rate of change in auditory cues, such as spatial and intensity change, can be measured in a duration discrimination task. Dooley and Moore (1988) concluded that the usual confound between signal duration and velocity can be used as a tool to measure sensitivity to rates of change of additional signal cues. Experiments 1 and 2 were designed to replicate and expand on the results reported in Dooley and Moore (1988).

The current results did not show that duration discrimination task performance was improved when additional auditory cues were present in the signal and therefore failed to confirm that the confound of signal duration and velocity can be used as a tool to measure sensitivity to rate of change.

The results of Experiments 1 and 2 did not show that the psychometric tool proposed by Dooley and Moore (1988) could be used to measure sensitivity to auditory cue rate of change, however many psychoacoustic experiments have measured human sensitivity to rates of change in different auditory dimensions by keeping either duration or velocity constant or by varying these in such a way that they are not reliable cues. Experiment 3 employs a typical approach to measure human sensitivity to auditory cue rate of change to address the issue of how multiple cues are interpreted when they are related to the same auditory event. For example, auditory events in motion naturally include co-varying information about the changes in direction and distance. It may be possible that in another type of discrimination task, such as velocity discrimination, performance may be influenced when one motion cue is available compared to listening conditions with more than one motion cue. Therefore, Experiment 3 was designed to explore the possible benefit of the availability of more than one naturally co-varying motion cue in a velocity discrimination task.

## *Experiment 3*

The goal of Experiment 3 was to determine whether the perception of differences in velocity was enhanced when the signal was moving along paths that involve simultaneous changes in both direction and distance. There are a couple of issues that are related to this perception. First, direction and distance motion cues naturally co-vary during many scenarios of relative motion for a listener and a sound source. One hypothesis is that listeners make more accurate judgments about differences in velocity between two moving auditory signals, such as two cars moving at different speeds, when both motion-related cues are available as opposed to when only one cue (either direction or distance) is available. Another hypothesis may be that listeners naturally use the correlation between the overall amount of change and the duration of a signal to make a judgment about differences in rates of velocity. For moving auditory events, the overall amount of change is correlated to the duration of the signal. In the previous experiments, this correlation was not useful since the compared signals had the same overall amount of change. However, in Experiment 3, listeners will be making decisions about the differences in velocity between the compared signals, which creates a situation where the overall amount of change is not the same for the two signals.

### *Participants*

Participants for this experiment were the same as in Experiment 2, who were: S2, S5, S6, S7, S8, and S9.

### *Procedure*

The task for this experiment was spatial velocity discrimination. A two-interval forced-choice task was employed in which participants heard a standard signal and a comparison signal. The standard signal always had a lower velocity than the comparison signal. In all conditions, participants were asked to indicate which signal was faster by pressing a corresponding button for all of the test conditions (see Appendix A for an example of the instructions that were provided to the participant). For every trial, feedback was provided through lights on the response box that indicated the correct response. Velocity discrimination thresholds were determined by an adaptive 3-down, 1-up staircase procedure. For a given threshold run, the durations of the standard and comparison signals varied randomly between 600 to 3000 ms, and thus were not reliable cues to the participant.

There were four test conditions with different kinds of motion paths, defined by how the sound source moves with respect to a stationary listener (Figure 7).

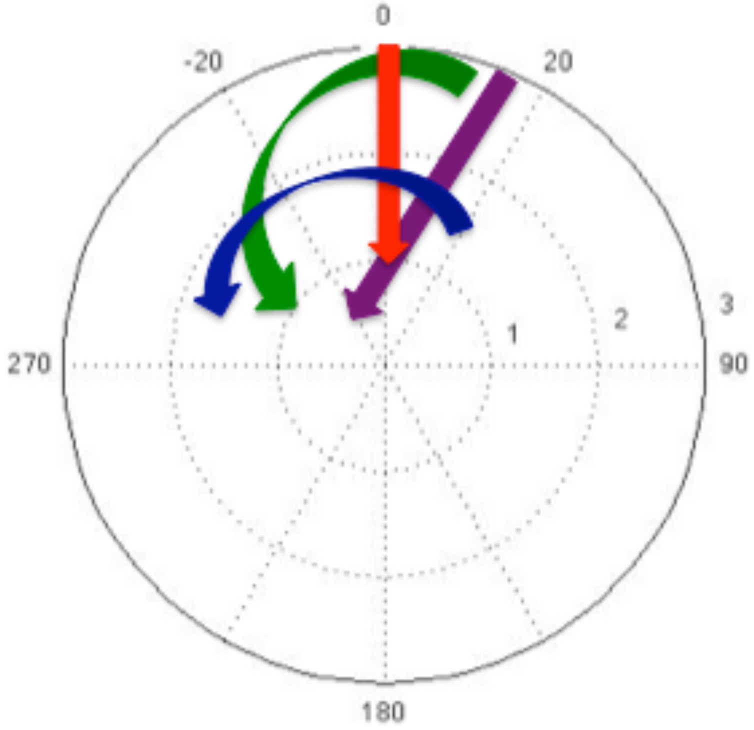

Figure 7. Illustration of the four conditions in Experiment 3. The blue path represents the circular condition, the red path represents the direct condition, the purple path represents the straight "miss" condition, and the green path represents the combination condition.

The four conditions were: 1) Circular: motion along a circular path with constant horizontal angular velocity; 2) Direct: motion along a direct approach path; 3) Straight “miss”: motion at a constant speed along a straight, approaching path that “misses” the participant on the right or left side; 4) Combination: motion along a curved, approaching “miss” path. The design of the stimulus conditions allowed for direction or distance cues or both cues to be available to participants. In the circular condition, the distance from the participant to the signal’s motion path was constant, but the direction information in the signal changed over time. In the direct condition, the direction of the signal was constant since it traveled along a direct approach path, but the distance (cued by intensity) in the signal changed over time. For the straight “miss” condition, the directional and distance cues both changed over time in a manner that was appropriate for a sound source moving along a straight “miss” path. In the combination condition, directional change corresponded to the circular path and distance change corresponded to the direct approach path. In the circular, direct, and straight “miss” paths, the simulated sound source moved at constant intrinsic velocity, measured in meters per second. In the combination path, the intrinsic velocity changed because of how the path was calculated. Each condition was completed on a different day for all but two participants who completed these conditions in three days instead of four. The circular and direct conditions were tested first before the straight “miss” and combination conditions were tested. The circular and direction conditions were tested first because these thresholds were required to calculate the motion path for the combination condition. The order of circular and direct conditions as well as the straight “miss” and combination conditions were counterbalanced across participants. The onset location, signal velocity, and the angle that defined the path trajectory were jittered by ±0.1 meters, ±0.1 meters per second, and ±0.1 radians, respectively. For the circular, direct, and straight "miss" conditions, the mean velocity of the standard stimulus was 1.5 meters per second, and the comparison velocity always had a faster velocity that varied psychophysically across trials.

For the circular condition, the standard stimulus moved on a path along the perimeter of a circle with a mean speed of 1.5 meters per second that was centered on the listener at a distance (radius) of 3.0 meters. The comparison stimulus moved along a similar path as the standard stimulus, but with a faster speed; at the beginning of a threshold run, the comparison stimulus had a mean speed of 2.0 meters per second. The orders of the standard and comparison stimuli were random. Since the circular condition included changes in sound source direction, but not distance, the ability to discriminate between the comparison and standard stimuli was based on differences in rate of change in direction. In this specific test situation the directional change was presumably conveyed mostly by changes in interaural time differences (ITDs).

In the direct approach condition, the standard stimulus was presented at a mean distance of 3.0 meters in front of a participant. The signal was directed straight toward the listener with a mean velocity of 1.5 meters per second. The comparison stimulus was on the same type of path, but traveled at a higher velocity. At the beginning of a threshold run, the comparison stimulus had a mean velocity of 2.0 meters per second. For this motion path there was no change in direction, but distance decreased linearly. Since intensity varies inversely with distance, there is a non-linear increase in the intensity of the sound because there is a linear decrease in distance. In this condition, the ability to discriminate between the standard and comparison stimuli was presumably based on comparing the rates of increase in intensity.

In the straight "miss" condition, the motion path approached the participant on a straight but indirect ("miss") path. The mean velocity of the standard stimulus was 1.5 meters per second. The velocity of the comparison stimulus was always faster than the standard and at the start of a threshold run the mean velocity was 2.0 meter per second. In this condition, both the direction and distance of the sound source will change over the course of the motion path. Therefore, the ability to discriminate between the compared stimuli could be based on information about direction, distance, or both.

In the combination condition, the motion path included a sequence of intensity values that occurred for the direct approach path and a sequence of directional values that occurred for the circular path. For each participant, the thresholds obtained in the circular and direct conditions were used to determine the path for the combination condition. The velocity discrimination thresholds from the circular and direct path conditions were used to determine the sequence of directions and intensities to which each participant was sensitive. These sequences were used to determine the path trajectory for the combination condition. To incorporate both aspects of the circular and direct conditions, a threshold ratio was determined as follows: threshold ratio = direct threshold / circular threshold. The combination condition threshold was psychophysically linked to the circular condition. Calculations were made after data collection to determine the combination condition threshold that is linked to the direct condition and then to determine an overall threshold for the combination condition that represents both the individual circular and direct contributions. This is discussed in more detail in the Results section as well as in

Appendix B. The standard signal had a mean velocity of 1.5 meters per second and at the beginning of a threshold run, the comparison signal had a mean velocity of 2.0 meters per second.

*Results*

For each participant the mean thresholds (in meters per second) across three to six threshold runs were calculated for all four conditions. Also, Weber fractions were calculated for each participant by dividing the mean velocity discrimination threshold by the mean velocity of the standard stimulus. For the circular, direct, and straight "miss" conditions, the mean velocity of the standard stimulus was 1.5 meters per second, and for the combination condition it was 2.1 meters per second averaged across all participants. The mean Weber fractions, standard deviations, and standard errors were computed across participants (Table 8, Figure 8). To analyze how information in the circular and direct paths contributed to the perception of the combination path, the "predicted" combination path results were computed using the following mathematical formula:

$$\text{Predicted Result} = (a * b) \,/\, [\Sigma\, (a^2 + b^2)]^{1/2} \qquad (\textit{eq. 3})$$

Where a = the Weber fraction of the circular path and b = the Weber fraction of the direct path. This formula was derived from assumptions that are outlined in the "integration model" described by Green and Swets (1974) and the mathematical expression for the summation of information from more than one acoustic component described by Buell and Hafter (1991) given below:

$$d'_{(1+2+\ldots n)} = [\Sigma\, (d_1'^2 + d_2'^2 + d_3'^2 \ldots\, d_n'^2)]^{1/2} \qquad (\textit{eq. 4})$$

Table 8. Calculated Weber fractions for individual participants in Experiment 3.

| | **Experiment 3 (Weber Fractions)** | | | | |
|---|---|---|---|---|---|
| | **Circular** | **Direct** | **Straight "Miss"** | **Combination (Actual)** | **Combination (Predicted)** |
| **Participant** | **(Direction is available cue)** | **(Distance is available cue)** | **(Distance & direction are available cues)** | **(Individual thresholds for distance & direction are available cues)** | **(The mathematical predicted threshold value based on the Circular & Direct thresholds)** |
| S 2 | 0.858 | 0.909 | 0.738 | 0.627 | 0.624 |
| S 5 | 0.589 | 0.563 | 0.632 | 0.488 | 0.407 |
| S 6 | 0.402 | 0.704 | 0.768 | 0.258 | 0.349 |
| S 7 | 0.694 | 0.523 | 0.348 | 0.570 | 0.418 |
| S 8 | 0.688 | 0.789 | 0.524 | 0.478 | 0.519 |
| S 9 | 0.505 | 0.596 | 0.364 | 0.313 | 0.385 |
| Mean Weber Fractions | 0.623 | 0.681 | 0.562 | 0.456 | 0.450 |
| Standard deviation | 0.160 | 0.148 | 0.182 | 0.144 | 0.102 |
| Standard error | 0.065 | 0.061 | 0.074 | 0.059 | 0.042 |

The results of the derived mathematical calculation represent what would be expected, or predicted, if information from the circular and direct paths available to the listener can be identified but does not undergo sensory integration, or in other words enhanced perception. If some sort of sensory integration were to result from this simultaneous presentation of information, then it would be expected that the actual results from the combination condition would be better than those from the predicted combination condition. Descriptive analysis shows that this is the case for half of the participants (S6, S8, and S9), although the comparisons between the Weber fraction results based on the actual combination velocity discrimination thresholds and the predicted combination velocity discrimination thresholds were not statistically significant.

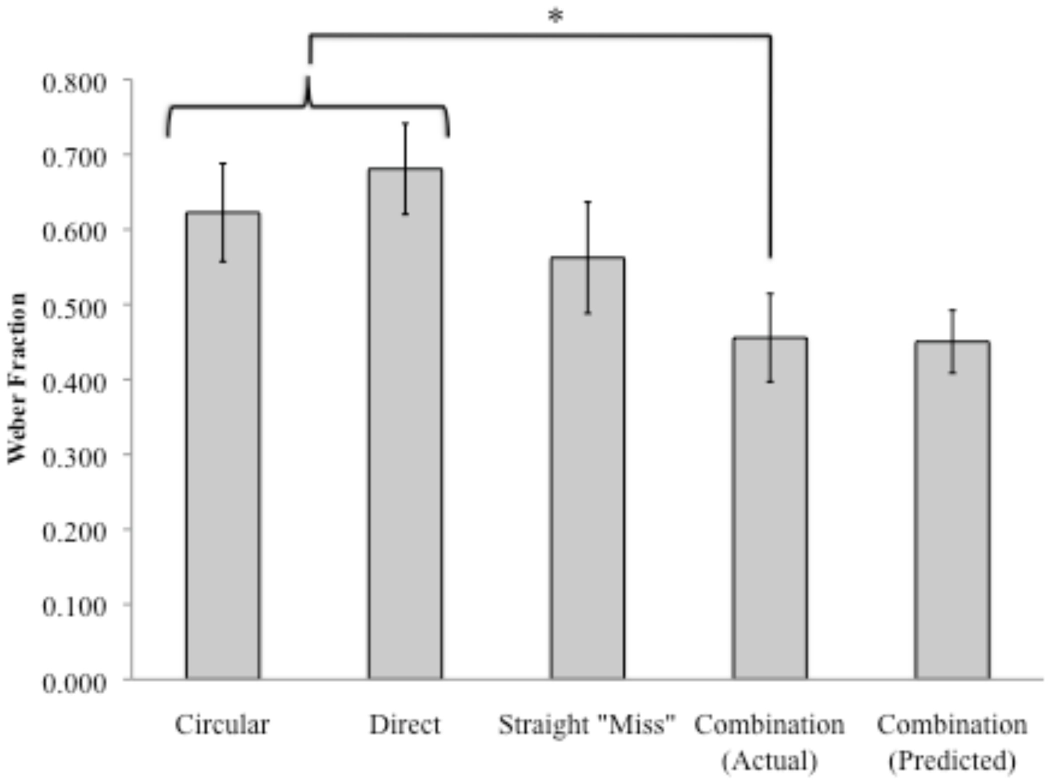

Figure 8. Experiment 3, grand average Weber fraction calculated results from n = 6. Error bars are equal to the standard error of the mean. A significant finding of $p < 0.05$ is represented by *.

The lack of statistical significance may be due to the small sample size in this experiment. The descriptive analysis suggests that information that is simultaneously available from two components of auditory motion (direction and distance) may be combined and integrated in such a manner that better-than-predicted performance is achieved. Since there was some evidence of this sensory integration in half of the participants in this study it is possible that a range of this ability extends across a larger human population. To demonstrate the extent of the possible range of auditory motion perception ability a large-scale study would need to be carried out. Although this would be an interesting study, it is beyond the scope of the current investigation.

An analysis of variance was carried out on the Weber fractions for all four conditions. There was a significant difference between conditions, $F_{(3,15)} = 3.41$, $p < 0.05$, $\eta^2 = 0.41$. Planned linear contrasts were done between the Weber fractions for the circular and direct conditions and for the straight "miss" and combination conditions. In addition, the average Weber fractions of the conditions with one motion cue (average of circular and direct) were compared to the average Weber fractions of the conditions with two motion cues (average of straight "miss" and combination). There was not a significant difference between the Weber fractions for the circular and direct conditions, nor was there a significant difference between the Weber fractions for the straight "miss" and combination conditions. Statistical analysis revealed that the average Weber fractions for the conditions with two motion cues (average of straight "miss" and combination) were significantly smaller than the average Weber fractions for the conditions with one motion cue (average of circular and direct), $F_{(1,5)} = 13.93$, $p < 0.05$, $\eta^2 = 0.736$. This result may be because half of the participants showed evidence that they could make use of the two available motion cues, perhaps integrating them in some way or by simply having additional information related to the moving signal, which yielded velocity discrimination thresholds that translated into lower Weber fractions for the combination condition. To further explore this, repeated measures analyses was carried out between the average Weber fractions for the conditions that provided one motion cue (average of circular and direct) and Weber fractions for the straight “miss” condition as well as the Weber fractions for the combination condition. There was not a significant difference between the average of the Weber fractions for the conditions that provided one motion cue (average of circular and direct) and the Weber fractions for the straight “miss” condition. However, there was a significant difference between the average Weber fractions for the conditions that provided one motion cue (average of circular and direct) and the Weber fractions for the combination condition, $F_{(1,5)} = 20.65$, $p < 0.05$, $\eta^2 = 0.805$ (Figure 8). This outcome shows that participants’ performance was significantly better when direction and distance cues were maximally sensitive and were simultaneously available compared to listening conditions where only one of these cues was available.

### *Discussion*

The aim of Experiment 3 was to determine if listeners were differentially sensitive to rates of spatial change when there were one or more moving cues presented in isolation or simultaneously. The results of this study showed that in general, the participants performed better on velocity discrimination tasks when they had both direction and distance cues in the moving signal available to them compared to conditions where only one of these cues was available. The combination condition motion path was designed to include direction and distance cues that were weighted to be perceptually equal to participants. This study showed that velocity discrimination performance was significantly better for the combination condition compared to the circular or direct path conditions, which had one motion cue available. Interestingly, there was not a significant difference between the velocity discrimination performance for the straight “miss” condition, which had both direction and distance cues, compared to the circular or direct conditions, which had either direction or distance cues. These results indicate that participants were more sensitive to differences in the rate of spatial change when both motion cues were available compared to listening situations where one cue was available for motion perception, but that this was only statistically significant only when direction and distance cues were individually weighted for each participant.

The fact that participants performed better in the combination condition that had individually weighted motion cues compared to the straight “miss” path that had equally weighted motion cues suggests that there is a range of spatial perception ability for how humans perceive certain auditory motion cues. In addition, the results also showed that participants did not always find that one motion cue was easier to perceive than the other. Specifically, Table 8 shows that the Weber fraction related to velocity discrimination threshold was higher in the direct path condition for five participants and was higher for the circular path condition for two participants. It is unclear as to why this variability exists across participants and also why certain auditory motion cues are easier to perceive than others. In general, variability among participants for auditory motion tasks is not uncommon and has been recorded informally in our own lab and has been shown in previous literature reports. In our own lab during an unrelated study, we recorded motion perception trials from participants who listened to auditory signals under insert earphones that were either stationary or “moving” by varying the interaural time difference of the signal between ears. Their task was to make a judgment as to whether the signal was moving or not. Most participants performed at 85% correct or better however a couple of individuals could not perform above chance.

Previously reported results have also indicated that there is likely a range in spatial acuity abilities across human participants. For example, Grantham (1986, Experiment I) reported that one subject had “longer-than-average spatial integration time for spatial resolution” compared to two other participants in a minimum audible movement angle experiment where the duration of the signal was varied. Variability in spatial acuity has also been demonstrated through functional imaging techniques in populations of humans with visual impairments. Gourgoux, Zatorre, Lassonde, Voss, and Lepore (2005) used a behavioral localization task that showed some early blind individuals had exceptional spatial abilities and others had average spatial abilities. In the same study, positron emission tomography was used to show that the early blind group with exceptional spatial ability demonstrated increases in the right striate and extrastriate visual cortices that were not present in the early blind group with average spatial abilities (Gourgoux, et al., 2005). Therefore, it is likely that a range of spatial perception abilities exists in the human population and that they do not exhibit equal sensitivity to different auditory motion cues, which may be shaped by environmental experiences or perhaps by hardwiring in the brain.

Although humans demonstrate varied abilities to perceive different motion-related cues, the results of the current study point to the possibility that there is an overall significant advantage for auditory motion perception when more than one spatial cue is available to the listener. The current study results are supported by previous research which has shown that performance in velocity discrimination tasks may be improved when more than one cue related to the motion path trajectory is available to the listener. Carlile and Best (2002) reported results from three conditions in which velocity discrimination performance was measured as a function of the available displacement cues when 1) duration was random (cue not available), 2) duration was held constant revealing spatial offset cues, and 3) duration was held constant revealing spatial onset and offset cues. Velocity discrimination performance was best for the third condition where the motion trajectory path included cues of spatial onset and offset compared to the other conditions tested. These previous results and the outcomes from the current study indicate that overall auditory motion perception is optimal when more than one motion-related cue is available in the listening environment.

Descriptive results shown in Table 8 suggest that half of the participants had better-than-predicted thresholds for the combination condition based on their thresholds for the circular and direct conditions. This provides some evidence for the possibility that auditory motion cues may be integrated in such a way that results in enhanced perceptual ability. There are several neurophysiology and functional imaging reports that provide evidence that enhanced perceptual responses are possible when more than one type of sensory cue is available. To date there are not previous reports that show enhanced behavioral responses to more than one motion cue when the sensory input is restricted to auditory information. Thus the outcomes of this study contribute to the current body of auditory motion literature by providing evidence that there is a perceptual benefit when multiple motion cues are available to listeners in their environments.

## *Conclusion*

The three experiments in this study were designed to measure human sensitivity to the rate of change of cues in auditory events and combinations of cues that contribute to the perception of auditory motion. The first two experiments aimed to determine if sensitivity to the rate of change in an auditory cue could be measured by using a psychometric tool proposed by Dooley and Moore (1988). They reported that when an additional auditory cue, such as rate of change in intensity, was paired with signals in a duration discrimination task, performance was improved compared to conditions without these additional auditory cues. That is, sensitivity to rate of change could be measured despite the usual confound involving signal duration and velocity-based cues. The results of Experiment 1 failed to replicate the results reported by Dooley and Moore (1988) and in fact showed poorer performance for conditions with additional velocity-based cues compared to conditions without these cues. Experiment 2 also aimed to explore the use of this psychometric tool, but considerable modifications were made to the methods to increase the salience and reliability of the velocity-based cues. Thus, the experimental design was intended to reveal the best possible results that could occur using this proposed tool. The results of Experiment 2 also failed to replicate the results reported by Dooley and Moore (1988) and showed that performance tended to be worse for conditions with additional auditory cues compared to conditions without these cues, although this did not reach statistical significance.

One possible explanation for this result may be that the difference in the rates of change in the compared signals was not salient to the listeners. This reasoning suggests that it would be possible to measure sensitivity to rates of change in a duration discrimination task. The Weber fractions in Experiment 1 were very small indicating that the auditory cues were perhaps not salient enough for participants to respond to. However, the methods were modified in Experiment 2 in such a way so that the difference in the rates of change for the additional cues would be obvious to the listeners. Despite these efforts, the results still showed that duration discrimination task performance was not improved when additional cues were available in the compared signals.

It is unclear why there is a discrepancy between the present findings and those reported by Dooley and Moore (1988). It is possible that, with extensive listening experience, participants can be trained to attend to differences in the rates of auditory cue change as opposed to attending to the overall extent or amount of change between two signals. Since Experiments 1 (but not 1a) and 2 included naïve listeners, it may be possible that duration discrimination performance could be used to estimate rate of change sensitivity in a sample of individuals who are more experienced with these types of signals. Thus, these experiments could be followed up with another series of similar experiments where participants are given extensive listening experience prior to actual testing. It may be that participants could learn to recognize the cues and how they change over time, which could improve overall duration discrimination performance.

Another possible reason that the results for Experiments 1 and 2 did not show improved duration discrimination performance when additional cues were available may be because the dynamic changes in the additional cues caused a distraction. It has been shown that when an auditory cue is changing rapidly, attending to these changes requires some attentional resources (Parmentier and Andres, 2010). These experiments were not designed to investigate issues concerning dual attention. However, it may be that the additional changing cues were distracting and caused participants to divide their attention between attending to the differences in duration and the differences in the rates of auditory cue change. This behavior would explain why participants performed worse in the conditions with the additional auditory cues compared to the conditions without these cues.

The snapshot and motion-sensitive mechanisms may also provide some insight into why the results of Experiments 1 and 2 showed that participants were not able to use additional velocity-based cues. Traditionally, the literature related to motion-sensitive and snapshot mechanisms has been in reference to moving auditory events but the underlying premise for both mechanisms can also be regarded in terms of how humans perceive auditory signals that change over time in other dimensions. In the current study, the effect of another type of changing cue, which was rate of intensity change, was measured in addition to rate of spatial position change. In this study it would not have been possible for participants to use a snapshot mechanism since the overall amount of auditory cue change was the same for the compared signals. The fact that participants were not able to use the rate of auditory cue change information to improve duration discrimination task performance suggests that they were not able to use the mid-portion of the compared signals effectively. Since the overall amount of change was the same in the signals, improved performance in the conditions with additional auditory cues could have only been achieved if the changing velocity-based cues throughout the compared signals were useful. An outcome such as this would have indicated use of a motion-sensitive mechanism (Grantham, 1997). Since the results of Experiments 1 and 2 showed that participant performance was worse in conditions with additional auditory cues, it may be that these changing velocity-based cues in the mid-portion of the signals were not useful. Since it was not possible for participants to use a snapshot mechanism and the results showed that they did not use a motion-sensitive mechanism, it is reasonable to assume that only duration information was used to evaluate the compared signals.

In addition, it may be that humans have a natural tendency to respond to the correlation between the duration and the overall *extent* of auditory cue change as opposed to the *rate* of change. In other words, it is possible that in a duration discrimination task, humans tend to focus on overall amount of change instead of cue changes over time. Since the duration of an auditory signal is most often linked to the *extent* of auditory cue changes, not necessarily with the *rate* of how these cues change, it makes sense that performance did not improve with added cues since the overall amount of change between the compared signals was the same. However, if listeners had extensive listening experience it is possible that they could be trained to listen for changes in the rates of auditory cues and be conditioned to de-emphasize the duration of the compared signals. This may explain some of the differences in results between Dooley and Moore (1988) and the current experiments. Specifically, the participants in Dooley and Moore (1988) showed a benefit when additional auditory cues were available, but performed worse in the baseline condition that did not have additional cues. This was especially true for the first author. The average baseline condition threshold reported by Dooley and Moore (1988) was 15 ms better than in Experiment 1. Therefore, it is possible that the reported results from Dooley and Moore (1988) reflect considerable practice effects and in addition, the listeners were perhaps conditioned to de-emphasize the duration information and were practiced to attend to the rate of additional cue changes.

One goal of this thesis was to measure human sensitivity to the rate of change of cues in auditory events. Although the first two experiments did not show that these measurements could be accomplished by the previously proposed psychometric method described above, other approaches have been used successfully. In Experiment 3, a more traditional method was used that involves maintaining one characteristic of the signal constant (either duration or velocity) and then varying the other in such a way that it is not a reliable cue. Another goal of this thesis was to investigate how combinations of auditory cues contribute to the perception that an auditory event is changing in spatial position over time. Experiment 3 employed a traditional method of measuring sensitivity to rates of auditory cue change to investigate if auditory motion perception is influenced by the availability of one or more types of motion-related cues. In Experiment 3, sensitivity to rate of spatial change was measured in a velocity discrimination task, with four conditions that had either one category of motion-related cue (direction or distance) or had both direction and distance cues. In this experiment, the signal durations and the extents of stimulus change were not available cues, therefore listeners had to rely on the velocity differences to make judgments about the compared signals. The results of this experiment showed that velocity discrimination performance was better for conditions with more than one motion-related cue compared to conditions with one cue. In addition to this novel finding, the results were significantly better for the condition that incorporated a combination of individually weighted motion-related cues compared to conditions with one motion-related cue available. In half of the participants this resulted in a better-than-predicted outcome which points to the possibility that enhanced auditory perception may be possible when auditory motion-related cues are presented in an optimal listening environment. To our knowledge this is the first time that the relationship between the categories of motion-related cues (direction and distance) has been examined in this way for non-speech auditory signals. Further investigations are warranted to examine how combinations of non-speech auditory cues interact with one another. The results of this study provide evidence of how humans can perform when multiple non-speech auditory cues are available. Therefore, it may be interesting to use this study design for other populations of participants, such as individuals with visual impairments or blindness. Information from these possible follow-up investigations may provide insight into what types or combinations of auditory cues are most important for human populations in everyday listening environments.

# APPENDIX A

The following are examples of the instructions that were given to participants prior to beginning an experiment. Each participant was asked to read over the instructions and then given an opportunity to ask questions about the task. The task instructions for Experiment 1were:

For this experiment you will sit in a chair in the center of the anechoic chamber.
You will hear a pair of sounds that may or may not move in front of you. Your task is to decide which sound is <u>longer</u>.

- If the 1st sound is longer, press button 1.
- If the 2nd sound is longer, press button 2.
- You will receive lighted feedback on the response box after you make your choice for each trial indicating which signal was <u>longer</u>.

**Practice test sessions (day 1 and day 2):**
You will listen to a total of 6 conditions each day. You may take a break if you need one at any time. Total testing time may range from 30-60 minutes each day.

**Test session (day 3):**
You will listen to a total of 12 conditions. After every 4 conditions, you will be given a 5-minute break and asked to step out of the chamber. Total testing time may range from 60-90 minutes.

**To begin a condition:**
When all 4 lights on the response box are illuminated and steady, you may press any of the buttons to begin the condition.

**At the end of a condition:**
When the condition is over, all 4 lights on the response box will flash several times. Please wait patiently while I set up the next condition. This may take a minute or two.

- There is a microphone in the chamber if you need to talk to me. Please let me know at any time if you need a break or have a question.

**Thank you for your participation!**

The participant task instructions for Experiment 2 were the same as those for Experiment 1 except for the following information about the test sessions:

**Four test sessions:**

Each test session will be on a different day (4 days total). We will collect data for up to a total of 6 threshold runs each day. You may take a break if you need one at any time. Total testing time may range from 20-40 minutes each day.

The following is an example of the participant task instructions that were given for Experiment 3, which were different than those for Experiments 1 and 2.

For this experiment you will sit in a chair in the center of the anechoic chamber.
On each trial you will hear two moving sounds, one after the other, with a short pause in between. Your task is to decide which sound moved faster. The duration of the sounds will be random. So, a sound with a shorter duration is not always faster. **It is important that you pay attention to how fast the sound moves, not how long or short it is.** From trial to trial it will be random whether the first or second sound was faster.

❍ If the 1st sound is faster, press button 1.
❍ If the 2nd sound is faster, press button 2.
❖ You will receive lighted feedback on the response box after you make your choice for each trial indicating which signal was faster.

In some test conditions the sounds will move around you, or move towards you, or both. Your task is always to decide whether the first or second sound was faster.

**Four test sessions:**

Each test session will be on a different day (4 days total). We will collect data for up to a total of 6 threshold runs each day. You may take a break if you need one at any time. Total testing time may range from 20-40 minutes each day.

**To begin a condition:**

When all 4 lights on the response box are illuminated and steady, you may press any of the buttons to begin the condition.

**At the end of a condition:**

When the condition is over, all 4 lights on the response box will flash several times. Please wait patiently while I set up the next condition. This may take a minute or two.

❖ There is a microphone in the chamber if you need to talk to me. Please let me know at any time if you need a break or have a question.

**Thank you for your participation!**

# APPENDIX B

The following describes the offline calculations that were made to determine the combination condition threshold. A custom Matlab routine was used to carry out these calculations. The combination condition threshold was determined for each participant based on each individual's circular component threshold and the ratio of the direct to the circular path thresholds. The sample rate was 244.14. The combination path threshold was determined based on the fact that none of the compared signals were presented at a distance closer than 0.5 meters to the participant. The mean velocity of the combination condition threshold was calculated based on 1000 iterations. The velocities for the standard and comparison signals of the combination condition were determined. The mean velocity difference between the compared signals was determined. The following are details about the program that was used to determine the combination condition threshold:

```
function mean_vel_diff = distribution_combo_velocities_new(THRESHOLD, RATIO)
% function mean_vel_diff = distribution_combo_velocities_new(THRESHOLD, RATIO)
% Feb. 4, 2010
% This function replaces the discredited script file DISTRIBUTION_BOTH_A.M
% In this version, a different algorithm is used to compute the combo
% path length.
% Arguments:
%   THRESHOLD: circular component of the combo threshold
%   RATIO: ration of direct to circular component of the combo threshold
SAMP_RATE = 244.14;
CLOSEST_DISTANCE_LIMIT = .5;
iterations = 1000;
ave_standard_velocity = zeros(iterations,1);
ave_comparison_velocity = zeros(iterations,1);
for kk = 1:iterations
   % get a range, duration, and standard velocity
   check_dist = false;
   while ~check_dist
      dist = 2.7 + rand .* 0.6;
      dur = 0.6 + rand .* 2.4;
      standard_vel = 1.35 + rand .* 0.3;
      path_length = dur .* standard_vel;
```

```
      if dist - path_length./2 >= CLOSEST_DISTANCE_LIMIT
         check_dist = true;
      end
   end
   angular_span = path_length ./ dist;  % in radians
   number_of_samples = round(SAMP_RATE .* dur);
   angular_increment = angular_span ./ number_of_samples;
   duration_per_sample = dur ./ number_of_samples;
   distance_increment = path_length ./ number_of_samples;
   % Get the distance and azimuth arrays.
   % While we're at it, get an array of instantaneous velocities
   start_azimuth = 0 - angular_span./2;    % for now, we assume midpoint is at 0deg
   stop_azimuth = start_azimuth + angular_span;
   start_distance = dist + path_length./2;
   stop_distance = start_distance - path_length;
   azimuths = [start_azimuth : angular_increment : stop_azimuth]';
   distances = [start_distance : -distance_increment : stop_distance]';
   N = number_of_samples;
   increment_dist = abs(distances(2:N).*exp(i.*azimuths(2:N)) - distances(1:N-1).*exp(i.*azimuths(1:N-
1)));
   velocities = increment_dist./duration_per_sample;
   len_vel = length(velocities);
   time = [0:len_vel-1]' .* dur ./(len_vel-1);
   % get sum of the distances for the combo
   total_distance = sum(increment_dist);
   % average standard velocity
   ave_standard_velocity(kk) = total_distance ./ dur;
   % ---------------------------------------
   % comparison stimulus
   % get a new distance and duration
   comparison_vel = standard_vel + THRESHOLD;
   velocity_for_distance = standard_vel + THRESHOLD .* RATIO;
   check_dist2 = false;
   while ~check_dist2
      dist2 = 2.7 + rand .* 0.6;
      dur2 = 0.6 + rand .* 2.4;
      path_length2 = dur2 .* comparison_vel;
      far_point = dist2 + path_length2./2;
      path_distance = velocity_for_distance .* dur2;
      near_point = far_point - path_distance;
      if near_point >= CLOSEST_DISTANCE_LIMIT
         check_dist2 = true;
      end
   end
   angular_span2 = path_length2 ./ dist2;  % in radians
   number_of_samples2 = round(SAMP_RATE .* dur2);
   angular_increment2 = angular_span2 ./ number_of_samples2;
   distance_increment2 = path_distance ./ number_of_samples2;
   duration_per_sample2 = dur2 ./ number_of_samples2;
   distance_increment2 = path_length2 ./ number_of_samples2;
   mid_distance = (far_point + near_point)./2;  % no longer needed
   start_azimuth = 0 - angular_span2./2;    % for now, we assume midpoint is at 0deg
   stop_azimuth = start_azimuth + angular_span2;
   start_distance = dist2 + path_length2./2;
   stop_distance = start_distance - path_length2;
   azimuths = [start_azimuth : angular_increment2 : stop_azimuth]';
```

```
   distances = [start_distance : -distance_increment2 : stop_distance]';
   N = number_of_samples2;
   increment_dist = abs(distances(2:N).*exp(i.*azimuths(2:N)) - distances(1:N-1).*exp(i.*azimuths(1:N-
1)));
   velocities = increment_dist./duration_per_sample2;
   len_vel = length(velocities);
   time2 = [0:len_vel-1]' .* dur ./(len_vel-1);
   % get sum of the distances
   total_distance2 = sum(increment_dist);
   % average velocity, comparison stimulus
   ave_comparison_velocity(kk) = total_distance2 ./ dur2;
end
subplot(3,1,1)
hist(ave_standard_velocity)
title('distribution of standard velocities for Combo Path')
subplot(3,1,2)
hist(ave_comparison_velocity)
title('distribution of comparison velocities for Combo Path')
subplot(3,1,3)
hist(ave_comparison_velocity - ave_standard_velocity)
title('distribution of the difference in velocities')
xlabel('Velocity (m/s)')
mean_standard_distr = mean(ave_standard_velocity);
mean_comparison_distr = mean(ave_comparison_velocity);
mean_vel_diff = mean_comparison_distr - mean_standard_distr;
```

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