DECRUITMENT OF THE PERCEPTION OF CHANGING SOUND INTENSITY FOR SIMULATED SELF-MOTION

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ABSTRACT

Of the many cues that could be used to gauge self-motion, auditory cues seem to be the least studied. Listeners could potentially use either a sweep of rising sound intensity to judge their self-motion towards an object or conversely use a sweep of falling sound intensity to judge their motion away from an object. Whether the sweep is rising or falling the listener must judge both the change in intensity across the sweep, and the temporal span of the sweep. Studies indicate that sweeping intensities are misperceived so that the sound intensity at the end of the sweep is judged differently than when the final sound intensity is presented alone. Although there is ongoing discussion as to whether the induced fading is greater for rising sound intensity as opposed to falling sound intensity, both phenomena affect the perception of self-motion. This paper presents a series of experiments that examined self-motion perception with auditory cues. Results confirm the finding of decruitment for a sweeping broadband sound source that decreases at various rates of acceleration. Furthermore, the phenomenon of decruitment was greatly diminished at higher accelerations indicating that this phenomenon is likely correlated to the lowest rate at which listeners can perceive a change in intensity.

1. INTRODUCTION

We are capable of estimating the magnitude of our own self-motion and the relative motion of other objects as we move about our natural environment. This perception is based on information arising from several sensory modalities including visual, auditory, and physical motion. In general, the perceived distance of self-motion is over-estimated when using visual or physical motion cues solely or even in conjunction, although judgments are more accurate when both cues are available [5, 7, 8]. In other words, the distance we perceive ourselves to have moved is greater than the actual distance moved. Despite the potential contribution of dynamic auditory localization to the perception of self-motion, few studies have examined the effects on auditory cues on the perception of self-motion. Indeed, the majority of studies on the role of auditory cues in self-motion perception focus primarily on constant velocity motion, ignoring acceleration, the required stimulus for the vestibular system [6].

Listeners could potentially use either a sweep of rising sound intensity to judge their self-motion towards an object or conversely use a sweep of falling sound intensity to judge their motion away from an object. Whether the sweep is rising or falling the listener must judge both the change in intensity across the sweep and the temporal span of the sweep. It turns out that sweeping intensities are misperceived so that the sound intensity at the end of the sweep is judged differently than when the final sound intensity is presented alone. There is substantial evidence of an accelerated gain in loudness with a rising sound intensity [10] and an accelerated loss in loudness with a falling sound intensity (the latter is known as *decruitment* [1, 2, 14, 15]). Although there is an ongoing discussion as to whether the induced fading is greater for a rising sound intensity as opposed to a falling sound intensity, both phenomena affect the perception of self-motion [3, 10, 15]. Given the accelerated loss in loudness associated with a decreasing sound sweep, a decreasing sound intensity sweep for the perception of self-motion should result in an overestimation of self-motion where subjects perceive themselves to have traveled farther than they actually have.

The phenomenon of decruitment diminishes with sweeps of lower duration [14, 16]. Similarly, Redlick *et al*. [13] found visual decruitment when subject's used an approaching visual stimulus to judge their self-motion which can be compared to the receding auditory decruitment reported by Teghtsoonian *et al*. [14]. Therefore, self-motion perception through auditory cues is quite likely effected by the phenomenon of decruitment.

Here we describe two experiments to examine our ability to judge the distance of self-motion under two different auditory stimulus conditions. Twelve subjects were presented with constant acceleration "auditory motion" over the range of 0.05-0.2$m \cdot s^{-2}$. The two experiments involved acoustic motion cues: (i) decreasing sound intensity to simulate the listener moving away from the sound (sound source intensity is expressed in W/$m \cdot s^{-2}$however the reduction was measured in sound pressure level (Decibels)), and (ii) a sound source physically moved away from a stationary subject.

1.1. Paper Organization

The remainder of this paper is organized as follows. A description of the experimental method is given in Section 2. Details regarding the subjects, equipment, stimuli, and experimental procedure are provided. Experimental results are presented in Section 3. A discussion of the experimental results and how they compare to existing studies is provided in Section 4. Finally, concluding remarks are presented in Section 5.

2. EXPERIMENTAL METHOD

2.1. Subjects

Subjects were unpaid volunteers and were either researchers, graduate students, professors or summer high school student assistants. Subjects had normal or corrected-to-normal vision and no reported history of auditory or vestibular disease/disorders. None of the subjects reported any difficulties in hearing the stimuli or in completing any of the tasks. Twelve subjects participated in experiments 1 (average age 27 years; range 17 to 40 years) and ten subjects participated in experiment two, eight of whom also completed the other experiments (average age 29 years; range 17 to 43 years).

2.2. Apparatus

2.2.1. Subject cart

For experiment one the subjects sat on a chair mounted on a cart (Figure 1(a)). Fixed in place next to the chair's right arm-rest was the "subject response button". A "reference point" (a large "X") was marked on the foam placed on the base of the cart within the subjects' view. All distance estimates were made relative to this marking. This cart did not move.

2.2.2. Loudspeaker Motion Cart and Assembly

For experiment two, a "loudspeaker cart" was constructed to move a sound source while the subject remained stationary. Loudspeakers were mounted on each of this cart's sides (Figure 1(b)). The loudspeakers were placed facing each other 1m apart. This cart was also guided by a track on the floor.

2.2.3. Auditory Stimulus

The auditory stimulus for each experiment consisted of a broadband, uniformly distributed, white-noise signal, sampled at a rate of 44.1kHz. The noise was band-pass filtered using a 256-point Hamming windowed FIR filter with low and high frequency cut-offs of 200Hz and 10kHz respectively. A broadband signal was used as sound source distance estimates are more accurate for broadband sounds [4, 9, 11, 12].

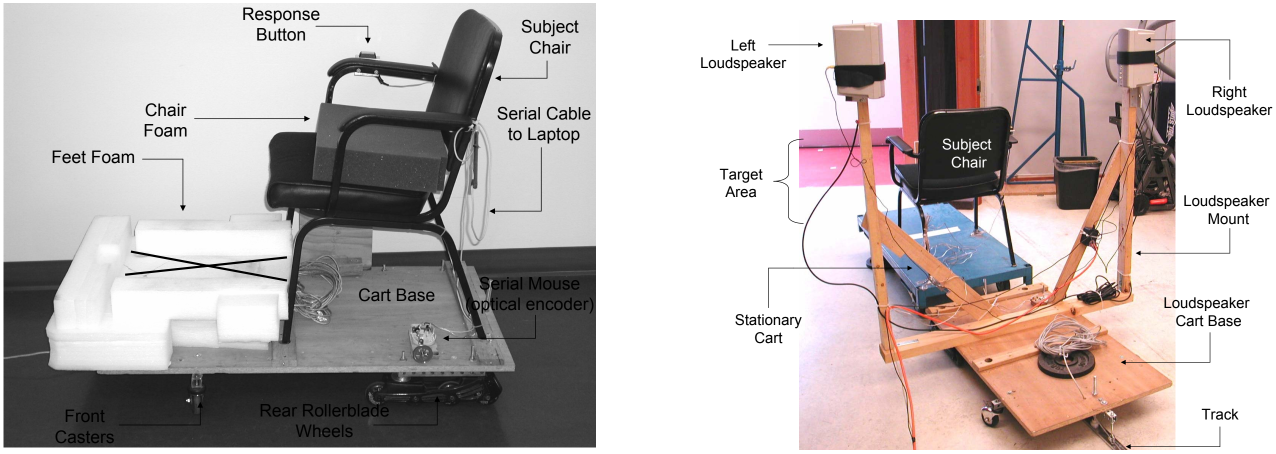
In order to ensure the subject did not learn to associate a particular sound level with a particular target distance or acceleration profile, the level of the sound stimulus was randomly chosen from one of three different initial levels for each presentation (66dB, 69dB and 72dB). This was measured with a Radio Shack sound level meter (model 33–2055) with an A-weighting averaged over 15s and placed at the starting position where the subject's head would be.

All auditory stimuli were played through a pair (left, right) of Yamaha YST-M15 loudspeakers. For experiment one, each loudspeaker was mounted on an adjustable-height camera tripod at the height of the seated subject's ears. The left and right loudspeakers were separated by 1m and placed on the inter-aural axis, positioned directly in line with the ears of the subject. For experiment two, the loudspeakers were mounted on the loudspeaker motion cart facing each other 1m apart and behind the subject (see Figure 1(b)). Sound level was also measured (for each of the three reference sound levels), at target distances of 1m, 2m, 3m and 4m. For each doubling of sound source distance, the level decreased by 2.7dB.

Although both experiments were not carried out in an anechoic environment, the background noise level was measured in the absence of the sound stimulus at the starting position and at each of the four target distances. The average background sound levels at each target distance and at the starting position was below 50dB (the minimum sound level measurable with the sound level meter) with a maximum level of 57dB. The average sound level during a typical trial was 54dB with maximum and minimum values of 56dB and 51dB respectively.

2.3. Experimental Procedure

Prior to the start of the experiments, subjects were briefed about the required task by one of the experimenters. There was no training ("learning phase") but subjects were given



(a) Subject cart.

(b) Loudspeaker motion cart.

Figure 1: (a) Subject cart used in experiments one and (b) loudspeaker motion cart used in experiment two.

several test trials to ensure they understood the tasks. Subjects were also instructed to sit in the chair with their back and head straight up and to keep their head stationary during each trial. In both experiments, each subject was presented with a large 1.5m $\times$ 1.0m, brightly colored "T"-shaped physical target at one of four distances (1, 2, 3 or 4m) in front of them. The target was held in place by one of the experimenters. Subjects were allowed to view the target for as long as necessary (typically under 30 seconds) and were also encouraged to move their head from side-to-side to obtain parallax cues in addition to size and disparity cues concerning the target's distance. Subjects were then blindfolded and presented with a sound stimulus whose level decreased at a rate matching one of the following accelerations (0.012, 0.025, 0.05, 0.1, $0.2m \cdot s^{-2}$). Conditions were presented in a random order. Both experiments comprised 20 trials with four target distances at five accelerations. Each condition was presented only once. Trials were randomly interleaved and carried out in a single session by all participants. Figure 2 provides a graphical summary of the procedure for each of the two experiments. In both experiments we simulated self-motion away from a sound source by decreasing the intensity of the sound source either at the speaker or by moving the speaker away from the subject.

2.3.1. *Experiment One: Decrease Intensity at Speaker*

This experiment investigated whether the reduction of sound intensity (sound level) alone can be used as a reliable cue for self-motion perception. The level of the auditory stimulus was decreased to simulate the reduction in intensity which would occur if the subject was actually accelerating away from the sound source at one of the five rates of acceleration. The level (in dB) was made inversely proportional to the distance between the listener and the loudspeakers and updated at a rate of 22,050Hz. Although this experiment did not include any physical motion, just before the stimulus was presented the motor used to pull the loudspeaker cart of experiment two was started to ensure the subject would not use the noise to identify this with no physical motion.

2.3.2. *Experiment Two: Decrease Intensity by Moving the Loud Speakers*

In this experiment, the subject remained stationary at the starting position, while the loudspeakers were moved. The sound source loudspeakers were mounted on a cart (see Figure 1(b)) and behind the subject's ears. The loudspeakers were accelerated backwards from the stationary subject at one of the five accelerations used in the other experiments. Subjects were induced to feel they were moving forward by the loudspeaker movement. They indicated they felt they had reached the target by pressing the response button.

3. EXPERIMENTAL RESULTS

For each condition the stimulus distance (i.e., target distance) was compared to the response distance (i.e. matched distance). The perceptual gain (g_p) is defined as the slope of stimulus to response distance [5]. When the response distance matches the perceived distance, the perceptual gain is unity. A perceptual gain greater than one indicates that the response distance is less than the stimulus distance. A perceptual gain of less than 1 occurs when the response distance is greater than the stimulus distance. A graphical summary of the resulting perceptual gains as a function of acceleration for both experiments are provided in Figure 3. The perceptual for experiment one are listed in Table 1 and the perceptual gains for experiment two are listed in Table 2.

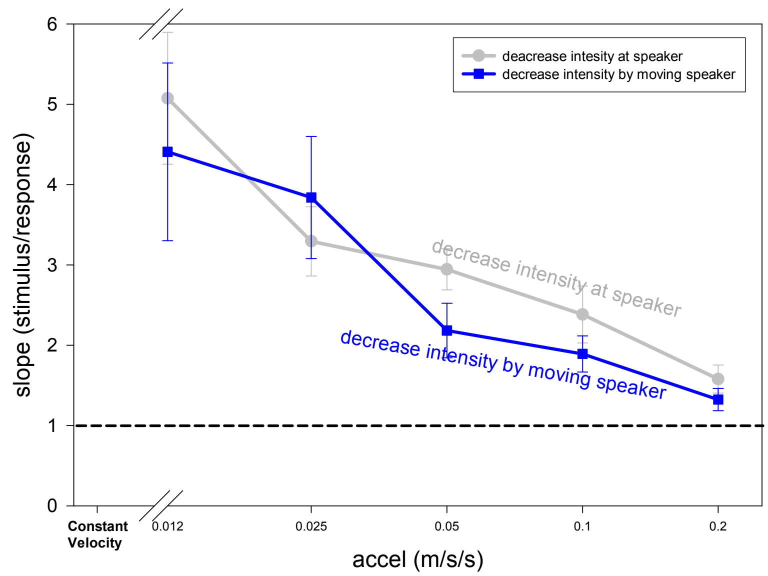


Figure 3: Summary of experimental results: perceptual gain (perceived distance / actual distance) as a function of acceleration (on log axis) for experiments 1 and 2.

Acceleration (m·s^{-2})	**Perceptual Gain (g_p)**
0.012	5.08 ±0.82
0.025	3.29 ±0.43
0.05	2.95 ±0.26
0.1	2.38 ±0.35
0.2	1.58 ±0.18

Table 1: Average perceptual gains for each acceleration of experiment one (decreasing intensity at speaker).

Acceleration (m·s^{-2})	**Perceptual Gain (g_p)**
0.012	4.40 ±1.1
0.025	3.84 ±0.76
0.05	2.18 ±0.34
0.1	1.89 ±0.22
0.2	1.32 ±0.14

Table 2: Average perceptual gain for each acceleration of experiment two (decrease intensity by moving speaker).

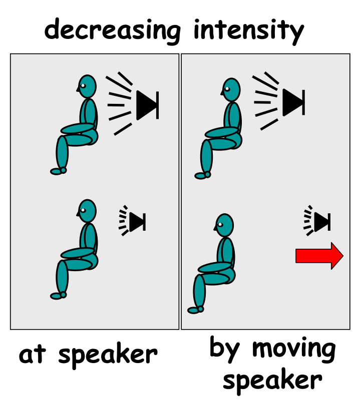


Figure 2: Experimental procedure for both experiments considered. Condition (i) decrease intensity at speaker, and (ii) decrease intensity by moving speaker.

3.1. Experiment One: Decreasing Intensity at Speaker

Averaged perceptual gain values for auditory motion only conditions by acceleration are shown as open circles in Figure 3. All perceptual gain values are greater than one, indicating that subjects thought they had gone farther than they really did. Perceptual gains are proportional to the inverse of acceleration and in contrast to the motion-only condition, low accelerations resulted in a perceptual gain much greater than one.

Acceleration (m·s^{-2})	**DAS**	**DMS**
0.012	0.05, 0.1,0.2	-
0.025	-	0.1, 0.2
0.05	0.012	-
0.1	0.012	-
0.2	0.012	-

Table 3: Tukey-Kramer multiple-comparison test for differences within conditions by acceleration. DAS denotes the decrease intensity at speaker while DMS denotes the physically moving the speaker experiment.

3.2. Experiment Two: Decreasing Intensity by Moving the Loud Speakers

Physically moving audio conditions are presented as dark squares in Figure 3. Similarly to the previous experiment, all perceptual gains are greater than one and proportional to the inverse of acceleration. Low accelerations resulted in a perceptual gain much greater than one. Furthermore, the responses of this experiment closely resemble the responses of the decreasing intensity at speaker experiment with no significant difference between them.

3.3. Effects of Condition and Acceleration

A repeated measures ANOVA test and post-hoc comparison test were also performed on the five different accelerations. Results of the ANOVA test confirm a significant difference of acceleration (**F** $(4, 36) = 8.32$, $p < 0.01$). Accelerations can be divided into two groups with the slow accelerations in the range of $0.012 m \cdot s^{-2}$- $0.05 m \cdot s^{-2}$and the fast accelerations $> 0.1 m \cdot s^{-2}$. The slow acceleration conditions showed a significant difference when compared to the fast accelerations.

A post-hoc multiple comparison test was performed to compare all pairwise differences between experiments and accelerations (see Table 3). In this table, the first column denotes acceleration while columns two and three denote the two experimental conditions tested. The entries of columns two and three denote which of the five accelerations are statistically different when considering each experimental condition individually.

4. DISCUSSION

This study makes a number of previously unknown observations. First that the distance subjects judged they moved relative to a stationary sound source (decrease at speaker) was considerably more than they actually did (i.e. the perceptual gain was greater than unity). This is especially true when the motion was of a low acceleration. In fact, perceptual gains greater than five were observed for the acceleration of 0.012m·s^{-2}. Therefore, the series of experiments described in this paper confirm the finding of decruitment for a sweeping broadband sound source that decreases at various rates of acceleration. Furthermore, as the experimental results demonstrate, the phenomenon of decruitment diminishes at higher accelerations (faster sweeps that have a shorter span), and for sweeps of lower duration [14, 16].

A comparison of audio-only cues to other sensory modalities for self-motion shows the robustness of this phenomenon. Compared to visual motion alone, the perceived magnitude based on auditory information is almost three times higher for low accelerations, but this diminishes for higher accelerations (shorter sweeps) [13]. The vision only decruitment found by Redlick *et al*. [13] is similar to the vision only decruitment reported by Teghtsoonian *et al*. [14] though one was approaching [13] and the other receding [14]. When compared to combined physical and visual motion [5], perceived magnitude using auditory information increases by a factor of approximately 2.3.

There is approximately a 4.5 times overestimation of the magnitude of self-motion using decreasing sound source level (experiment one: decreasing intensity at speaker). This is more pronounced than the results found in the auditory literature (a difference of 3.1 for a tone and a difference of 2.47 for a broadband noise [15]. This difference may be explained by (i) a methodological difference; the objective measure used in the self-motion study described here uses visual targets as a metric, and (ii) the range of change used in the self-motion study described here was only 6dB, much less than the 30dB reported by Teghtsoonian *et al*. [15]. The experimental methods described here are similar to Neuhoff's [10] since subjects judge when they reach a target previously shown, although in this study subjects were presented with a decreasing sound intensity stimulus in contrast to the increasing sound intensity stimulus used by Neuhoff [10]). We avoided using an increasing sound source since we felt subject might wait until the source rose and just started to fall to judge their motion. However, if we had used an increasing intensity sound source we likely would have seen more dramatic overestimates of self-motion [10].

5. SUMMARY

The majority of the research effort examining our perception of self-motion has concentrated on the visual and vestibular senses. Although vision plays a critical role the understanding of our surroundings and a large portion of the brain is dedicated to visual processing, it is certainly not the only cue available to us and at times it cannot be used (e.g. in the dark or for objects which are not within our visual field). Furthermore, the integration of multi-sensory information is more likely to provide more accurate information than a single modality. In contrast to the visual system, the auditory system is omni-directional and can function in the dark and in other situations where vision is restricted (e.g. fog, heavy snow, etc.)

The series of experiments presented here confirm the finding of decruitment for a sweeping broadband sound source that decreases at various rates of acceleration simulating self-motion away from a sound source. The results also bridge the gap between the work on approaching and receding auditory stimuli. The application of principles of auditory perception to self-motion reveals some new features of interest. Designers of simulators should be aware of the phenomenon of decruitment with slow accelerations using auditory cues in the absence of physical motion. In particular, researchers should be careful when conducting self-motion studies where auditory cues are present.

The significant effect of acceleration and increased accuracy at high accelerations suggests that decruitment is a factor of a temporal threshold at which humans can perceive a change in intensity. These results have implications for the designers of immersive virtual environments that wish to simulate self-motion.

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