Effect of whole body vibrations on sound localization

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In order to assist the human operator modern auditory interfaces increasingly rely on sound spatialization to display auditory information and warning signals all around the listener. However, we often operate in environments that apply vibrations to the whole body, e.g., when driving a vehicle. So there is a concern that vibrations impair spatial hearing and thereby the efficacy of sound spatialization. While effects of whole-body vibrations have been found to impair simple front-back discrimination, their effect on sound localization per se has received scant attention. Here we report three experiments that used a variety of sound localization performance measures and vibration manipulations. The first was a free-field localization experiment that compared performance under conditions with and without vibration (a 5 Hz sinusoidal movement along the vertical axis). The other experiments used classical psychophysical forced choice procedures and sound lateralization tasks in which stimuli were presented over headphones and position was manipulated through interaural time differences. In experiment 2 we used two vibrations (4 and 8 Hz) at two magnitudes (0.084 and 0.169 ms^{-2}). In experiment 3, sound lateralization was assessed at central and more peripheral locations. In none of the experiment did we observe an effect of whole-body vibrations on localization performance.

1 Introduction

Exposure to vibrations is common in all types of transport or when operating industrial machinery. In the most pervasive form of exposure, vibrations are applied to the whole body when human operators are supported by vibrating structures, such as vehicles in motion. The effect of whole body vibrations on human performance has been investigated in various work environments such as aviation, maritime, and land-based vehicle operations [9] as well as in laboratory studies (see [2] for a review). There is converging evidence for disruptive effects of whole body vibrations on perceptual tasks (e.g. visual target detection), cognitive tasks (e.g. mathematical reasoning), and fine motor tasks (e.g. tracking or switch activation). Detrimental effects on audition have also been reported with temporary hearing threshold shifts and combined effects of vibration and noise on hearing thresholds (e.g. [8,15]).

Auditory interfaces increasingly rely on sound spatialization to display auditory information and warning signals all around the listener. However, the effect of vibrations on auditory localization has received scant attention. To our knowledge there is only one dedicated study. Tajadura-Jiménez et al. [16] studied the effect of concurrent whole body vibrations on front-back localization of an auditory stimulus presented on the median plane. They found that the presence of vibrations at the same frequency as the sound (i.e., 60 Hz) biased the localization of front sounds towards the back. These results then show a detrimental effect of vibrations on spatial hearing. However, reversals are neither a common nor a representative measure of sound localization performance, which poses the question of generalizability. For instance, although front-back reversals are commonly found in the sound localization literature, they are relatively rare (between 3% and 6% of the trials, [1,7]). Tajadura-Jiménez et al. [16] used a low frequency auditory stimulus that was relatively hard to localize and that increased the chances of observing reversals. Also, the authors only used two speakers, one in directly front and one directly in the back of the listener.

The aim of the present study was to expand the investigation on the effects of whole-body vibration on sound localization by employing more varied and sensitive measures of sound localization performance. We report on three experiments. In the first experiment, participants were asked to indicate the location of sounds presented on a circular array of loudspeakers surrounding them in an acoustically treated room. This so-called free-field localization experiment allowed us to investigate front-back reversals on a large range of spatial locations as well as use more sensitive measures of sound localization performance, such as the angular error between the physical and perceived sound location. In the other two experiments, we used headphone presentations, in which we manipulated sound location through interaural time differences and assessed sound lateralization by means of standard psychophysical threshold estimation techniques.

If whole-body vibrations affect sound localization we presume this effect to be negative and therefore expect to see worse sound localization performance.

2 Experiment 1

In the first experiment participants performed a free-field sound localization task. The stimulus was a band-pass noise and participants were asked to indicate where the noise came from. They were unconstrained in their localization response.

There were several reasons for these choices. First, participants in Tajadura-Jiménez et al.'s [16] study could only respond whether they had heard the sound in the front or in the back. Although this binary response method was apparently sensitive enough to register a change in auditory perception it does tell us the extent in which hearing was affected. For instance, do vibrations only affect front-back reversals or do they have a more elaborate effect on spatial hearing? In addition, the task used in [16] was not criterion free. It could be argued that vibrations affected cognitive decisional processes as opposed to perceptual processes.

For a more complete appreciation of the effects we therefore need to consider sound localization using a larger range of performance measures that are also (decision) criterion free. Second, [16] only included two test locations, exactly in front and in the back of the listener. Numerous studies have shown that spatial hearing is most precise directly in front of the listener. We wanted to see how other, more peripheral, locations are affected by vibrations. Third, the auditory stimulus in [16] was deliberately hard to localize. We are interested in seeing if the localization of more ecological sounds is affected as well.

2.1 Method

Eighteen participants (8 female, age range: 22-30) completed the experiment. All participants had normal hearing.

Testing took place in the Immersive Presence Lab (IPL) of the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) in Montreal (Canada). The room is 6 m (W) x 7.8 m (L) x 3.2 m (H), has a measured reverberation time of 0.16 s, and features a semi-spherical frame with a radius of 2.5 m that supports 24 planar speakers that can be positioned anywhere on the structure. Each speaker consisted of two planar magnetic transducers Level 9 PFT 150 (Richmond, BC, Canada), with a frequency range of 0.2–20 kHz (63 dB) after compensation. Except for the speakers all audio equipment was installed outside of the lab to minimize background noise (for details see [3]).

For the present study, 12 speakers were uniformly spaced along a circle in the horizontal plane at ear level. Their positions were -150 to 180° at 30° intervals. Negative values indicate a position to the left of the participant. Built into the floor, in the middle of the semi spherical frame, was a motion platform Odissée Motion Simulator (D-Box, Longueil, QC, Canada). The response of the platform is linear up to a frequency of ~70 Hz. A rigid chair without any padding was placed on (or over, see below) the motion platform. The participant was seated on the chair such that the head was in the center of the speaker array. Responses were collected by means of a quasi-continuous digital rotary dial presented to them on an iPod (Figure 1).

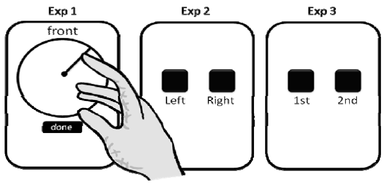

Figure 1: Illustration of the iPod and response interfaces used in the three experiments (not to scale). The interface was hidden from view during stimulus presentation and was shown and active only after the presentation of the sound.

Auditory stimuli and vibrations were supra-threshold. The auditory stimulus was a 1 s narrowband (1/3 octave, center frequency = 1000 Hz) noise, presented at 60dB. To generate whole body vibrations the motion platform was moved along the vertical axis with a sinusoidal profile at 5 Hz with a magnitude of 0.09 ms^{-2} r.m.s. This frequency was chosen because studies showed that people are particularly sensitive to whole-body vibrations in this range [6,10].

Sound localization on the azimuth was assessed under three randomized and blocked conditions. In the auditory only condition the motion platform was stationary. In the vibration condition, the platform started vibrating 1 s before the onset of the auditory stimulus and continued until 1 s after the offset of the auditory stimulus. A control condition was created to present the same (or very similar) acoustic environment as in the vibration condition. The motion platform moved as in the vibration condition but the participants were isolated from the vibration by placing the chair on a construction that straddled the moving platform. In all three conditions the 12 azimuth angles (corresponding to the 12 speakers) were tested in random order, each for a total of five times. Before testing there was a short training session without vibration to familiarize the participants with the task. At no point in the experiment was there any performance feedback to the participant.

2.2 Results

Sound localization performance was quantified using a number of measures. First, we determined the number of front–back reversals. We also quantified accuracy and precision of sound localization performance. Accuracy reflects biases in sound localization and was calculated by subtracting the physical location from the perceived location such that a negative value corresponds to an error to the left and a positive value and error to the right. Precision was quantified by the standard deviation in localization errors. We will refer to these two measures as constant and variable error, respectively. Before calculating these error measures, responses that were categorized as front–back reversals were first 'flipped' along the interaural axis [18]. Statistical analyses were performed with R (version 2.14.1) using the 'car' package for conducting the repeated measures ANOVAs [4]. The significance level was set at 0.05.

There were a surprisingly large number of front-back reversals. Averaged across all conditions 40% of the responses were classified as reversals. Per condition, we found an average of 37.2% (Standard Error of the Mean = 2.5%) in the auditory only condition, 42.9% (SEM 2.0%) in the control condition, and 40.5% (SEM 2.6%) for the vibration condition. A oneway repeated measures ANOVA showed a significant effect of condition ($F(2,34) = 3.71$. $p < 0.05$) on the number of front-back reversals. Follow-up t-tests using Bonferroni adjusted alpha levels of .0167 per test (.05/3), showed a marginally significant difference between the auditory only and control condition ($t(17) = 2.50$, $p = 0.023$). The vibration condition was not significantly different from either the auditory only or the control condition (both p-values > 0.16).

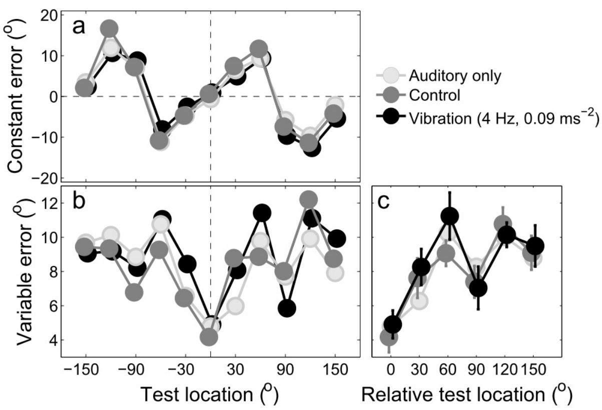

Figure 2: Auditory localization error for Experiment 1. a. Accuracy: constant errors in localization responses as a function of azimuth for the three conditions. b. Precision: variable errors as a function of azimuth. The error bars are not shown for clarity. c. Precision. The mean variable errors after collapsing across the left and right hemispace. Error bars represent the standard error of the mean.

Figures 2a and b show, respectively, the measures for accuracy and precision as a function of test location. The constant error data were submitted to a 3 (condition) x 11 (test location) repeated measures ANOVA, which gave a significant effect for test location ($F(10,170) = 14.5$, $p < 0.0001$) but not for condition ($F < 1$), or the interaction ($p > 0.32$). The same ANOVA for the variable error data gave a significant effect for test location ($F(10,170) = 4.55$, $p < 0.0001$) but not for condition (F < 1), or the interaction ($F < 1$). Because the variable error data were fairly symmetrical we collapsed the data across the left and right hemispace.

The results are plotted in Figure 2c. A 3 (condition) x 6 (relative test location) repeated measures ANOVA gave a significant effect for test location ($F(5,85) = 10.9$, $p < 0.0001$) but not for condition or the interaction (both F's < 1).

2.3 Discussion

Accuracy was biased in a particular way. For test locations between -60° and +60° there was a tendency to "overshoot" the target. Finding an overshoot in the central region of the frontal hemispace is not an uncommon finding (e.g., [14]). Interestingly, a virtually identical result, within the same range and with the same magnitude (errors between -10° and 10°) was reported in [12]. However, contrary to other reports we find that beyond 60° we find a sudden jump to a tendency to undershoot. This could be explained in part by supposing there was a tendency to enter a response closer to the cardinal axes. Precision was the best at 0° and quickly decreased for more peripheral locations, although there was a clear 'local' increase in precision at 90°. This pattern, including the magnitude of the errors, is in keeping with literature (e.g., [7]).

However, more pertinent is that the results showed no effect of whole-body vibration on any of the sound localization performance measures, including front-back reversals. This means that we did not replicate the detrimental effect of vibration observed by Tadajura-Jiménez et al. [16]. We elaborate on this in the general discussion.

The accuracy and precision measures were based on localization responses that were corrected for reversals. Nevertheless, they also did not show any effect of the presence of vibrations. It could be suggested that the vibration was not strong enough. However, the magnitude in our experiment (0.09 ms^{-2} r.m.s.) was nearly twice as large as in [16](i.e., 0.05 ms^{-2} r.m.s.). It could also be suggested that using a narrow-band noise stimulus made sound localization more robust again vibration. We hold this as a likely explanation. However, we are reminded of the very high rate of reversals, which suggests that the stimulus was not trivially easy to localize. We currently do not have an explanation why the rate of reversals was so high.

3 Experiment 2

Sound localization accuracy and precision in Experiment 1 were generally consistent with the literature. Nevertheless there was an unusually high rate of front–back reversals. We therefore turned to a different measure of sound localization performance to assess the effects of vibration, a sound lateralization task. Moreover, whereas in Experiment 1 we only have one vibration frequency here we extended the range of vibrations, using two frequencies at two different magnitudes.

3.1 Method

Fifteen participants (4 female, age range 19-44) completed the experiment. All participants had normal hearing.

The auditory discrimination thresholds were measured under five conditions: two vibration frequencies (4 and 8 Hz) each presented at two different vibration magnitudes (0.084 and 0.169 ms^{-2} r.m.s.), plus an auditory-only baseline condition. We used a 1-interval forced choice procedure, in which on each trial the participant was presented with one of the eight stimuli. The task was to indicate whether the sound had come from the left or the right of the subjective straight ahead. Each of the eight stimuli was tested 15 times for a total of 120 trials per condition. The conditions were blocked and their order randomized according to a Latin-square. The stimulus was a 50 ms white noise with 5 ms linear on and off ramps. To create interaural time differences we used Matlab to make a stereo signal to be played at 44.1 kHz. This way, by shifting the left and right channels by one sample a 22.4 µs time difference is created. Using this principle eight stimuli were created with ITDs of ±44.1 µs, ±88.2 µs, ±220.5 µs, and ±308.7 µs.

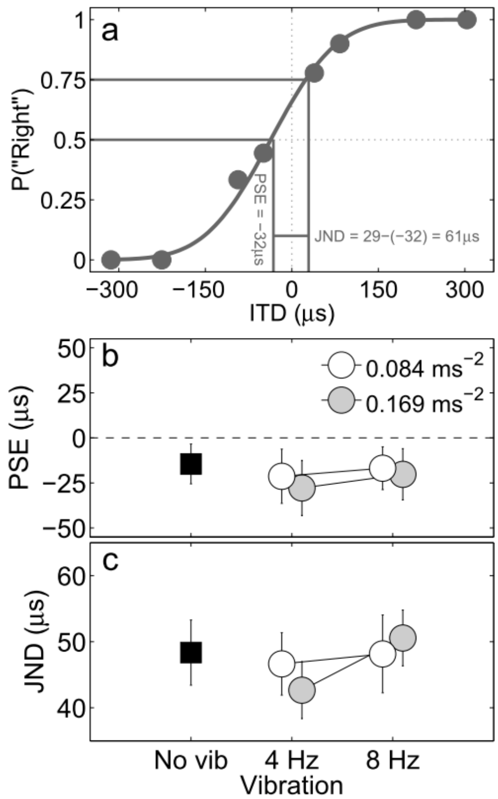

Figure 3: Experiment 2. a. Exemplary data from one participant in the 4 Hz, 0.084 ms^{-2} condition. Psychometric functions were constructed by taking the proportion of trials in which the stimulus was perceived to be to the right. Cumulative Gaussians were fitted to these data using the software package psignifit for Matlab [17]. From these fits we obtain two measures of performance, the point of subjective equivalence (PSE) and the just-noticeable difference (JND). The mean PSE (panel b) and JND (panel c). Error bars show the standard error of the mean.

The analysis of the psychometric functions is explained in Fig 3a and the caption. The Point of Subjective Equivalence (PSE) corresponds to the interaural time difference for which stimuli are perceived to be coming from straight-ahead; is a measure of bias. The Just Noticeable Difference (JND) is an index of how sensitive the listener is to changes in interaural time differences; the smaller the JND the more sensitive. If vibration has a detrimental effect on sound localization we expect the JND to increase. Because the vibration affects the entire body we do not expect any direction specific effects and therefore no difference in the PSE.

3.2 Results and discussion

The results from two participants were discarded because they had difficulties performing the task and consequently we were not able to obtain reliable fits for their psychometric functions. The mean PSEs and JNDs for the remaining 13 participants are shown in Fig 3b, and c, respectively. A oneway repeated measures ANOVA with all five conditions showed a significant effect for neither the PSE nor the JND (both F's < 1). Because there was no difference between the experimental and baseline condition we excluded the latter and re-analyzed the PSE with a 2 (Frequency: 4 or 8 Hz) x 2 (Acceleration: 0.084 ms^{-2} or 0.169 ms^{-2}) repeated measures ANOVA, which still revealed no significant main effects or interaction (all p-values > 0.27). The same ANOVA also showed no significant main effects or interaction for the JND (all p-values > 0.10).

Thus neither the frequency nor a doubling in the magnitude of the vibration had any effect on sound lateralization performance.

4 Experiment 3

Experiment 2 relied on an internal reference (the subjective straight ahead) which was nominally at 0 µs. That is, the reference was at a location that corresponds where people are generally most precise. This may have contributed to being unable to show an effect of vibration. Moreover, because there was no explicit reference the task was not criterion free. Therefore, in this experiment we employed task that featured an explicit reference and tested at peripheral locations.

4.1 Method

Twelve participants (6 female, age range 18-30) completed the experiment. All participants had normal hearing.

The auditory discrimination thresholds were measured under two conditions: no vibration and vibration (4 Hz with a magnitude of 0.169 ms^{-2}). We used a 2-interval forced choice procedure, in which on each trial the participant was presented with a sequence of two stimuli, separated by a short break whose duration was random sampled from a uniform distribution between 1600 and 2100 ms. One was the reference and the other was one of eight comparison stimuli distributed symmetrically around the reference. The order of reference and comparison was randomized. The task was to indicate which one of the two was perceived as more to the right. Answers were entered using the iPod which featured a simple two button interface (Fig 1). For each of the two conditions there were a total 3 references x 8 comparisons x 12 replications = 288 trials, divided over two blocks of 144 trials. The resulting four runs were tested according to an ABBA scheme, where half the participants started with the no vibration condition. There were three references, at 0 µs and at ± 250 µs, which corresponds to sound at 0° and approximately ±30° [5]. The stimuli were created in the same fashion as in Experiment 2.

4.2 Results and discussion

The PSE with respect to their corresponding reference were analyzed with a 2 (condition) x 3 (reference) repeated measures ANOVA. None of the terms were significant (all p-values > 0.19). This was also true for the intercept term ($F < 1$), which meant that no bias was observed. More pertinent, the same ANOVA for the JNDs (see Figure 4) showed neither a significant effect of reference ($F(1,9) = 1.17$, $p = 0.31$) nor for the condition and the interaction (both F's < 1).

The results are unambiguous; we again did not observe any effect of whole-body vibration on sound localization performance.

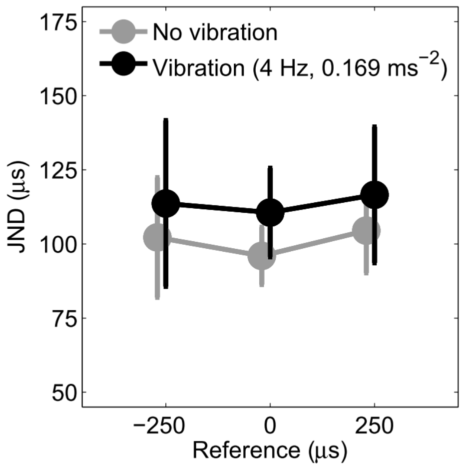

Figure 4: Mean JND of Experiment 3. Error bar show the standard error of the mean.

5 General discussion

Three experiments, using different methodologies, were conducted to study the effects of whole body vibration on sound localization performance. The results were straightforward; none of the experiments revealed a reliable effect of vibration.

Our results are in contrast to an earlier study that did show a significant impairment in front-back discrimination by whole-body vibration [16]. This disparity could be due to methodological differences. One obvious difference is the vibration frequency used. Whereas we used relatively low frequencies, in [16] the frequency was an order of magnitude larger (i.e., 60 Hz). Tadajura-Jiménez et al.'s [16] reason for choosing this frequency was to have an overlap in sensitivity in vibratory-tactile and auditory perception. In addition, there is also the possibility that their experimental design and task in made it more susceptible to influences by decisional factors. Psychophysical methods are available that could help to distinguish between perceptual and decisional contributions to the effect (i.e., signal detection theory) and should be pursued in future experiments. In addition, Tadajura-Jiménez et al. [16] did not control for masking. Although, their vibratory stimulus was "[…] delivered from the two shakers at a somatosensorily suprathreshold level, but […] completely inaudible." (p 1314), because no control condition, similar to ours, was included the possibility that vibrations masked the sound at the same frequency cannot be excluded. We also need to consider that with 40% of trials being categorized as reversals, we found a rate that is much higher than found in the sound localization literature, where it is typically between 3 and 6% ([1,7]). Thus one possible explanation for the lack of an effect on the number of front-back reversals could be that it was 'swamped' by the high base rate. In short, the results in terms of front-back reversals are unclear.

However, our other measures unequivocally show a lack of an effect of whole-body vibration on sound localization. Free-field localization performance was both qualitatively and quantitatively consistent with the extant literature in terms of accuracy as well as precision, which speaks to their validity. Nevertheless, they showed no effect of vibration whatsoever. The same was true for the headphone based sound lateralization experiments.

As always with negative effects it could be argued that the manipulations were either not appropriate or at the very least that the particular parameters settings were inadequate. One possible problem could be with the frequency range tested. However, it appears that humans are not less sensitive to 4 and 8 Hz than to 60 Hz, if anything they are more sensitive ([6,10]). Also, the magnitudes of our vibratory stimuli were well above threshold (~0.01 ms^{-2}; [13]) and always larger than that in [16]. Thus, the vibratory stimulus does not appear to be inadequate.

We therefore turn to the auditory stimulus. We used a narrowband noise for the free-field localization experiment and white noise for the headphone experiments. It is a commonly known fact that such stimuli are much easier to localize than pure tones (e.g., [11]). Thus, we need to consider the possibility that any potential effects of whole-body vibration were countered by relatively robust sound localization. Our motivation for using the noise stimuli was to test for effects of vibration on sound localization of more ecologically representative sounds. Future studies should look into this issue. However, if detrimental effects of vibration are only demonstrable for (low frequency) pure tones, than this is of theoretical but not practical interest.

6 Conclusion

Modern auditory interfaces increasingly rely on sound spatialization to display auditory information and warning signals around the listener. Because we often operate in environments that apply vibrations to the whole body, e.g., when driving a vehicle, there is a concern that vibrations might impair spatial hearing, which in turn could inadvertently affect the efficacy of sound spatialization. Because we were unable to find any detrimental effects of vibration on sound localization we conclude that such concerns are not warranted.

Acknowledgments

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