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# Vibrotactile – auditory interactions are post-perceptual

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**Abstract.** Vibrotactile stimuli can elicit compelling auditory sensations, even when sound energy levels are minimal and undetectable. It has previously been shown that subjects judge auditory tones embedded in white noise to be louder when they are accompanied by a vibrotactile stimulus of the same frequency. A first experiment replicated this result at four different levels of auditory stimulation (no tone, tone at detection threshold, tone at 5 dB above threshold, and tone at 10 dB above threshold). The presence of a vibrotactile stimulus induced an increase in the perceived loudness of auditory tones at three of the four values in this range. In two further experiments, a 2-interval forced-choice procedure was used to assess the nature of this cross-modal interaction. Subjects were biased when vibrotaction was applied in one interval, but applying vibrotaction in both intervals produced performance comparable to conditions without vibrotactile stimuli. This demonstrates that vibrotaction is sometimes ignored when judging the presence of an auditory tone. Hence the interaction between vibrotaction and audition does not appear to occur at an early perceptual level.

## 1 Introduction

Anecdotally, when a vibrotactile stimulus is applied to the fingertip it may produce the sensation of hearing a tone of the same frequency. Indeed, observers often report that they are 'hearing' the vibrotactile actuator, and are surprised to find that this sensation disappears when they remove their fingertip. The auditory experience that accompanies a vibrotactile stimulus suggests that early sensory representations corresponding to both modalities are being activated by a single-modality stimulus.

Alternatively, the apparent auditory experience may not be a bona fide perceptual experience, but a response bias induced by the demand characteristics of the task. In most perceptual tasks, subjects are asked to report the occurrence of a target experience, in this case an auditory tone. These reports are then compared between two different conditions, for example with and without the presence of a stimulus in a second modality, in this case a vibrotactile stimulus. If the threshold level of evidence at which subjects report that they have the target experience differs between conditions, then perceptual experience might appear to differ between conditions, when in fact only the criterion level as to what constitutes an experience has changed. Such changes in criterion are often called 'response bias', and are assumed to arise at a post-perceptual decision stage (Green and Swets 1966). Response bias is an important consideration in multisensory perception experiments. For example, a vibrotactile stimulus might influence auditory detection thresholds because it contributes to auditory experience, or because it influences a subject's willingness to admit that an experience has occurred. Only if the latter explanation based on response bias can be excluded can one conclude interaction between modalities in early sensory areas.

Brain-imaging, psychophysiological, and electrophysiological studies have suggested that various kinds of tactile stimuli can elicit early responses in cortical areas traditionally viewed as purely auditory, such as the auditory belt area (Foxe et al 2000, 2002; Fu et al 2003; Schurmann et al 2006). These studies show that an early sensory account of the effect of a vibrotactile stimulus on auditory perception is plausible. However, their correlational nature makes it difficult to infer that early auditory areas play a causal role in generating this specific illusion.

The auditory experience that accompanies a vibrotactile stimulus seems somewhat analogous to the percepts reported by synaesthetes. In these cases, stimuli such as monochromatic letters or numbers can give rise to a vivid perception of colour (Galton 1880; Hubbard and Ramachandran 2005). The distinction between perceptual and post-perceptual processes has been investigated extensively in synaesthesia. Behavioural and neuroimaging studies have shown that for many synaesthetes, letters or numbers elicit colour sensations that produce both early sensory effects (eg facilitate rapid visual search by causing a character to stand out) and activate extrastriate areas such as V4 that are associated with colour processing (Dixon et al 2000; Hubbard et al 2005; Sperling et al 2006). By analogy, when vibrotaction gives rise to an auditory percept, it seems plausible that some form of tactile – auditory sensory interaction is occurring, with a neural substrate capable of influencing the brain areas that give rise to the conscious perception of sound.

The example of synaesthesia demonstrates how brain-imaging data can be supplemented by psychophysical paradigms. However, psychophysical studies of the way tactile stimuli might affect auditory perception are scarce. Although in a few older studies the possible masking effects of auditory stimuli on tactile thresholds and vice versa have been investigated (Gescheider and Niblette 1967; Gescheider et al 1969), only one recent study has assessed specifically the effect of vibrotactile stimuli on auditory perception (Schurmann et al 2004).

Schurmann et al (2004) presented subjects with a reference tone embedded in white noise (200 Hz tone, 10 dB above detection threshold) and asked them to adjust the intensity of a subsequently presented probe tone to match this reference. This task was performed in two conditions: either with or without an additional vibrotactile stimulus of identical frequency presented synchronously with the probe tone. Subjects selected a lower intensity level with the addition of the vibrotactile stimulus (on average 12% lower), which suggests that this stimulus increased the perceived loudness of the probe tone.

Schurmann et al's (2004) result is consistent with the suggestion that a vibrotactile stimulus produces an auditory percept, as this illusory percept would be expected to sum with and therefore increase the perceived loudness of a real auditory stimulus. However, it is unclear whether the apparent increase in perceived loudness represents an early sensory interaction, or an interaction occurring in some later multisensory brain area (with unbiased information retained in early sensory areas). In order to address this issue, in experiment 1 we first replicated Schurmann et al's (2004) effect across a range of auditory stimulus intensities, including intensities very near to typical detection thresholds. In experiments 2 and 3, using a bias-free forced-choice procedure, we then tested whether vibrotaction affected auditory stimulus detection at threshold in a manner predicted by the apparent increase in perceived loudness. Our results suggest that the illusory sound percept produced by vibrotactile stimuli is not generated in early perceptual areas, as it does not always affect auditory detection in the same manner as an additional physical sound source.

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## 2 Experiment 1

In experiment 1 we sought to reproduce a vibrotactile enhancement of perceived auditory loudness. We also wanted to characterise the effect by measuring it across a range of baseline auditory intensities, including in the absence of any auditory stimulus and at detection threshold.

### 2.1 *Methods*

2.1.1 *Subjects.* Twelve subjects gave informed consent before taking part in the experiment (six male; mean age 24.8 years, SD = 3.6 years).

2.1.2 *Apparatus and stimuli.* The experiment was controlled by a PC producing auditory and vibrotactile stimuli at 44100 Hz with the use of a 12 bit A/D card (National Instruments DAQCard 6715). Vibrotactile stimuli were 120 Hz sinusoids presented for 1 s. They were delivered via a vibrator (101 vibrator driven by PA25E amp: Ling Dynamic Systems). The vibrator was housed in a sound-proofed box to dampen the subtle noise it made. Subjects sat comfortably, with their left arm inserted into an opening in the side of the box in order to contact the vibrator with the distal phalanx pad of their left index finger. The amplitude of the vibration was approximately 34 dB above 75% detection threshold [measured for one author only (KY) on the basis of a 2-interval forced-choice procedure]. Auditory stimuli were 120 Hz pure tones embedded in white noise, also presented for 1 s. These were presented via two small speakers (one for the pure tone and one for the white noise) placed on top of the box that held the vibrator (in order to maintain approximate spatial congruence between the auditory and tactile stimuli) at a distance of ~50 cm from the subject's head. White noise was produced on each trial by generating random voltages from a uniform distribution [−0.5 to 0.5 V, 0.29 V root mean square (RMS)]. White noise and background noise summed to 71 dBA, measured at the location of the subject's head. Four different standard tone intensities were used: no tone; a near threshold tone (equivalent to an RMS voltage of 0.495 V delivered to the speaker); 5 dB above threshold (this dB value is based on voltage applied to the speaker; 0.877 V RMS); and 10 dB above threshold (1.563 V RMS). We present our results in terms of voltages applied to the speakers; speaker output was approximately linear within our voltage range.

2.1.3 *Design.* A two-factor (2 × 4) repeated-measures design was employed. The first factor, tactile stimulation, compared trials in which the vibrotactile stimulator was touched to those in which the participant's finger was not in contact with this device. The second factor, auditory intensity, compared four different standard tone intensities (no tone, threshold tone, +5 dB, and +10 dB). Each trial consisted of two presentation intervals (see procedure below). Subjects completed 50 trials from each condition, divided into 25 intervals with the standard interval presented first and 25 trials with the standard interval presented second. Trials containing different auditory intensities were pseudo-randomly interleaved into two blocks of 200 trials each. Tactile stimulation occurred in only one of these two blocks, with block order counterbalanced across subjects.

2.1.4 *Procedure.* Each trial consisted of two 1 s stimulus intervals, separated by a gap of 500 ms. One interval was the standard interval, and the other the comparison interval. In the tactile stimulation block, the standard interval contained white noise, an auditory tone selected from one of the four possible standard intensities (including no tone), and a vibrotactile buzz to the index finger. In the block without tactile stimulation, subjects removed their finger from the vibrator and let it hang freely. The vibrator still activated in the standard interval, in order to make sure that differences between the conditions did not depend upon auditory transmission from this source, but it was not touched. In both kinds of block, the comparison interval contained white noise and an auditory tone. Subjects indicated which interval contained the stronger tone to an experimenter, who entered their response into the computer. The comparison tone varied in intensity from trial to trial. It was selected randomly on each trial from a condition-specific distribution (one for each standard auditory intensity). Each distribution was initially uniform, but was updated after each accepted trial according to the generalised P'olya urn model (Rosenberger and Grill 1997, $k = 8$). This procedure produces many values close to the point of subjective equality (PSE). For the four standard auditory-intensity conditions (no tone, 0.495 V RMS, 0.877 V RMS, and 1.563 V RMS), distributions covered the region 0 to 2.121 V, 0 to 2.121 V, 0 to 2.121 V, and 0.141 to 2.970 V RMS, in increments of 0.106 V, 0.106 V, 0.106 V, and 0.141 V RMS, respectively.

2.1.5 *Analysis.* The proportion of times a subject judged the comparison stimulus to be louder for each auditory intensity value that had been presented as a comparison was determined separately in each condition. Cumulative Gaussian psychometric functions were fitted to these data with the psignifit toolbox version 2.5.6 for Matlab (see http://bootstrap-software.org/psignifit/), which implements the maximum-likelihood method described by Wichmann and Hill (2001). PSEs were estimated from these functions. These were the auditory intensity value where the louder judgment occurred with a probability of 0.5. Just noticeable differences (JNDs) were estimated as the difference between the auditory intensity value where the louder judgment occurred with a probability of 0.75 and the PSE.

### 2.2 *Results*

Figure 1 shows the mean proportion of trials (across all participants) in which subjects judged the comparison stimulus to be louder than the standard stimulus, for each experimental condition. The best-fitting cumulative Gaussians are also displayed. Cumulative Gaussians appear to provide a reasonable fit in most cases. One possible exception is the 0 V standard condition in which the vibrator was not being touched. Here, the proportion of trials judged louder appears to begin at a plateau of 0.5 for low-intensity comparison stimuli, then rise sharply at a little under 0.5 V RMS. This would be consistent with no tone being perceived in the standard stimulus interval. Performance would be expected to be at chance in this condition below an absolute detection threshold, as neither the standard nor the comparison stimuli could be detected. A cumulative Gaussian that assumes initial performance at 0.5 is displayed in this condition for comparison. The threshold (0.495 V RMS) standard condition with no vibrator contact also seems to deviate slightly from the pattern found in other conditions. In this condition, even with a comparison stimulus of 0 V, subjects still occasionally judged this stimulus to be louder than the standard (with a probability of just under 0.2). This observation is also to be expected, as subjects would have occasionally failed to detect the standard stimulus (which was near threshold) and therefore been forced to guess when the comparison stimulus was also very weak (ie below threshold).

Figure 2 summarises the PSE data from figure 1, showing the mean auditory intensities judged equal to the four different standard intensities with and without vibrotactile stimulation. To generate these data points, curves were fitted and PSEs determined for each subject separately in each condition before averaging (whereas figure 1 shows curves fitted to the data points pooled across all subjects). When the vibrator was not being touched, subjects were quite accurate in judging whether a comparison stimulus was more or less intense than the standard. Hence PSEs were fairly similar to actual stimulation intensities. However, when a vibrotactile stimulus was delivered alongside the standard, subjects judged substantially louder comparison tones to be of equal intensity to the standard.

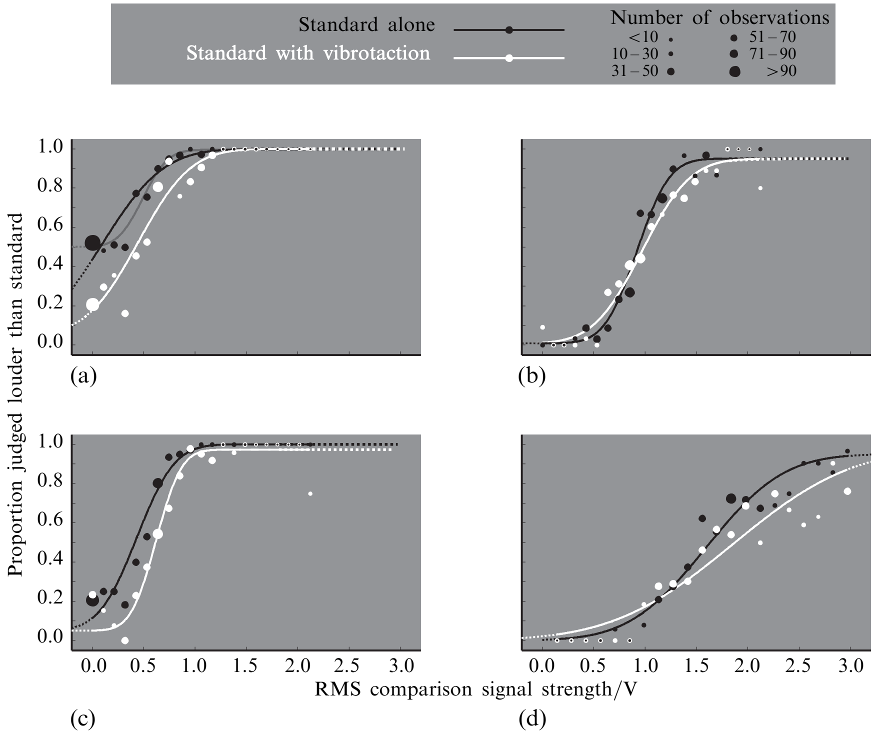

**Figure 1.** Psychometric functions in experiment 1, determined for four intensities of a standard auditory stimulus embedded in a constant level of white noise and accompanied by a vibrator: (a) 0 V RMS; (b) 0.877 V RMS; (c) 0.495 V RMS; and (d) 1.563 V RMS. Data are shown separately for blocks in which the vibrator was touched or not touched. Psychometric functions shown in black/white were constrained to start between 0 and 0.05 and end between 0.95 and 1.00. In the 0 V intensity condition, for the block in which the vibrator was not being touched, an additional (grey) function is plotted, constrained to start at 0.5.

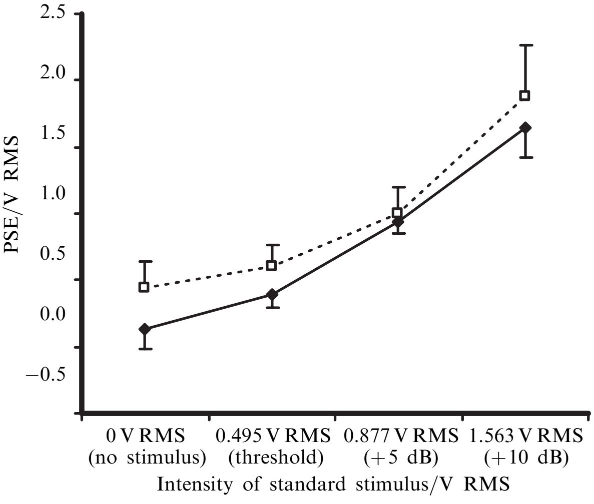

**Figure 2.** Points of subjective equality (PSEs) in experiment 1, determined for four intensities of a standard auditory stimulus embedded in a constant level of white noise and accompanied by a vibrator. Data are plotted separately for blocks in which the vibrator was touched or not touched. Error bars denote standard deviations.

To assess baseline biases without tactile stimulation, PSEs for each standard intensity were compared to the relevant standard voltage with a one-sample $t$-test. Reliable differences emerged in the no-signal condition (mean PSE $= 0.137$ V, $t_{11} = 2.98$, $p = 0.013$) and with standard intensities of 0.495 V (mean PSE $=$ 0.392 V,

$t_{11} = -3.41$, $p = 0.006$) and 0.877 V (mean PSE = 0.944 V, $t_{11} = 2.48$, $p = 0.03$), but not with a standard intensity of 1.563 V (mean PSE = 1.640 V, $t_9 = 1.23$, $p = 0.244$).

To compare conditions with and without tactile stimulation, a two-factor ($2 \times 4$) repeated-measures ANOVA was employed. The ANOVA showed a reliable main effect of tactile stimulation ($F_{1,11} = 13.89$, $p = 0.003$) and the predictable main effect of auditory intensity ($F_{2,20} = 271.72$ Greenhouse – Geisser corrected, $p < 0.001$), but also an interaction ($F_{2,17} = 4.67$ Greenhouse – Geisser corrected, $p = 0.033$). The interaction was explored with a posteriori paired $t$-tests, which indicated that PSEs were significantly greater in the touch than in the no-touch conditions at standard intensities of 0 V [$t_{11} = 5.06$, $p < 0.001$; individual trend (PSE touch > PSE no touch) in eleven out of twelve subjects], 0.495 V ($t_{11} = 3.59$, $p = 0.004$; individual trend in eleven out of twelve subjects), and 1.563 V ($t_{11} = 2.55$, $p = 0.027$; individual trend in nine out of twelve subjects), but not with a standard intensity of 0.877 V ($t = 0.92$, ns; individual trend in seven out of twelve subjects).

We also determined JNDs in each of the eight conditions, although these data were not analysed further. For the conditions without tactile stimulation, JNDs were lowest with a standard intensity of 0.877 V (0.228 V) and highest with a standard intensity of 1.563 V (0.563 V). JNDs in the 0 V and 0.495 V conditions fell between these values (0.380 and 0.293 V, respectively). For the conditions with tactile stimulation, JNDs again rose as the suprathreshold standard intensity increased from 0.877 V (0.326 V) to 1.563 V (0.752 V) but this time subthreshold and threshold intensity conditions yielded lower JNDs (0 V JND = 0.303 V; 0.495 V JND = 0.173 V).

### 2.3 *Discussion*

Across three out of four of the values tested, the presence of vibrotaction led subjects to perceive auditory tones as significantly louder than in the absence of vibrotaction. This was true even when no standard tone was being presented at all. Hence experiment 1 is broadly consistent with the idea that the vibrotactile stimulus effectively adds-in the percept of an auditory tone which sums with any physically present tone. Our +10 dB condition used approximately the same auditory intensity as Schurmann et al (2004), although our vibration delivery system was different and slightly stronger. Schurmann et al reported a decrease in matched intensity from auditory plus vibrotactile stimulation to auditory stimulation alone of 12%. Our data are comparable, with a decrease of 13% in this condition.

Small biases were evident in our data when no vibrotactile stimulus was being presented, and may have resulted from the sound energy produced by the vibrator despite our attempts to shield it. Although no subjects reported being able to hear the vibrator during pre-experimental demonstrations, their ability to detect it was not formally assessed. However, the fact that this bias reversed in the 0.495 V condition suggests other explanations more specific to the particular standard intensities being tested. While the statistical explanations presented in the following paragraphs may seem to lack parsimony, they will be bolstered by a failure to find any evidence for auditory transmission from our vibrotactile stimulus in experiment 2.

As noted in the results section, a positive PSE is actually predicted in the 0 V condition if we assume an absolute threshold for perception of our stimulus. The absolute threshold is best determined by fitting a curve that spans probability values from 0.5 to 1.0, and determining where it first deviates from 0.5. Fitting the data with a curve that spans probability values from 0 to 1.0 as we did would be expected to yield a value somewhere between zero and this threshold value, as the curve should reach a probability of 0.5 at approximately the midpoint of the various below-threshold values that were tested.

Similar considerations apply to the threshold (0.495 V) standard condition without tactile contact. Given an absolute perceptual threshold, we would expect the psychometric function to start at some low but non-zero probability (reflecting that subjects were guessing on those trials where the standard stimulus was not perceived) and rise from there. In this case, fitting with a curve that spans the range from 0 to 1.0 (or thereabouts—our curves actually contained guessing parameters, so were free to start as high as 0.05 and finish as low as 0.95) would tend to mean that the functions will start to rise slightly too early, pulled by the initial non-zero probabilities. This would explain why the derived PSE was slightly below the value presented as a standard.

Finally, for the two suprathreshold conditions, fitting a symmetrical cumulative Gaussian would be expected to introduce a small bias into the estimated PSE. According to Weber's law (Fechner 1860), the JND between two suprathreshold stimuli is expected to rise with the magnitude of those stimuli. This law is evident in our JND data: we found that the JND was higher for the +10 dB condition than for the +5 dB condition, evident in the shallower slopes displayed in figure 1. Weber's law implies that the intensity difference between the 0.5 probability value (the PSE) and a higher probability value (eg the 0.75 point) will be greater than the difference between the 0.5 probability value and the equivalent lower probability value (eg the 0.25 point). By fitting with a symmetrical function (where these two differences must be identical) we are likely to slightly overestimate the true PSE. This small bias may have been more detectable in the 0.877 V standard condition, where the data were less noisy.

These considerations suggest that results in the non-contact conditions need to be interpreted with some caution. However, contact with the vibrator did appear to have an effect over and above its possible role as an auditory source. PSEs were always substantially higher in the tactile-contact conditions than in the non-tactile conditions, and were also higher than the standard stimulus intensities that were being matched. One concern in both our experiment and that of Schurmann et al (2004) is that this apparently tactile effect might in fact be the result of bone conductance of the vibrator's signal to the eardrum. Although not specifically designed to do so, our later experiments will rule out this possibility.

Although we found an effect of vibrotactile contact on auditory PSEs for three out of four intensities of the standard stimulus, no significant difference emerged with tactile contact in the conditions with the 0.877 V standard stimulus. Our JND data indicate that subjects performed well in this condition. The failure to obtain a difference here raises a note of caution about interpreting the effect of the vibrotactile stimulus as being equivalent to that which would be produced by a real auditory stimulus. We return to this point in section 5, in the light of our subsequent experiments.

Having replicated and extended the result of Schurmann et al (2004) using a subjective paradigm, we next tested whether the same vibrotactile stimulus would affect auditory detection thresholds with a bias-free 2-interval forced-choice procedure. Weber's law states that the ability to discriminate a constant change in stimulus intensity differs depending upon the baseline (or pedestal) level of the signal (Fechner 1860). A 'near miss to Weber's law' has been observed for auditory tones embedded in noise (Neff and Jesteadt 1996; Schlauch et al 1995); for suprathreshold stimuli, the JND generally increases with pedestal intensity, but there is better relative discrimination at higher intensity levels, and JNDs at low intensities may be smaller than the detection threshold itself. This pattern is broadly confirmed by our own data from conditions without tactile contact: for suprathreshold stimuli, the JND increased with pedestal intensity (from +5 to +10 dB) but JNDs were also higher for subthreshold (0 V) and threshold stimuli than for low-intensity suprathreshold stimuli (+5 dB). Our own and previous data therefore indicate that a given intensity difference between two suprathreshold tones will be more difficult to detect when both tones are incremented by an additional tone at the same frequency. When one or both of the original tones are subthreshold, detection rates are again likely to be affected by the addition of a pedestal, but the direction of the change is more difficult to predict, and will depend on the size of the pedestal. These factors allow us to make predictions about the likely effect of an additional vibrotactile stimulus in a two-interval forced-choice task. If the vibrator elicited a neural response in auditory areas identical to that produced by a real auditory tone, then we ought to see a change in detection rates when we compare the discrimination of a threshold tone from no tone, with the discrimination of the same two stimuli boosted by a touch-induced illusory auditory percept.

## 3 Experiment 2

### 3.1 *Methods*

3.1.1 *Subjects.* Eight subjects, including one author (KY) and two subjects who had participated in experiment 1, took part in the experiment (four male, mean age = 29.0 years, SD = 5.5 years).

3.1.2 *Apparatus and stimuli.* The apparatus was identical to that used in experiment 1. Stimuli were also identical, with the exception of the intensity of the auditory tone embedded in noise (see below).

3.1.3 *Design.* A two-factor ($2 \times 3$) repeated-measures design was employed. The first factor, tactile contact, compared trials in which the vibrotactile stimulator was touched to those in which the participant's finger was not in contact with the device. The second factor, vibration, compared trials in which no vibration was delivered with those in which vibration was delivered in either both intervals (double stimulation) or in just one of the two intervals (single stimulation). In the latter case, an equal number of trials was presented where the tactile stimulation occurred in either the target or the non-target intervals. Subjects completed 52 trials from each condition, divided into 26 intervals with the target interval presented first and 26 trials with the target interval presented second. Trials containing different kinds of vibration were pseudorandomly interleaved into two blocks of 156 trials each. Tactile stimulation occurred in only one of these two blocks, with block order counterbalanced across subjects.

3.1.4 *Procedure.* Before starting the main experiment, subjects completed two runs of a one-up, two-down staircase in order to establish their 71% threshold for detecting the auditory stimulus. Each trial consisted of two 1 s intervals separated by 0.5 s. One interval contained white noise, and the other contained white noise plus an auditory tone, with this 'target' interval selected randomly on each trial. Subjects judged which interval contained the tone. The staircase controlled the intensity of the tone; intensity was raised after an incorrect response and lowered after two consecutive correct responses. The staircases could present stimuli with RMS voltages in the range 0.007 V to 0.849 V. The first staircase started from an easily detectable value (0.849 V RMS) and the second staircase began with virtually no signal in the target interval (0.007 V). The step size of the staircases was initially 0.141 V RMS, but was halved every two reversals. The staircases terminated after eight reversals, with the midpoint of the final two reversals taken as an estimate of the subject's detection threshold. Estimates from the two staircases were then averaged and used in the main experiment.

The same two-interval forced-choice procedure was used in the main experiment, but all target intervals contained tones presented at the subject's individual threshold intensity, as determined from the staircases. Hence each trial contained one interval containing only white noise, and one interval containing white noise plus a threshold tone (the target). Subjects had to indicate which interval was the target interval.

The order of the target interval (first or second) was counterbalanced within each condition (see section 3.1.3). Depending on the experimental condition within each block, the vibrator was either not activated in either interval, activated in both intervals, or activated in just one of the two intervals. Depending on the experimental block, the vibrator was either touched or no contact was made. The dependent variable was the percentage of correct discrimination.

### 3.2 *Results*

The mean threshold value determined from the staircases and presented in target trials was 0.483 V RMS ($SD = 0.131$ V). This was very similar to the threshold value used in experiment 1 (0.495 V).

Figure 3 shows the percentage of correct discrimination scores for the different experimental conditions. The left part of the figure shows differences between the three types of vibrotactile stimulation in blocks with and without vibrator contact. In general, performance was slightly worse in the block in which the vibrator was being touched. However, the critical comparisons are between the three conditions within this block. Figure 3 shows that there is little difference in discrimination performance between trials with no tactile stimulation and trials with tactile stimulation in both intervals, or indeed between these conditions and trials where the tactile stimulus is applied in just one of the two intervals. Performance is also comparable in all conditions when the vibrator was not touching the skin. However, to better understand the effect of the vibrator in the single-interval stimulation condition, in the right-hand side of figure 3 performance in trials where the vibrotactile stimulus occurred during the target interval (congruent trials) is plotted separately from trials where this stimulus occurred in the noise-only interval (incongruent trials). A large difference is now evident, suggesting that when a single vibrotactile stimulus was delivered in just one of the two intervals, it strongly biased subjects to select that interval as the target interval.

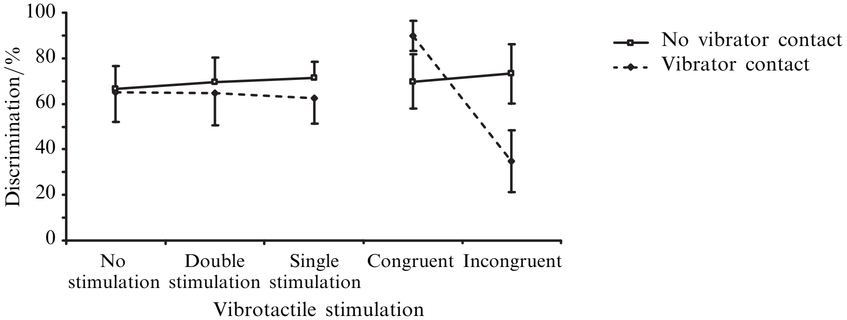

**Figure 3.** Discrimination scores in the 2-alternative forced-choice signal-detection task used in experiment 2. The left-hand side of the figure shows performance with a vibrator activated in neither, one, or both intervals, plotted separately when it was touched or not touched. The right-hand side of the figure shows data from the single-interval vibration condition separately for trials where the vibration accompanied the signal (congruent) or the noise (incongruent). Error bars show standard deviations.

These observations were investigated statistically. A 2 × 3 repeated-measures ANOVA on the data shown in the left part of figure 3 showed no significant differences between conditions (for tactile contact, $F_{1,7} = 1.75$, $p = 0.227$; for vibration: $F_{2,12} = 0.29$ Greenhouse–Geisser corrected; for the interaction: $F_{1,9} = 1.37$ Greenhouse–Geisser corrected, $p = 0.285$). Hence the ANOVA provided no justification to further investigate the theoretically important comparison between the no-stimulation and double-stimulation conditions with tactile contact. Mean discrimination scores differed by only 0.2% between these two conditions, with four subjects showing a drop in performance, three showing a rise, and one showing identical performance. Note that for this sample, power was 0.8 to find a real difference as small as 4% between these two conditions.

For the data on the right hand side of figure 3, a $2 \times 2$ repeated-measures ANOVA showed a significant main effect of tactile contact ($F_{1,7} = 8.60$, $p = 0.02$), a significant main effect of congruence ($F_{1,7} = 38.96$, $p < 0.001$), and a significant interaction between them ($F_{1,7} = 112.59$, $p < 0.001$). Repeated-measures $t$-tests confirmed the apparent difference between congruent and incongruent trials in the single stimulation conditions with tactile contact. A difference emerged with tactile contact ($t_7 = 9.95$, $p < 0.001$; trend evident for all eight subjects) but not without it ($t_7 = 0.778$, ns; four subjects improved in the congruent condition, three got worse, and one showed an identical performance).

### 3.3 *Discussion*

When a vibrotactile stimulus was delivered in one of two intervals, subjects were strongly biased to respond that a threshold auditory tone had also been presented in that interval. However, when the vibrotactile stimulus was delivered in both intervals, performance was unaffected compared with the same judgment made without any vibrotactile stimulus being delivered. The single-stimulus result is straightforwardly consistent with the results from experiment 1. The vibrotactile stimulus appears to induce an illusory auditory percept which causes subjects to judge that a tone was presented in that interval. However, the double-stimulus result suggests strongly that this illusory percept does not occur in early sensory areas. Had it done so, the effect of the vibrotactile stimulus should have been basically identical to the effect of adding a real auditory tone in both intervals. Because the ability to detect a difference between two signals depends upon the strength of the weaker signal (Weber's law), we would expect differences in discrimination rate to arise as a result of this change, but such a difference was not observed. This was despite the fact that the experiment had sufficient power to detect a difference of only 4%.

In the no-contact conditions, we found very similar discrimination rates, regardless of whether the vibrator was active in neither, one, or both intervals. Hence there was no evidence for auditory transmission from this source. It is therefore unlikely that auditory transmission occurred in experiment 1, which used the same vibrotactile stimulus. We have already discussed alternative accounts of the biases obtained in the no-touch conditions of that experiment.

In discussing experiment 1, we also alluded to the possible role of bone conductance in generating the changes in the mean PSEs we observed when the vibrator was touched. Bone conductance might also account for the bias observed here in the single-stimulation condition with vibrator contact. However, our failure to find a difference between the no-stimulation and double-stimulation conditions rules out this explanation. Transmission via this route would be expected to exactly mimic the effect of a real auditory stimulus, and thus affect discrimination in the double-stimulation condition as previously discussed.

Our main conclusion from experiment 2 is based on the assumption that discrimination rates would have been different for no-tone versus threshold-tone discriminations compared to discriminating between two higher auditory intensities produced by adding a tone in both intervals. However, we have not mapped out discrimination rates for our tone in noise stimuli with a wide range of pedestal auditory intensities, and can only be guided by the JND results from experiment 1, along with previous reports detailing the detection thresholds for pure tones or pure tone increments in noise (eg Neff and Jesteadt 1996; Schlauch et al 1995). Furthermore, it is possible that the vibrotactile stimulus does not simply add a constant illusory tone, but rather that the interaction is more complex, depending on the level of the real auditory tone that is being supplemented, as suggested by experiment 1. These considerations are important because our conclusion depends upon a negative result (no difference between the no-stimulation and double-stimulation conditions). It is possible that the vibrotactile stimulus did produce neural activity in early sensory areas equivalent to that produced by a real tone, but just by chance; the illusory percepts that were created were approximately as difficult to discriminate as a no-tone/threshold-tone pair.

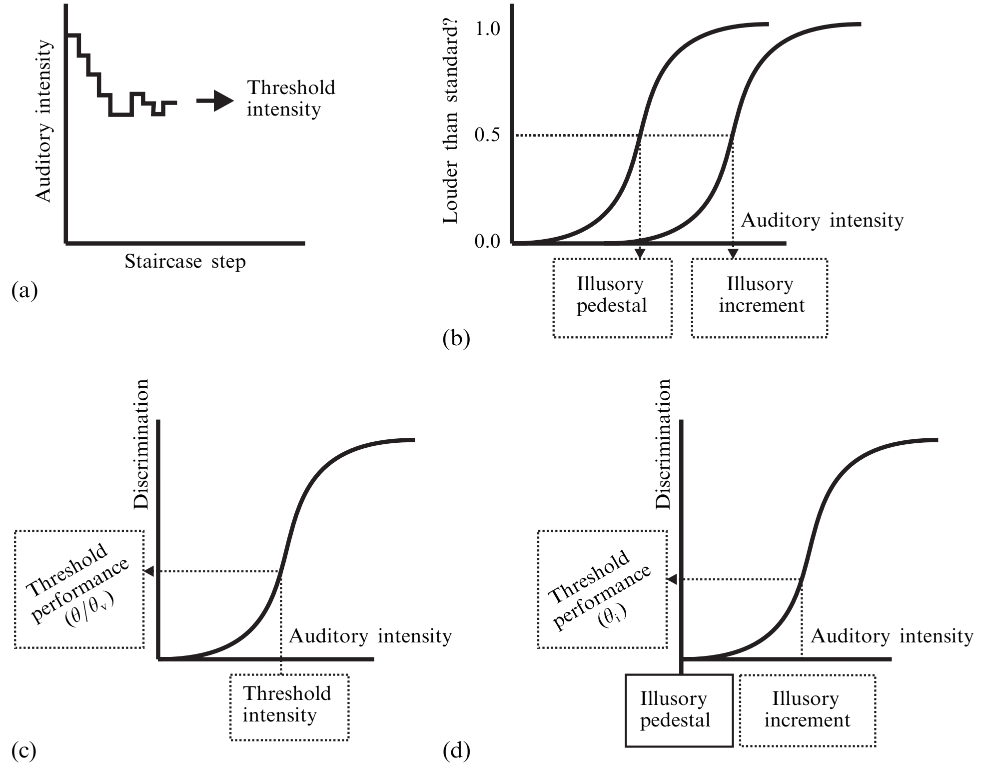

**Figure 4.** Schematic of the method/logic applied in experiment 3. (a) Threshold intensity is determined for each subject by using a staircase. (b) A subjective procedure is used to estimate the auditory intensity that is perceived equal to a vibrotactile stimulus (the illusory pedestal) and the intensity perceived equal to the vibrotactile stimulus plus a threshold tone (the illusory increment) for each subject. (c) A 2-alternative forced-choice procedure is used to estimate discrimination between two intervals, one of which contains a tone. This discrimination function is measured with and without concurrent vibrotaction. The figure shows a typical discrimination function. We can use the discrimination functions to read off the percentage correct scores at the intensity value previously estimated in (a) to be the detection threshold. This score measures our subjects' ability to discriminate white noise from a threshold tone. These scores are compared between conditions with and without vibrotaction. (d) An illusory-pedestal discrimination function is determined when detecting a tone increment against a pedestal value based on subjective estimates of the effect of vibrotaction. We can now directly compare the threshold performance obtained with and without vibrotaction ($\theta_v$ and $\theta$, respectively) to that obtained from our illusory-pedestal function ($\theta_i$). The appropriate comparison is with the point on the illusory-pedestal function where the increment in auditory intensity is equal to the difference between the illusory percept with or without a threshold tone. If the vibrotactile stimulus affects early sensory areas like a real tone would, we expect $\theta_i$ to equal $\theta_v$ but to differ from $\theta$. Alternatively, if the effects of vibrotaction are post-perceptual, we expect $\theta_v$ to equal $\theta$, but $\theta_i$ to differ from both.

For this reason, we performed a final experiment in which we again compared discrimination performance in a no-stimulation condition and in a double-stimulation condition. However, we now added a further condition designed to mimic the illusory auditory percept implied by the use of a subjective method like that employed in experiment 1. We wished to demonstrate that the vibrotactile stimulus should have affected performance in the double-stimulation condition if it influenced early sensory representations like a real tone, but failed to do so. Our approach was as follows. We determined the 71% detection threshold for each subject. Next, we assessed for each subject the illusory effect of the vibrator in two different conditions. First, we determined the tone intensity that seemed equivalent to vibrotaction alone. Then we determined the extent to which vibrotaction increased the perceived intensity of a tone that was detected with 71% probability when presented alone. We termed the lower of these values our illusory pedestal, meaning the level of apparent auditory stimulation attributable to vibrotaction. We then proceeded to measure three auditory intensity discrimination functions. The first compared white noise to white noise plus a tone of varying intensity. The second was identical to the first, but included a vibrotactile stimulus in both intervals. The third compared white noise plus our illusory pedestal to the identical stimulus plus a further tone increment.

If the vibrotactile stimulus does not influence early sensory representations of our auditory stimuli, the auditory intensity discrimination functions should be identical in the no-vibrotaction and double-vibrotaction conditions. However, as we have already seen, this negative result would not be conclusive on its own. The possibility remains that the discrimination function produced when a tone is compared to no tone happens to be the same as that produced when stimuli that are perceptually identical to mixtures of tones and vibrotaction are compared to a stimulus that is perceptually identical to vibrotaction alone. Comparing threshold performance estimates derived from no-vibrotaction and vibrotaction discrimination functions with performance at the appropriate point on the illusory pedestal discrimination function will allow us to reject this possibility. The logic of this comparison is schematised in figure 4.

## 4 Experiment 3

### 4.1 *Methods*

4.1.1 *Subjects.* Nine subjects were tested, but one was rejected because fits to his data implied a negative PSE in the initial section of the experiment (see below), precluding the estimation of an illusory pedestal function in the second part of the experiment. Hence data from eight subjects were analysed (six male, mean age = 29.9 years, SD = 4.29 years). These included four subjects who had participated in either experiment 1 or experiment 2.

4.1.2 *Apparatus and stimuli.* The apparatus was identical to that used in experiment 1. Stimuli were also identical, with the exception of the intensity of the auditory tone embedded in noise (see below).

4.1.3 *Design.* The experiment consisted of two parts, both employing a single-factor repeated-measures design. The first part of the experiment had two conditions, which differed in the intensity of the standard tone (no tone versus 71% threshold). Subjects completed 80 trials from each condition: 40 trials with the standard interval presented first and 40 trials with the standard interval presented last. Trials from different conditions were pseudo-randomly interleaved into a single block of 160 trials.

The second part of the experiment had three conditions. The first two conditions (no stimulation and double stimulation) differed in the presence or absence of a vibrotactile stimulus (presented in neither interval or in both intervals, respectively). The third, illusory-pedestal, condition mimicked the implied effect of vibrotaction in the first part of the experiment. In this condition there was no vibrotactile stimulation, but a pedestal tone was added to both intervals. Subjects completed 100 trials from each condition: 50 intervals with the standard interval presented first and 50 trials with the standard interval presented last. Trials from different conditions were pseudo-randomly interleaved into a single block of 300 trials.

4.1.4 *Procedure.* Initially, the 71% detection threshold was determined for each subject by averaging the results of one ascending staircase and one descending staircase, with the staircase procedure described in experiment 2. The first part of the experiment was similar to experiment 1. In the first condition, the standard interval contained white noise and a vibrotactile stimulus. In the second condition, it additionally contained a pure tone at 71% threshold intensity. In both conditions, the comparison interval contained white noise plus a tone of variable intensity. Tone intensities were selected randomly on each trial from adaptive distributions containing values from 0 V to 1.414 V in increments of 0.071 V RMS. Subjects were instructed to ignore the vibrotactile stimulus and to judge which interval contained a more intense tone.

In the second part of the experiment, the standard interval contained white noise (no-stimulation or double-stimulation conditions) or white noise with a pedestal tone (illusory-pedestal condition). In the double-stimulation condition, the comparison interval also contained a vibrotactile stimulus. In the illusory-pedestal condition, the intensity of the pedestal was determined by the data from the first part of the experiment, and was set as the lower of the two values judged equal to the standard stimuli in the two conditions described above (0 V and 71% threshold standard tone intensities, with vibrotaction).

For all three conditions, the comparison interval contained white noise plus a tone of variable intensity. Ten different tone intensities were tested, with 10 trials at each intensity (method of constant stimuli). The bottom three intensities were 0 V, 0.057 V, and 0.106 V RMS. The top two intensities were 0.707 V and 1.061 V RMS. The remaining central values were individually selected for each subject so as to closely surround their 71% detection threshold. In the illusory-pedestal condition, these intensities were added to the pedestal used in the standard interval. In the double-stimulation condition, the comparison interval also contained a vibrotactile stimulus. Subjects were told to ignore the vibrotactile stimuli on those trials in which they occurred, and judge which interval contained the more intense tone.

### 4.2 *Results*

Figure 5 shows the mean proportion of trials (across all participants) in which subjects judged the comparison stimulus to be louder than the standard stimulus, for each experimental condition. The best-fitting cumulative Gaussians are also displayed. Figure 5a shows data from the first part of the experiment, in which the comparison stimulus was being compared to a vibrotactile stimulus (with or without an additional 71% threshold tone). As in experiment 1, subjects were biased, as though the vibrotactile stimulus appeared tone-like in quality. This was mainly evident in the condition where the standard interval contained no actual tone. Here the vibrotaction was nevertheless judged equivalent to a tone of 0.422 V intensity (one-sample $t$-test against 0 V, $t_7 = 5.45$, $p = 0.001$; PSEs $> 0$ V for all eight included subjects, but one subject excluded with a negative PSE). Note that in this condition, unbiased performance would have begun at around 0.5. In the second condition, a 71% threshold tone (mean intensity 0.417 V) was judged on average equal to a tone of 0.446 V ($t_7 = 0.661$, ns; PSEs $>$ 0.417 V for three out of eight subjects).

Figure 5b shows the mean discrimination performance in two of the three conditions tested in the second part of the experiment (the no-stimulation and double-stimulation conditions, in which the standard interval contained only white noise and the vibrator

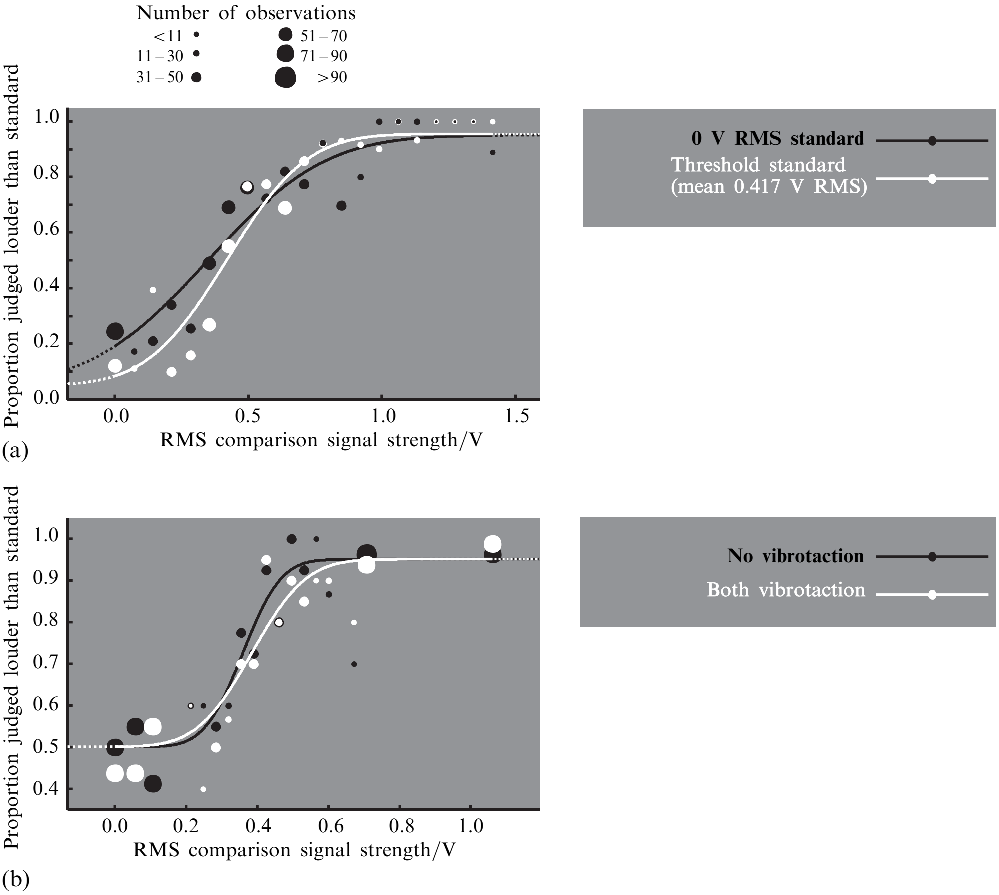

**Figure 5.** Psychometric functions from experiment 3. (a) The two conditions in the subjective task, in which the vibrotactile stimulus was active in one interval (either alone or with an individually determined 71% threshold stimulus) and was compared to an auditory tone of varying intensity. (b) Data for the no-vibrotactile-stimulation and double-vibrotactile-stimulation conditions of the objective task.

was either not used, or was applied in both conditions). It is immediately apparent that performance was very similar in the two conditions, in line with the results of experiment 2. The mean 75% discrimination threshold was 0.394 V in the no-stimulation condition, and 0.424 V in the stimulation condition. These values did not differ from each other significantly ($t_7 = 1.382$, $p = 0.209$; stimulation threshold > no-stimulation threshold in six out of eight subjects). Mean slopes, measured as the difference between the 58th and 92nd percentiles for each subject, were also similar (0.121 for no stimulation, 0.112 for double stimulation), with no significant difference emerging ($t_7 = 0.246$, ns; stimulation slope > no-stimulation slope in three out of eight subjects, identical in one subject).

In order to conclusively determine the nature of the illusory effect of the vibrotactile stimulus, we used our fitted sigmoids to determine performance for each subject in the no-stimulation condition at the 71% threshold intensity found previously with our staircase procedure. We compared this score with performance at the same intensity in the double-stimulation condition. We also compared it with performance in the illusory-pedestal condition, at an intensity increment equal to the difference between percepts for no stimulus and a threshold stimulus implied by the data from the first part of experiment 3. Mean scores were 83% in the no-stimulation condition, 77% in the double-stimulation condition, and 63% in the illusory-pedestal condition.

A single-factor repeated-measures ANOVA revealed a significant difference across conditions ($F_{1,9} = 5.34$ Greenhouse – Geisser corrected, $p = 0.034$). In follow-up $t$-tests, the no-stimulation estimate differed significantly from the illusory-pedestal estimate ($t_7 = 3.28$, $p = 0.013$; trend evident in seven out of eight subjects) but not from the double-stimulation estimate ($t_7 = 1.42$, $p = 0.199$; discrimination greater in no-stimulation condition for four subjects, with one subject showing no difference). For the latter comparison, power was $>0.99$ to detect a 20% drop in performance (equivalent to that obtained between the no-stimulation and the illusory-pedestal condition).

### 4.3 *Discussion*

Experiment 3 demonstrated once again that (i) a vibrotactile stimulus made white noise sound as if it contained a low-intensity pure tone stimulus (partially replicating the results of experiment 1) and that (ii) subjects were equally successful at discriminating an auditory stimulus in noise from noise alone whether or not both stimuli were accompanied by vibrotactile stimulation (replicating the results of experiment 2, and confirming that the slope of the discrimination function was also unchanged). Experiment 3 also went further, comparing directly performance with vibrotaction in both intervals and a threshold tone in just one interval with performance for two suprathreshold tones, presented at levels designed to mimic the effect of the vibrotactile stimulus as might be inferred for each subject based on data recorded only a few minutes earlier. This comparison addresses an alternative account of our failure to find a difference in detection rates between the no-stimulation and double-stimulation conditions of experiment 2; namely that the combined auditory percept produced by the vibrotactile and auditory stimuli in that experiment just happened to be exactly as hard to discriminate as a threshold tone and noise. When we attempted to mimic the illusory effect of vibrotaction, we found that discrimination performance dropped significantly, demonstrating that our experiment had enough power to detect such a change. If the vibrator had provided stimulation effectively identical to a tone, discrimination performance should also have declined greatly in the double-stimulation condition. However, this was not found. Hence, these data strongly support our previous inference that the vibrotactile stimulus is not producing a neuronal response similar to a real auditory tone. Vibrotaction is thus unlikely to be producing activity in early sensory areas. Of course, we could only estimate the illusory effect of vibrotaction based on the data from the first part of experiment 3, and these estimates will be imprecise to some extent. Hence, it is still possible that performance with and without vibrotaction did not differ because vibrotaction happened to produce two virtual stimulus levels that were exactly as difficult to discriminate as the noise-only versus threshold pairing. However, the results of experiment 3 make this possibility seem less likely.

## 5 General discussion

We carried out three experiments investigating how a vibrotactile stimulus affected auditory perception of tones at the same frequency. In experiment 1, subjects compared the intensity of two auditory tones embedded in white noise. The presence of a vibrotactile stimulus alongside an auditory standard caused subjects to judge a louder comparison tone to be equal in intensity to the standard tone, replicating and extending the results of Schurmann et al (2004). This bias was evident for three out of four different intensities of the auditory standard. Subjects were even induced to match a suprathreshold auditory tone to white noise alone when the white noise was accompanied by the vibrotactile stimulus. It is noteworthy, however, that the bias was most striking in the conditions of greatest uncertainty (with near threshold or relatively strong tones) and was absent in the condition where the comparison would be expected to be most precise (ie the +5 dB condition, which had the lowest JND). This result seems consistent with a possible response bias. In experiment 2, we employed a bias-free 2-interval forced-choice procedure in which subjects had to determine which of two intervals contained a tone. Performance was skewed when a vibrotactile stimulus appeared in just one interval, but was unaffected when this stimulus appeared in both intervals. This result is unexpected if the vibrotactile stimulus was simply acting like a second tone, adding to the strength of the real tone. In experiment 3 we replicated both results, and showed that the result of experiment 2 was not a fluke of the particular illusory auditory intensity levels added by the vibrotactile stimulus.

In information-processing terms, our data are compatible with an account that places the effect of the vibrotactile stimulus after the initial perceptual processing of auditory input has been carried out. Hence this effect might reasonably be considered a response bias, arising when a decision is made. Considered in terms of processing sites within the brain, the simplest account would be one in which auditory and vibrotactile stimuli are processed in their own sensory areas, with some higher-order area receiving from both unimodal regions. This higher-order area would both generate a conscious percept and form a decision. It is also possible, however, that a combined auditory – tactile representation is being formed in a secondary sensory area, such as the auditory belt area shown in recent studies to also represent somatosensory stimuli (Foxe et al 2002; Fu et al 2003; Schurmann et al 2006). In this case the decision area would typically consult this region but also have access to earlier sensory areas. The major constraint our data suggest is that a pure auditory representation capable of guiding precise comparisons must exist in some early brain region projecting to the site of the interaction with the vibrotactile stimulus. This representation might even be subcortical.

In our experiments we applied both subjective and objective methods to evaluate a sensory experience. We obtained a reliable effect of vibrotaction on auditory intensity only when using subjective methods, and not when using bias-free objective methods such as two-alternative forced choice. This pattern of results is consistent with response bias. Response biases are generally considered an inconvenient artifact that should be eliminated from study. However, we do not consider our results to be trivial. Indeed, we consider that a dissociation of this kind is just as theoretically interesting as an effect obtained with objective methods. Our response bias implies an important higher-order psychological process, in this case one that is experienced as a compelling percept of increased loudness. Disregarding such an effect seems rather like throwing out the baby with the bathwater.

Although the specific effect of vibrotactile stimuli on auditory perception has not been widely investigated, other studies have provided evidence for early bimodal sensory interactions with the use of different kinds of stimuli. In synaesthesia research, the locus of bimodal integration has been addressed in terms of the pre-attentive versus post-attentive nature of synaesthetic interactions. Although the heterogeneity of this unusual subject pool has led to some conflicting reports, it seems that at least some synaesthetic experiences arise quite automatically and at a pre-attentive stage of processing (Hubbard and Ramachandran 2005). This suggests that these experiences are being driven by early sensory activations, in line with results from brain-imaging studies (Sperling et al 2006). Interactions between bisensory stimuli in normal subjects are rather less compelling than in those with synaesthesia in terms of their subjective quality. Nonetheless, a number of studies have yielded results compatible with early sensory interactions between stimuli from two sensory modalities. For example, the presence of a light can make white noise sound louder (Odgaard et al 2004) and improve detection of threshold stimuli (Lovelace et al 2003) in a manner consistent with an early sensory interaction. However, the opposite effect (white noise making a light seem brighter) appears to be the result of a response bias or other post-sensory process (Odgaard et al 2003). It therefore seems likely that different combinations of stimuli will have behavioural effects via different routes. Our data clearly demonstrate that very early sensory interactions should not simply be assumed.

To conclude, we have shown that, while a vibrotactile stimulus biases subjects as though it were an auditory tone in certain circumstances, it does not affect auditory judgments in the same manner as a real tone. We therefore consider that it has its effect by biasing responses made in higher-order brain areas with multimodal inputs rather than by creating a combined bisensory representation in very early sensory areas.

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