Perceptual interactions in the loudness of combined auditory and vibrotactile stimuli

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The loudness of auditory (A), tactile (T), and auditory-tactile ($A+T$) stimuli was measured at supra-threshold levels. Auditory stimuli were pure tones presented binaurally through headphones; tactile stimuli were sinusoids delivered through a single-channel vibrator to the left middle fingertip. All stimuli were presented together with a broadband auditory noise. The A and T stimuli were presented at levels that were matched in loudness to that of the 200-Hz auditory tone at 25 dB sensation level. The 200-Hz auditory tone was then matched in loudness to various combinations of auditory and tactile stimuli ($A+T$), and purely auditory stimuli ($A+A$). The results indicate that the matched intensity of the 200-Hz auditory tone is less when the $A+T$ and $A+A$ stimuli are close together in frequency than when they are separated by an octave or more. This suggests that $A+T$ integration may operate in a manner similar to that found in auditory critical band studies, further supporting a strong frequency relationship between the auditory and somatosensory systems. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3377116]

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I. INTRODUCTION

Our previous research on auditory-tactile perceptual interactions (Wilson *et al.*, 2008; Wilson, 2009; Wilson *et al.*, 2009, 2010) provides evidence for the integration of near-threshold level auditory (A) and tactile (T) tonal stimuli when presented simultaneously in an objective detection context. Specifically, we found that for 250-Hz auditory and tactile stimuli presented in an auditory broadband noise of 50 dB sound pressure level (SPL), (i) performance was highest when the two stimuli were presented synchronously, (ii) the increase in performance was not affected by the relative phase of the auditory and tactile sinusoidal stimuli, and (iii) performance for non-overlapping stimuli improved only if the tactile stimulus preceded the auditory stimulus. Additionally, we found the highest rates of detection for the combined-modality stimulus when frequencies in the two modalities were equal or closely spaced (and were within the Pacinian range, i.e., 50 Hz and higher). These results suggested that perceptual integration of auditory and tactile stimuli at near-threshold levels depends both on absolute frequency and relative frequency of stimulation within each modality. To extend this research to supra-threshold stimuli is nearly impossible because of the difficulty of measuring detection for stimuli well above threshold. Instead we examined auditory-tactile integration as a function of how the loudness of auditory and tactile stimuli combines using the frequency relationship determined previously as a basis for this study.

In the auditory domain, it is well established (Marill, 1956) that two-tone stimuli that lie within a critical band are more effectively integrated, as far as detection is concerned, than two tones that lie in different critical bands. This effect is similar to that observed in our experiments with auditory and tactile stimuli: detection is higher when the frequencies of the auditory and tactile stimuli are equal or closely spaced than when they are farther apart. For loudness, on the other hand, two auditory tonal stimuli are louder when they occupy different critical bands than when they lie within the same critical band. It is important to determine whether the frequency spacing of auditory and tactile stimuli has a similar effect on perceived strength of combined auditory-tactile stimuli at supra-threshold levels.

There have been several studies investigating auditory-tactile interaction using loudness as a metric. These studies have demonstrated that the combined loudness of an auditory-tactile stimulus can exceed that of the auditory component alone (Schürmann *et al.*, 2004; Gillmeister and Eimer, 2007; Yarrow *et al.*, 2008) or of the tactile component alone (Gescheider *et al.*, 1974). For example, Schürmann *et al.* (2004) found that the average intensity required to produce equal loudness of an auditory-only reference tone was 12%–13% (roughly 0.5 dB) lower under the combined auditory-tactile condition compared with the auditory-alone condition, thus suggesting a facilitative interaction between the auditory and tactile stimuli. Gillmeister and Eimer (2007) found that presentation of a tactile square-wave stimulus increased magnitude estimates of a white noise auditory stimulus when the stimuli were presented synchronously. Yarrow *et al.* (2008) measured the effect of a 120-Hz 34-dB SL tactile tone on the loudness of partially masked (71 dBA white noise) 120-Hz auditory tones using the method of constant stimuli to estimate points of subjective equality. They found that the presence of vibration tended to increase the loudness of the auditory stimulus. It should be noted, however, that based on the results of other experiments, Yarrow *et al.* (2008) attributed the increase in loudness to a bias effect, concluding that the tactile stimulus “does not affect

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auditory judgments in the same manner as a real tone." Finally, Gescheider *et al.* (1974) observed that magnitude estimates of a tactile vibratory signal were increased in the presence of a simultaneous auditory tone.

We used a matching paradigm to measure the level of an auditory probe tone as its loudness was compared with either a two-tone auditory complex or a two-tone auditory-tactile complex (i.e., one pure tone presented through each of the two sensory modalities). We modeled our experiment on the classical study of auditory critical bands by Zwicker *et al.* (1957), who found that the matching level of an auditory probe tone remained constant when the frequencies were within one critical band, but increased when the frequencies of the tone complex fell outside of one critical band. Since the loudness of pure tones increases with level, this implies that the loudness of a tone complex of constant power is constant if the tone components fall within one critical band, but increases as they fall in adjacent critical bands.

In our study, a number of auditory and tactile tonal stimuli were equated in loudness to a fixed-level auditory probe tone. We then determined the level of the probe tone that matched the loudness of pairs of auditory tones or a combination of auditory-tactile tones. The frequencies chosen for the $A+A$ tones represented within or outside critical band separations as specified for auditory-alone conditions (Zwicker, 1961; Swets *et al.*, 1962). For the $A+T$ signals, the tactile tones were either the same frequency as the auditory tone or different by substantial amounts.

II. METHODS

We tested five subjects (one female; 18–39 years; median age of 22 years; all audiometrically normal) after obtaining informed consent. Our experimental setup was similar to previous experiments described in detail in Wilson *et al.* (2009). In all presentations, the auditory and tactile stimuli were accompanied by broadband auditory noise to eliminate possible auditory artifacts from the tactile device. Stimuli were pulsed on with a 500-ms duration including 20 ms on/off ramps. The tactile stimulus was presented to the tip of the left middle finger through an Alpha-M Corporation (Dallas, TX) vibrator. The auditory stimuli were presented diotically via Sennheiser (Old Lyme, CT) HD580 headphones. The two stimuli in each combined condition were simultaneous. All sinusoidal stimuli had a starting phase of 0°.

A. Baseline detection

Measurements of auditory-tactile integration for threshold-level signals were obtained for the baseline condition of Wilson *et al.* (2009). Detection performance was measured using a two-interval, two-alternative forced-choice (2I-2AFC) procedure and was obtained for all conditions in the presence of a diotic auditory broadband noise at an overall level of 50 dB SPL. The experimental conditions included separate runs for a 250-Hz auditory tone (A), a 250-Hz tactile vibration (T), and the combined $A+T$ stimulus using the 2I-2AFC procedure described by Wilson *et al.* (2009). For the A-alone and T-alone conditions, the level of the stimulus was adjusted to produce performance in the range of 63%- to 77%-correct in the 2I-2AFC task. These same levels were then employed in testing the detectability of the $A+T$ stimulus. A minimum of three measurements were made on each of the subjects, plus repetitions to verify the results.

B. Adaptive thresholds

Auditory masked thresholds and tactile absolute thresholds were measured using an adaptive three-interval, two-alternative forced-choice (3I-2AFC) procedure with trial-by-trial correct-answer feedback. Stimuli were presented with equal *a priori* probability in one of the three intervals, and the listener's task was to identify the interval containing the signal. Each interval was cued on a visual display during its 500-ms presentation period with a 500-ms inter-stimulus interval. The background noise was presented over headphones starting 500 ms before the first stimulus interval, played continuously throughout a given trial, and terminated 500 ms after the completion of the third interval. During the experimental run, the level of the signal was adjusted adaptively using a 1-up, 2-down rule to estimate the stimulus level for 70.7% correct detection (Levitt, 1971). The step size was 4 dB for the first two reversals, 2 dB for the next two reversals, and 0.5 dB for the remaining six reversals. The final threshold estimate was the mean presentation level of the final six reversals. In the time between trials (when the noise was not presented), the subject responded by selecting the interval that contained the signal (using a mouse or keyboard) and was provided with visual correct-answer feedback.

A broadband diotic noise with an overall level of 55 dB SPL was presented over headphones for both the auditory and tactile measurements. [The broadband noise level was increased over that employed in the baseline detection experiment (Sec. II A) due to the use of higher-level tactile signals in the loudness-matching study discussed below.] Auditory thresholds were measured for frequencies of 200, 250, 300, and 547 Hz. Tactile thresholds were measured for frequencies of 20, 250, and 400 Hz.

C. Loudness matching

The stimuli used in the adaptive-threshold tests were then equated in loudness to a 200-Hz auditory tone at a level of 25 dB above threshold (SL). The loudness-matching paradigm, which was based on procedures described by Silva and Florentine (2006) and Jesteadt (1980), employed a two-interval adaptive comparison in which the probe was presented randomly in one interval and the reference was presented in the other interval. The visually cued intervals were 500 ms in duration with a 500-ms inter-stimulus interval; the background noise was initiated 500 ms before the onset of the first interval and terminated 500 ms after the offset of the second interval. Two interleaved tracks were presented randomly in a given run. One track contained an initial probe level set much higher than the reference level and a second track contained an initial probe level set much lower than the reference level. On each trial, the subject was instructed to select which of the two intervals contained the "stronger" stimulus. The level of the probe was adjusted adaptively us-

TABLE I. The average levels (and standard errors) of the auditory and tactile stimuli (defined in the first row) used in the experiments. Auditory measurements of threshold and equal loudness are given in dB SPL. Tactile measurements of threshold and equal loudness are given in dB re 1 μm rms displacement. The second row provides measures of thresholds obtained with a 3I-2AFC adaptive procedure. The third row provides measurements of loudness matches of each stimulus to a 200-Hz reference stimulus at 25 dB SL. The fourth row describes the equal-loudness stimuli in terms of their individual sensation levels.

	Auditory				Tactile		
Frequency (Hz)	200	250	300	547	20	250	400
Threshold (dB)	26.6 (0.3)	25.7 (0.4)	26.9 (0.8)	27.3 (0.5)	−3.6 (1.2)	−29.2 (2.6)	−18.2 (3.1)
Equal loudness (dB)	51.6 (0.3)	49.7 (0.3)	49.2 (0.3)	47.7 (0.4)	5.1 (0.4)	−12.3 (0.9)	−6.9 (0.8)
Sensation level (dB)	25.0	24.0	22.3	20.4	8.7	16.9	11.3

ing a 1-up, 1-down rule to estimate the level at which the probe was judged to be louder than the reference on 50% of the trials. The initial step size was 4 dB for the first two reversals, 2 dB for the next two reversals, and 0.5 dB for the final six reversals. Each run yielded two loudness matches, based on the average of the probe levels across the final six reversals in each of the two tracks.

Tones with levels equated in loudness to the 25-dB SL 200-Hz auditory tone (i.e., auditory tones of 250, 300, and 547 Hz and tactile tones of 20, 250, and 400 Hz) were then combined into auditory-auditory $(A+A)$ or auditory-tactile $(A+T)$ reference stimulus pairs. The 200-Hz tonal auditory probe stimulus was then matched in loudness (same paradigm as before) to six different pairs of stimuli: (1) $A(250\text{ Hz})+A(300\text{ Hz})$, same critical band (CB); (2) $A(250\text{ Hz})+A(547\text{ Hz})$, different CBs; (3) $A(250\text{ Hz})+T(250\text{ Hz})$; (4) $A(547\text{ Hz})+T(250\text{ Hz})$; (5) $A(250\text{ Hz})+T(400\text{ Hz})$; and (6) $A(250\text{ Hz})+T(20\text{ Hz})$. The adaptive loudness-matching process was repeated four times per condition per subject, resulting in eight values per condition.

The loudness-matching tests were typically conducted over the course of three 2-h test sessions, one each for loudness matches of $(A+A)$ signals, $(A+T)$ signals where A was fixed at 250 Hz, and $(A+T)$ signals where T was fixed at 250 Hz. Thus, only two different two-tone complexes were tested in any given session. Each session began by obtaining adaptive thresholds for the 200-Hz auditory probe and for the other auditory and tactile frequencies involved in that day's testing. Then the level of each stimulus making up the complexes was matched to a 200-Hz reference signal set at 25 dB SL. Finally, the probe level was measured for each of the two different two-tone complexes whose order of presentation was selected randomly. Both of the loudness-matching steps described above were typically repeated four times within a given test session.

III. RESULTS

A. Baseline detection

The average detection scores (and standard errors of the mean) in the 250-Hz condition were A-alone: 71.6% (0.50%), T-alone: 73.7% (0.65%), and $A+T$: 86.1% (1.43%), with retest scores A-alone: 68.7% (0.88%) and T-alone: 71.3% (1.33%). The average scores for the single-modality retest conditions were slightly lower than the scores obtained in the original tests. The average detection score for the combined condition was between that predicted by the "Pythagorean sum" (80.3%) and "Arithmetic sum" (88.6%) models of detection (Wilson *et al.*, 2009). This suggests that the subjects were capable of integrating the 250-Hz auditory and tactile stimuli as well as those tested previously.

B. Adaptive thresholds

The average results of our adaptive measurements of detection thresholds for the auditory tones in 55 dB broadband noise and tactile absolute detection thresholds (and standard errors) are presented in Table I [in the row labeled "Threshold (dB)"].

Our average auditory masked thresholds are consistent with those reported previously by Wilson (2010). The 250- and 400-Hz tactile detection thresholds are comparable to those reported by Wilson (2010). Our average tactile detection threshold at 20 Hz is comparable to the measurements of Bernstein *et al.* (1986) (Figs. 1 and 3 for adult subjects) if an allowance is made for a difference in contactor area. Generally, we regard the measurements of detection thresholds as within the range of previous measurements.

C. Loudness matching

Figure 1 shows the results of the loudness-matching experiment averaged across five subjects and four repetitions of each condition (resulting in eight measurements, which were averaged together for each subject). The average level of the 200-Hz auditory probe when set to 25 dB SL was 51.6 dB SPL. The average levels of the auditory and tactile pure tones when matched to the 25-dB SL 200-Hz tone are presented in Table I [in the row labeled "Equal loudness (dB)"].

We found that presenting two equal-loudness auditory stimuli required a 3.0-dB increase in the probe level to match the loudness when the two frequencies were within one critical band $[A(250\text{ Hz})+A(300\text{ Hz})]$ and a 4.5-dB increase when the two stimuli were in different critical bands $[A(250\text{ Hz})+A(547\text{ Hz})]$. Presenting an auditory and a tactile tone led to a 5.2-dB increase when the two frequencies were the same (250 Hz) but a 7.0-dB increase when the auditory frequency was greater $[A(547\text{ Hz})+T(250\text{ Hz})]$, a 7.3-dB increase when the tactile frequency was greater $[A(250\text{ Hz})+T(400\text{ Hz})]$, and an 8-dB increase when the tactile frequency was lower $[A(250\text{ Hz})+T(20\text{ Hz})]$. Paired t-tests between the two $A+A$ conditions showed, as expected, a significant difference between the matching probe levels

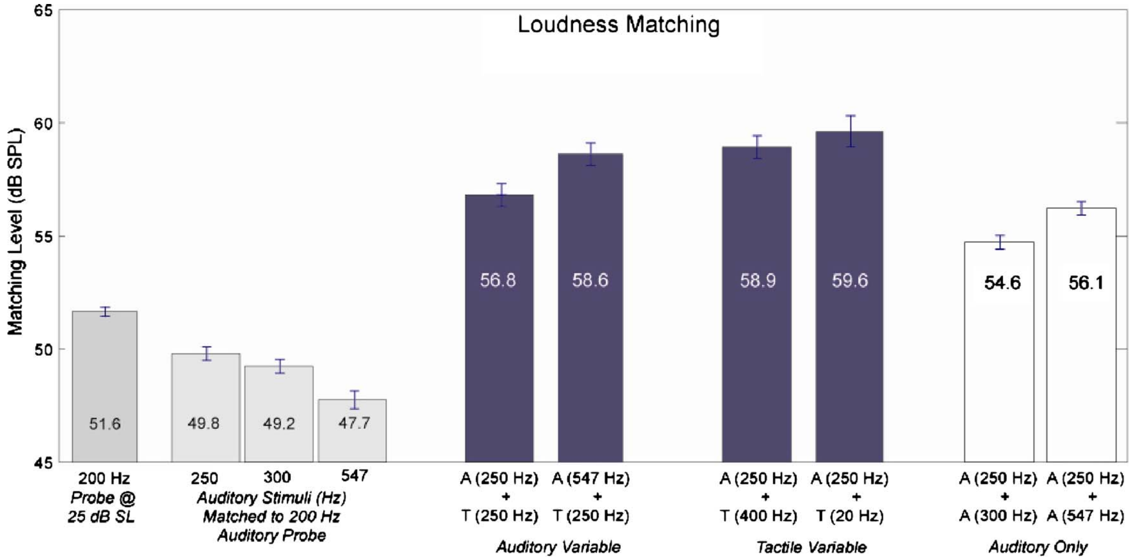

FIG. 1. (Color online) SPL of auditory probe averaged across five subjects with eight repetitions per condition. The dark gray bar represents the average sound pressure level of the 200-Hz auditory probe at 25 dB SL; the light gray bars represent the average levels of the auditory pure tones when matched to the 25-dB SL 200-Hz tone. The black bars represent the level of the probe when matched to a combined auditory-tactile reference stimulus, and the white bars represent the level of the probe when matched to a two-component auditory reference stimulus. Error bars are one SEM.

($p=0.00013$). Paired t-tests between the $A+T$ conditions showed that the probe level in the equal-frequency condition [$A(250\text{ Hz})+T(250\text{ Hz})$] was significantly lower than all other $A+T$ conditions (all p-values <0.001). Additional paired t-tests showed that matching probe levels in the [$A(547\text{ Hz})+T(250\text{ Hz})$] and the [$A(250\text{ Hz})+T(400\text{ Hz})$] conditions were not significantly different from one another ($p=0.53$), and neither were the probe levels in the [$A(250\text{ Hz})+T(400\text{ Hz})$] and [$A(250\text{ Hz})+T(20\text{ Hz})$] conditions ($p=0.14$), while the probe levels in the [$A(547\text{ Hz})+T(250\text{ Hz})$] and the [$A(250\text{ Hz})+T(20\text{ Hz})$] conditions were significantly different from one another ($p=0.02$). We obtained a similar pattern of results when we conducted loudness-matching experiments with 250-Hz tactile tones and 250- and 547-Hz auditory tones that were individually equated in SL rather than loudness.

Very little data are available with which our tactile equal-loudness data can be compared. Goff (1967) measured equal magnitude contours relative to a 100-Hz standard by the method of limits. Using a 100-Hz tactile vibration presented at 25 dB SL as a reference, she found equal sensation magnitude was achieved by 13.2, 23.5, and 21.0 dB SL tactile tones at 25, 200, and 400 Hz, respectively. We found that using an auditory 200-Hz tone presented at 25 dB SL as a reference, equal magnitude was achieved by 8.8, 16.9, and 11.3 dB SL tactile tones at 20, 250, and 400 Hz, respectively. The data of Verrillo *et al.* (1969) indicate somewhat less dependence of the equal magnitude contour (in terms of sensation level) on frequency than the measurements of Goff (1967). However, the measurements of Verrillo *et al.* (1969) were made on the thenar eminence rather than the fingertip. Our equal magnitude results are reasonably comparable to those of Goff, with allowances made for differences in the reference contours considered.

IV. DISCUSSION

When a tactile sinusoidal vibration is applied to the fingertip, the sensation produced often has an auditory component at the same frequency (Yarrow *et al.*, 2008) and tactile stimuli can also have an effect on the perception of sound (Gillmeister and Eimer, 2007; Ro *et al.*, 2009). This leads quite naturally to the question of how the auditory and tactile components of a multimodal sensation combine. Wilson *et al.* (2009) have shown, using objective measures, that certain combinations of auditory and tactile sinusoidal vibrations result in a significant increase in detectability above the levels when the stimuli are presented in isolation. This increase is not due to changes in response bias (e.g., Yarrow *et al.*, 2008), as indicated by a detection theory analysis. Although it is tempting to compare this increase in detectability to the increase one observes when different components of an auditory signal are combined (Marill, 1956; Green, 1958), there are clear differences in the two cases. An observer can attend to the auditory component of an auditory-tactile stimulus by removing his finger from the vibrator or favor the tactile component by tensing his middle-ear muscles. In purely auditory experiments, it is very difficult (impossible?) to hear out the components of a two-tone complex.

Evaluating the loudness of multi-component stimuli can present difficult problems. If the various components do not fuse perceptually, decisional biases may be responsible for loudness changes as opposed to sensory factors. Schürmann *et al.* (2004) are unsure whether the interaction between sensory modalities takes place at the perceptual or decision level. Yarrow *et al.* (2008) attributed the increase in loudness of the auditory component of such multimodal stimulus to a bias effect.

We sought to overcome this problem by two means. First, we practiced and tested our subjects on the baseline detection condition (250-Hz auditory, 250-Hz tactile, and their combination). All five of our subjects achieved higher $A+T$ scores than in the A-alone or T-alone conditions using methods and analyses that eliminated the effects of response bias. Second, we equated the loudness of the auditory and tactile components of the multimodal stimulus so that when the subjects judged the loudness of the $A+T$ stimulus, they were dealing with similarly strong auditory and tactile stimuli.

Examination of Table I suggests that findings of Schürmann *et al.* (2004) and Yarrow *et al.* (2008) may apply to very different stimulus conditions than those considered in the present research. Specifically, these prior studies are representative of conditions in which the tactile stimulus is much stronger than the auditory stimulus. Schürmann *et al.* used a 24–28 dB SL 200-Hz vibration and a 200-Hz auditory tone presented at 10 dB SL in white noise at 60 dB SL. According to our measurements, a 16.9 dB SL tactile vibration at 250 Hz is equivalent in loudness to a 24.0 dB SL masked auditory tone (see Table I). It is possible that the relatively weak effect (0.5 dB) that Schürmann *et al.* found may have been due to this mismatch.

Yarrow *et al.* (2008) used a 120-Hz tactile vibration presented at 34 dB SL and an auditory stimulus consisting of a 120-Hz tone presented in 71 dBA white noise at 0–10 dB SL (above the detection threshold in the noise). Although we did not test at 120 Hz, comparing our results with Yarrow *et al.*'s, it is clear that auditory stimuli that are considerably more intense than 0–10 dB SL are equal in loudness to tactile stimuli that are presented well below 34 dB SL.

Recent neurophysiological studies have shown that the auditory and tactile systems interact in the central nervous system (Schroeder *et al.*, 2001; Foxe *et al.*, 2002; Schürmann *et al.*, 2006), and several psychophysical studies have shown a strong facilitative relationship between the two systems that is dependent on temporal and frequency similarity (Jousmäki and Hari, 1998; Guest *et al.*, 2002; Schürmann *et al.*, 2004; Schnupp *et al.*, 2005; Gillmeister and Eimer, 2007; Yarrow *et al.*, 2008; Wilson *et al.*, 2008; Ro *et al.*, 2009; Wilson *et al.*, 2009; Wilson, 2009; Yau *et al.*, 2009). Our results indicate that the increase in loudness between auditory and tactile stimuli is dependent on relative frequency, with greater loudness increases in the case of greater frequency separation between the auditory and tactile tones, as is found in the purely auditory studies of loudness matching (Zwicker *et al.*, 1957).

Our auditory-only ($A+A$) results are consistent with those reported by Zwicker *et al.* (1957), who showed that as the frequency separation between components in an auditory tone complex increases beyond a critical band, the level of a loudness-matched auditory probe tone increases as well. Our results further suggest that a similar frequency relationship exists between the auditory and tactile senses; the level of the matched probe tone being larger when the auditory and tactile tones are different compared with when they are equal. The greatest increase in probe level was found when the tactile stimulus was 20 Hz, a frequency outside the range of the Pacinian channel (which is most sensitive to 250-Hz sinusoids), and which could be considered a different physiological channel from the Pacinian channel (Marks, 1979; Makous *et al.*, 1995). Nearly the same increase in matching level is found for 400-Hz tactile sinusoids, suggesting that there may be a critical band organization in the tactile channel associated with the Pacinian system (Bensmaia *et al.*, 2005) or that some form of cross-modal critical band relation may exist between auditory and tactile stimuli.

Recently, Leibold *et al.* (2007) and Leibold and Jesteadt (2007) investigated the relationship between the loudness of five-tone complexes and the masked threshold of individual components in the presence of the other four components. They found that when the overall spacing of the complex increased from 0.7 to 3.5 equivalent rectangular bandwidth (ERB), the masked threshold of the outer two tones decreased by roughly 6 dB while the level of the probe tone at the center of the complex that was matched in loudness to these complexes increased by 5 dB. Like Liebold *et al.*, we also found an increase in the matched-tone level (of 1.5 dB) when the spacing of our auditory two-tone complex increased from 0.9 to 4.5 ERB. Our findings for auditory-tactile interactions are similar to this. Consider a 250-Hz auditory tone: the greatest detectability occurs when it is paired with a 250-Hz tactile tone; when it is paired with a 400-Hz tactile tone detectability is reduced from 86.6% to 82.0% (Wilson *et al.*, 2008; Wilson, 2009, 2010). On the other hand, when a tactile 250-Hz tone is paired with an auditory 547-Hz tone instead of an auditory 250-Hz tone, the level of a tone that is matched in loudness must be increased by 1.8 dB. These results imply that as the interaction (as measured by mutual masking or detectability) between the tones that constitute a multi-tone complex decreases, the loudness of the complex increases both for auditory-auditory and auditory-tactile stimuli.

While our previous study examined the relationship between auditory and tactile frequencies at near-threshold levels of detection (Wilson *et al.*, 2008; Wilson, 2009), our current study extends this work by showing that the frequency relationship found at near-threshold levels is preserved at supra-threshold stimulus levels. This finding has important implications for stimuli in the real-world, as most of our day-to-day environmental interactions occur at supra-threshold levels. For example, our perception of texture is highly influenced by the interaction of auditory and tactile inputs to our sensory systems (Jousmäki and Hari, 1998). Language production may also be influenced by the perception of self-produced speech sounds and by the vibrations caused by these productions in the speaker's own vocal tract and lips. While the sense of hearing extends in the lower range to roughly 20 Hz, the sense of touch extends to frequencies below 1 Hz. With significant interactions between auditory and tactile stimuli at supra-threshold levels, it is possible that the sense of touch extends the sense of hearing to frequencies below the audible range.

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