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Research Report

# Tactile enhancement of auditory detection and perceived loudness

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ABSTRACT

To study the effects of touch on auditory processing, we examined whether uninformative and irrelevant tactile stimuli presented together with task-relevant sounds can improve auditory detection (Experiment 1), and enhance perceived loudness (Experiment 2). We demonstrated that irrelevant tactile signals facilitate the detection of faint tones, and increase auditory intensity ratings. These crossmodal facilitation effects were found for synchronous when compared to asynchronous auditory–tactile stimulation, and were stronger for weaker than for louder sounds. They are interpreted in terms of a multisensory integration mechanism that increases the strength of auditory signals, and adheres to the rules of inverse effectiveness and temporal (but not spatial) co-occurrence. This integration might be mediated by auditory–tactile multisensory neurons in regions of auditory association cortex that are also involved in auditory detection and loudness discrimination.



## 1. Introduction

The integration of information from different sensory sources is thought to serve an important adaptive function, as complementary views based on input from separate sensory modalities yield a clearer picture of our sensory environment. Multisensory integration has been extensively investigated on the basis of single-cell recordings, where it is defined as an enhancement of neural responses to multimodal compared to unimodal stimulation. Multisensory integration in superior colliculus, a subcortical structure involved in the control of spatially coordinated head and eye movements, appears to be guided by three principles (Stein and Meredith, 1993; see also Holmes and Spence, 2005). Multisensory integration is stronger for weaker signals (inverse effectiveness), and is stronger for stimuli that are closer in space (spatial rule) as well as in time (temporal rule). These three principles are thought to facilitate attentional selection between competing sources of stimulation by determining the extent to which sensory information originates from the same source (cf. Stein and Meredith, 1993). Whether the same rules also apply to multisensory interactions in other cortical and subcortical structures, and to tasks that do not involve spatial attention, is currently under debate (e.g., Stein et al., 1996; Holmes and Spence, 2005). The aim of the present study was to investigate the role of multisensory interactions in the perception of sounds. More specifically, we examined whether uninformative and irrelevant tactile stimuli presented together with task-relevant sounds can improve the detection of these sounds (Experiment 1), and result in an enhancement of perceived loudness (Experiment 2).

While numerous behavioral studies have demonstrated that the simultaneous presence of visual and auditory stimuli improves visual as well as auditory detection in humans

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(Frassinetti et al., 2002; Lovelace et al., 2003), and enhances perceived brightness (Stein et al., 1996; but see Odgaard et al., 2003) as well as loudness (Odgaard et al., 2004), only few behavioral studies have so far investigated similar interactions between audition and touch. An enhancement of auditory processing by touch has been demonstrated as a facilitation of response speed to suprathreshold stimuli (Murray et al., 2005), and as an increase in the perceived intensity of a faint tone (Schürmann et al., 2004). While this is compatible with a multisensory mechanism that facilitates the processing of weak events, earlier studies have produced conflicting results. Under certain conditions, the presence of tactile events reduces auditory detectability (Gescheider and Niblette, 1967; Gescheider, 1970; Gescheider et al., 1969, 1970) and the detection of tactile events can likewise be impaired by sounds (Gescheider and Niblette, 1967; Gescheider, 1970). However, tactile detection can also be enhanced by simultaneously present auditory stimuli (Gescheider et al., 1974). This latter finding was interpreted as evidence that irrelevant tones facilitate neural activity in the tactile system, leading to an increase in both signal and noise level. This would affect response criteria alongside affecting perceptual sensitivity, rather than increase perceptual sensitivity alone (Gescheider et al., 1974).

In summary, previous behavioral studies have shown that auditory–tactile integration effects can be observed in auditory and tactile detection tasks, as well as in tasks requiring the judgment of auditory or tactile intensity. These interactions between hearing and touch may be implemented by auditory–tactile multisensory neurons that have been identified in the caudal belt of auditory association cortex in the macaque (Schroeder et al., 2001; Fu et al., 2003), with regions in auditory association cortex along the superior temporal gyrus as a possible human homologue (Foxe et al., 2002). However, the questions whether behavioral auditory–tactile integration effects reflect crossmodal suppression or enhancement, and whether they are primarily based on early sensory or later decisional mechanisms are far from resolved.

The aim of the present study was to investigate the impact of irrelevant tactile stimuli on auditory perception, in order to test whether tactile modulations of auditory processing adhere to the principles of multisensory integration as described by Stein and Meredith (1993). Multisensory integration results in an enhancement of neural responses to an auditory event by the presence of a tactile stimulus, and should therefore improve auditory detection performance as well as perceived sound intensity. This was tested in two experiments. In Experiment 1, we employed a 2-interval forced-choice procedure to study the effects of irrelevant tactile events on observers' ability to detect faint sounds. In Experiment 2, we asked observers to judge the loudness of sounds at different intensities in order to investigate whether and how irrelevant tactile stimuli would affect the perceived intensity of auditory stimuli. According to the principle of inverse effectiveness, multisensory integration is most pronounced for weak sensory stimuli. Thus, effects of irrelevant touch on auditory detection (in Experiment 1) and perceived loudness (in Experiment 2) should be largest for low-intensity sounds. According to the temporal rule, multisensory integration should only occur when stimuli are temporally aligned. This assumption was tested in both experiments by presenting auditory and tactile stimuli either simultaneously or asynchronously, and investigating whether effects of irrelevant touch on auditory detection and perceived loudness depend on synchronous presentation. Finally, the spatial rule postulates that multisensory integration is contingent upon the spatial alignment of sensory events. This was tested in Experiment 2, where tactile stimuli were either spatially aligned with auditory events, or were presented on the other side of the body midline.

## 2. Experiment 1

This experiment tested whether the detectability of auditory signals is improved by concurrent touch. Observers made a forced-choice response indicating which of two visually marked temporal intervals contained an auditory signal. Task-irrelevant tactile stimuli were delivered in both intervals, and in spatial alignment with the tones. On any given trial, these tactile events occurred at the same time relative to interval onset. Thus, both intervals were identical in all respects except for the presence or absence of an auditory stimulus. The auditory stimulus (50 ms) always occurred centered in one of the intervals (350–400 ms after interval onset). The critical manipulation concerned the temporal relationship between tactile stimulation and target tones. In some trials, tactile stimuli were presented simultaneously with the tone (350–400 ms after interval onset). In other trials, they occurred earlier (150–200 ms after interval onset), or later (550–600 ms after interval onset) than the auditory stimulus. If the presence of a temporally coincident tactile stimuli facilitates auditory stimulus detection, as predicted by the temporal rule of multisensory integration, this should be reflected in an improvement of observers' ability to choose the time interval where the target tone occurred on trials where tactile stimuli and tones were presented synchronously, relative to trials where a tactile event either preceded or followed the target tone. While tactile signals preceding tones may be alerting and thus facilitate detection in an unspecific manner, there is no reason to assume that tactile signals that follow tones should have any effect on performance. Performance obtained from trials in which touch followed tones may thus be seen as baseline. Three different target tone intensities were employed in order to investigate whether the benefits of synchronous touch on auditory detection performance would be most pronounced for weak auditory signals, as predicted by the principle of inverse effectiveness.

### 2.1. *Results*

Fig. 1 shows mean percentages of trials where intervals were correctly identified as containing the target tone, for each level of auditory stimulus intensity and auditory–tactile SOA. While accuracy was close to chance (0.5) for intensity 1, and no clear effect of SOA was apparent, a marked effect of SOA was present for intensity 2. Here, synchronous touch (0 ms SOA) improved auditory detection performance relative to asynchronous early touch (– 200 ms SOA) and asynchronous late touch (+ 200 ms SOA). A similar effect can also be seen for intensity 3, although the difference between synchronous and asynchronous early touch was less pronounced.

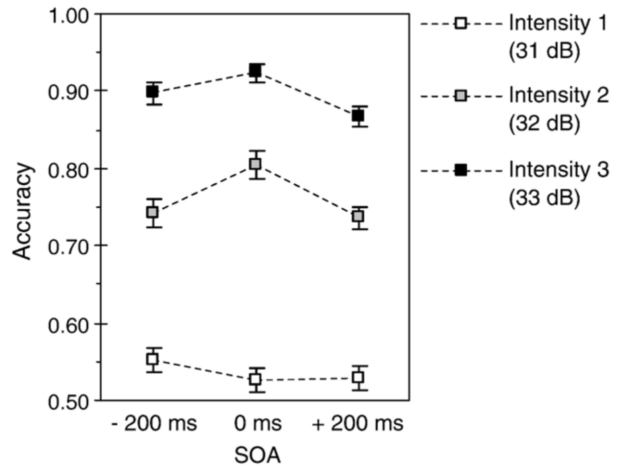


**Fig. 1 – Effect of tactile stimuli on auditory detection accuracy as a function of SOA and auditory intensity, Experiment 1. Shown are mean percentages of trials where the interval containing an auditory target was correctly detected. Vertical bars indicate standard error of the mean. Tactile stimuli occurred before (−200 ms), synchronous with (0 ms), or after (+200 ms) auditory stimuli.**

The data were normalized using arcsine transformation of the square root of the proportion obtained in each condition for each participant. This procedure converts binomially distributed data, such as proportions, into normally distributed data, and enables parametric analysis (Hogg and Craig, 1995). The normalized data were first subjected to a repeated measures analysis of variance (ANOVA) for the within-subject factors auditory intensity and SOA. As predicted, auditory detection performance was affected by SOA ($F(2,48)=9.1$, $P<0.001$). Detection performance was also affected by auditory intensity ($F(2,48)=365.4$, $P<0.001$). An interaction between auditory intensity and SOA ($F(4,96)=3.5$, $P=0.015$) indicated that the effect of tactile events at different SOAs varied for the three auditory intensities used (see Fig. 1). This interaction was further explored by two-tailed paired samples *t*-tests that were run between each SOA level for all three auditory intensities (with alpha Bonferroni-adjusted for multiple comparisons). For auditory intensity 1, detection performance in synchronous touch trials (0.53) did not differ from performance in asynchronous early touch trials (0.55; $t(24)=1.4$, $P=0.163$) and in asynchronous late touch trials (0.53; $t(24)=0.12$, $P=0.908$). Asynchronous early touch trials did not differ from asynchronous late touch trials ($t(24)=1.1$, $P=0.295$). Further analyses revealed that detection accuracy for intensity 1 tones was significantly above chance (0.5) only for asynchronous early touch trials ($t(24)=3.1$, $P=0.005$), but not for synchronous ($t(24)=1.7$, $P=0.111$) or asynchronous late touch trials ($t(24)=1.7$, $P=0.094$). For intensity 2, detection performance in synchronous touch trials (0.81) was significantly better than performance in asynchronous early touch trials (0.74; $t(24)=2.4$, $P=0.027$) as well as performance in late touch trials (0.74; $t(24)=3.1$, $P=0.005$), while there was no difference between asynchronous early and late trials ($t(24)=0.31$, $P=0.759$). For intensity 3, performance in synchronous touch trials (0.92) was better than in asynchronous late touch trials (0.87; $t(24)=4.0$, $P=0.001$), but did not differ significantly from asynchronous early touch trials (0.90; $t(24)=1.7$, $P=0.101$). Here, performance in asynchronous early touch trials was better than in late touch trials ($t(24)=2.4$, $P=0.025$).

In summary, Experiment 1 demonstrated that the presence of synchronous tactile information improved the accuracy of detecting weak auditory stimuli close to threshold (intensity 2). Here, detection performance with synchronous touch was significantly enhanced relative to asynchronous early or late touch trials, thus providing new evidence that the temporal rule of multisensory integration applies to auditory–tactile interactions in an auditory detection task.

For more intense auditory stimuli (intensity 3), synchronous tactile events also enhanced the detection of auditory targets relative to asynchronous late touch. However, the fact that the performance benefit for synchronous relative to asynchronous early touch failed to reach statistical significance, and the observation that improved auditory detection was also observed for asynchronous early relative to late touch suggests that early tactile stimuli may have acted as a temporal attentional cue (Correa et al., 2005, 2006). Such temporal alerting effects from touch may have enhanced auditory perceptual sensitivity independently of, and in parallel with, crossmodal interaction processes.

The principle of inverse effectiveness implies that performance benefits of multisensory integration should be largest for weak sensory stimuli. The fact that effects of synchronous as compared to asynchronous touch on detection performance were more pronounced for intensity 2 than for intensity 3 (see Fig. 1) is in line with this prediction. However, no evidence for any tactile facilitation of auditory detection was observed for the faintest tones (intensity 1). It is likely that these tones may have been too close to threshold to profit from the presence of concurrent touch.

## 3. Experiment 2

To test whether irrelevant tactile information can also affect the perception of auditory intensity, we adapted the procedure pioneered by Stein et al. (1996) for perceived brightness and Odgaard et al. (2004) for loudness. In Experiment 2, observers were asked to judge the intensity of a tone on a nine-point scale. Tones were presented at one of seven different suprathreshold intensities. In different trials, tones were either presented in isolation (baseline), or were accompanied by synchronous or asynchronous tactile stimuli. In addition, when present, these tactile events were either spatially aligned or nonaligned with the tones. There were two auditory locations (left or right speaker). Tactile location (the hand with the tactor in front of the speaker in the same hemifield) was varied between blocks.

This procedure made it possible to simultaneously investigate all three principles of multisensory integration. According to the temporal role, multisensory integration depends on temporal alignment. Thus, any facilitatory effects of touch on auditory intensity judgments should only be found in the presence of synchronous touch, analogous to Experiment 1. Perceived auditory intensities should be enhanced with synchronous touch, whereas intensity judgments with asynchro-

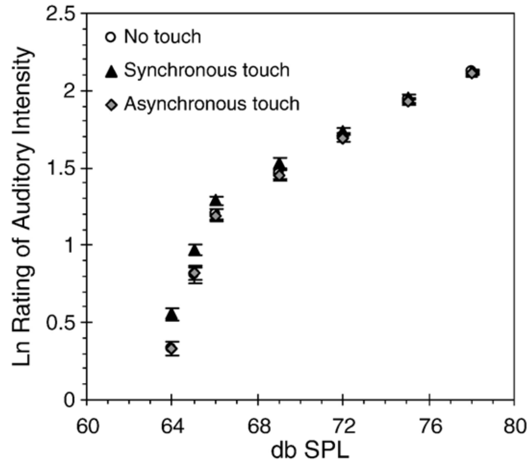


**Fig. 2 – Effect of tactile vibrations on auditory intensity ratings, Experiment 2. Shown are the logarithms of mean intensity ratings for each level of auditory intensity. Vertical bars indicate standard error of the mean. Tactile stimuli were either absent (no touch), presented synchronously with the tones (synchronous touch) or contained a gap during which tones were presented (asynchronous touch).**

nous touch should not differ from judgments observed in the absence of tactile stimuli (baseline). According to the principle of inverse effectiveness, enhancements of perceived auditory intensity by synchronous touch should be more pronounced for low as compared to higher auditory stimulus intensities. Finally, the spatial rule predicts that these crossmodal enhancement effects should only be observed when tactile and auditory stimuli are spatially aligned. Thus, these effects should be present on synchronous touch trials where tactile and auditory events are presented at spatially aligned locations, but not on trials where these events are presented at different locations. Furthermore, on trials where no tactile stimuli are presented at all, the location of the hand with the tactor should not affect perceived auditory intensity.

### 3.1. *Results*

Fig. 2 shows mean intensity judgments (logarithm of geometric means) to auditory stimuli in synchronous touch, asynchronous touch and no touch (baseline) trials. As loudness judgment is a power function of physical intensity (e.g., Stevens, 1956, 1961), means were log transformed in order to improve the linearity of the series. Untransformed means can be seen in Table 1 for all conditions of touch and spatial congruency.

As predicted, intensity judgments were consistently higher in the presence of synchronous tactile vibrations than in asynchronous touch and no touch trials. Enhancement of perceived auditory intensity by synchronous touch was most pronounced for the lowest auditory intensity (67.7% increase) and weakened proportionately for higher intensities (0.05% increase at the highest intensity). In contrast, asynchronous tactile vibrations appeared to have no effect on perceived loudness. Intensity judgments of tones accompanied by asynchronous tactile stimuli were almost identical to judgments made in no touch trials.

To confirm these observations, statistical analyses were conducted for pairwise combinations of the synchronous touch, asynchronous touch and no touch (baseline) conditions. An ANOVA compared intensity judgments (log transformed data) in baseline and synchronous touch trials for the within-subject factors touch (synchronous versus no touch), auditory intensity (1 to 7) and spatial congruency (auditory stimuli presented at spatially aligned versus nonaligned locations with respect to the tactor). There was a main effect of auditory intensity ($F(6, 114)=663.7$, $P<0.001$). As predicted, auditory intensities were judged higher in the presence of synchronous tactile vibrations than in their absence (main effect of touch: $F(1, 19)=82.1$, $P<0.001$). Enhancement by synchronous touch differed for the seven auditory intensities (interaction between auditory intensity and touch: $F(6,114)=13.4$, $P<0.001$), with more pronounced effects for lower intensities (see Fig. 2). In order to test this formally, we calculated the difference between ratings made in no touch trials and those made in synchronous touch trials, and averaged these differences for the lowest three auditory intensities (1 to 3) and for the highest three auditory intensities (5 to 7). A two-tailed paired sample *t*-test comparison between averaged difference ratings for lower and higher intensities showed that the difference between ratings in no touch and synchronous touch trials was significantly larger for lower than for higher intensities ($t(19)=7.2$, $P<0.001$). Higher intensity ratings were given to tones at locations coincident with the location of the hand receiving tactile stimuli than to

**Table 1 – Mean auditory intensity ratings (standard errors) for all conditions of auditory intensity, touch and spatial congruency, Experiment 2**

| | No touch | | Synchronous touch | | Asynchronous touch | |
|---|---|---|---|---|---|---|
| | SC [a] | SNC [a] | SC | SNC | SC | SNC |
| 64 dB SPL | 1.41 (0.08) | 1.45 (0.07) | 1.85 (0.10) | 1.71 (0.08) | 1.50 (0.07) | 1.35 (0.07) |
| 65 dB SPL | 2.32 (0.13) | 2.28 (0.10) | 2.83 (0.10) | 2.53 (0.12) | 2.35 (0.10) | 2.31 (0.11) |
| 66 dB SPL | 3.48 (0.12) | 3.27 (0.12) | 3.73 (0.12) | 3.60 (0.13) | 3.43 (0.16) | 3.25 (0.11) |
| 69 dB SPL | 4.51 (0.13) | 4.19 (0.14) | 4.71 (0.17) | 4.64 (0.17) | 4.32 (0.15) | 4.31 (0.14) |
| 72 dB SPL | 5.51 (0.12) | 5.45 (0.15) | 5.79 (0.10) | 5.65 (0.17) | 5.65 (0.16) | 5.28 (0.13) |
| 75 dB SPL | 7.05 (0.14) | 6.87 (0.12) | 7.18 (0.15) | 7.02 (0.11) | 6.95 (0.10) | 6.82 (0.12) |
| 78 dB SPL | 8.51 (0.06) | 8.24 (0.10) | 8.45 (0.09) | 8.32 (0.10) | 8.40 (0.08) | 8.15 (0.09) |

SC=spatially coincident, SNC=spatially non-coincident.
[a] Spatial coincidence in no touch conditions refers to the location of the tactile stimulator.

tones at non-coincident locations (main effect of spatial coincidence: $F(1,19)=11.9$, $P=0.003$). However, and surprisingly, there was no interaction between spatial coincidence and touch ($F(6,114)=1.2$, $P=0.282$), suggesting that effects of spatial coincidence on intensity ratings were present independently of whether tactile vibrations were actually delivered (on synchronous touch trials) or not (on no touch trials). That is, the presence of the tactor on the hand in the location of the speaker presenting a tone on a given trial was sufficient to induce an increased intensity ratings for this tone compared to one originating from the other speaker.

A second ANOVA compared intensity judgments in synchronous and asynchronous touch trials, with the factor touch now defined in terms of synchronous versus asynchronous touch. There was a main effect of auditory intensity ($F(6, 114)=645.7$, $P<0.001$). Tones were judged as more intense when they were accompanied by synchronous than asynchronous tactile vibrations (main effect of touch: $F(1,19)=48.0$, $P<0.001$). Enhancement by synchronous touch differed for the seven auditory intensities (interaction between auditory intensity and touch: $F(6,114)=12.6$, $P<0.001$), with larger effects for lower intensities (see Fig. 2). A two-tailed paired sample $t$-test comparison between averaged differences between ratings in synchronous versus asynchronous touch trials, computed separately for lower (1 to 3) and higher (5 to 7) auditory intensities, demonstrated a significantly larger difference between ratings in synchronous and asynchronous touch trials for lower than for higher intensities ($t(19)=5.2$, $P<0.001$). Again, there was a main effect of spatial coincidence ($F(1,19)=23.2$, $P<0.001$), but no interaction between spatial coincidence and touch ($F<1$). Higher intensity ratings were given when tones and tactile stimuli were spatially coincident, independent of whether tactile stimuli were synchronous or asynchronous with the tones.

A third ANOVA compared intensity judgments in baseline and asynchronous touch trials, with the factor touch now defined in terms of asynchronous versus no touch. There was a main effect of auditory intensity ($F(6, 114)=667.3$, $P<0.001$). Auditory intensity judgments made in the presence of asynchronous tactile vibrations were no different from judgments made in the absence of touch (main effect of touch: $F<1$), and there was also no interaction between auditory intensity and touch ($F<1$). Again, there was a main effect of spatial coincidence ($F(1,19)=11.4$, $P=0.003$), but no interaction between spatial coincidence and touch ($F(6,114)=1.1$, $P=0.316$), suggesting that higher intensity ratings were given to tones spatially coincident with the hand receiving tactile stimuli, independent of whether tactile vibrations were actually presented.

In summary, Experiment 2 demonstrated that perceived auditory intensity is systematically affected by the presence of irrelevant touch. Relative to baseline (no touch), intensity ratings increased when tones were accompanied by synchronous tactile vibrations, and this increase was most pronounced for lower tactile intensities, as predicted by the principle of inverse effectiveness. Auditory intensity ratings were analogously increased for synchronous relative to asynchronous touch, thereby demonstrating that temporal coincidence is critical for such crossmodal enhancement effects to occur. This mirrors the findings obtained in Experiment 1, and provides further evidence for the importance of the temporal rule of multisensory integration. The observation that asynchronous tactile stimuli did not enhance perceived loudness relative to baseline (no touch) trials demonstrates that in the absence of temporal alignment, touch did not have an effect on perceived auditory intensity. In addition, the absence of any difference between baseline and asynchronous touch trials also shows that the effects of synchronous touch observed in Experiment 2 cannot be attributed to a general unspecific alerting effect induced by the mere presence of tactile stimuli on bimodal trials. While the design of Experiment 2 cannot exclude the possibility that response bias may have contributed to the enhancement of intensity ratings, the absence of enhancement for asynchronous touch in contrast to the enhancement found for synchronous touch shows that bias alone is unlikely to be responsible for auditory–tactile enhancement. If response bias or unspecific alerting accounted for enhancement, enhancement should have been present for both synchronous and asynchronous touch.

As regards the spatial rule of multisensory integration, the results obtained in Experiment 2 were unexpected. Although main effects of spatial coincidence were present, reflecting the fact that auditory stimuli were generally perceived as louder when they were presented adjacent to the hand that could receive tactile stimulation, these effects appear entirely independent of any multisensory mechanisms underlying loudness enhancement. According to the spatial rule, enhancements of auditory intensity ratings by (synchronous) touch should only be observed on trials where tactile events were present and were spatially aligned with auditory stimuli. This should have been reflected by significant interactions between touch and spatial coincidence. However, no such interactions were found, indicating that the effect of spatial coincidence on auditory intensity ratings was entirely independent of whether tactile stimuli were synchronous, asynchronous, or absent. That is, spatial effects were present even when no auditory–tactile enhancement occurred. Several possible explanations may account for this surprising pattern of spatial effects. First, the mere presence of the tactile stimulator on one of the hands in unimodal and in bimodal trials may have served as a tactile stimulus, and thus have produced consistent spatial coincidence effects for both trial types. Given the speed and strength of tactile habituation, this possibility appears unlikely. Second, observers' expectation of tactile stimuli on the hand where the tactile stimulator was located may have induced enhanced intensity judgments in response to tones from this location in unimodal trials. A recent paper (Reed et al., 2006) offers a third possible explanation as to why spatial congruency effects were observed on unimodal trials. Reed et al. showed that visual targets appearing near a task-irrelevant hand were detected faster than targets at other locations. They suggested that the context of the hand can bias the distribution of spatial attention by increasing the salience of space near the hand relative to other locations. If multimodal representations of stimuli in near (peripersonal) space are based on body part-centered coordinates (see Holmes and Spence, 2004, for a comprehensive review), and stimuli located near a hand are generally more salient, tones presented close to a visible hand may have been generally perceived as louder even when no tactile stimuli were delivered to this hand.

## 4. General discussion

The present experiments investigated whether uninformative and irrelevant tactile events can facilitate auditory detection and enhance perceived auditory stimulus intensity. Experiment 1 used a criterion-free 2-interval forced-choice procedure to demonstrate that the detectability of weak sounds is enhanced when these sounds are accompanied by synchronous tactile stimuli. Experiment 2 demonstrated that auditory stimuli accompanied by synchronous tactile vibrations are judged as louder than when the same auditory stimuli are presented in isolation, or together with asynchronous tactile events. This tactile enhancement effect was more pronounced for lower than higher auditory intensities, but was not modulated by the spatial alignment of auditory and tactile stimuli.

In sum, the results of the present study indicate that interactions between hearing and touch produce behavioral benefits in auditory tasks, and that these interactions adhere to the principle of inverse effectiveness and to the temporal rule of multisensory integration. This study thus contributes to a growing body of evidence that suggests that auditory–tactile integration is based on multisensory mechanisms that serve important adaptive functions in humans.

### 4.1. *Crossmodal enhancement in stimulus detection and intensity perception*

Research on interactions between visual and auditory modalities has shown that detection performance can be enhanced by events in another modality. Frassinetti et al. (2002) found that irrelevant sounds facilitated the detection of visual stimuli, especially when they were spatially aligned, although this facilitation effect was accompanied by a shift in response bias. Lovelace et al. (2003) have demonstrated that an irrelevant light can enhance the detectability of sounds, even when observers' response criteria remain unchanged, suggesting an early visual–perceptual enhancement of perceived loudness. Irrelevant sounds can also enhance tactile detection (Gescheider et al., 1974), and the present Experiment 1 has demonstrated that uninformative and irrelevant synchronous touch can facilitate the detection of weak auditory events.

The benefit of synchronous touch for auditory detection performance observed in Experiment 1 is contrary to Gescheider and Niblette's (1967) and Gescheider's (1970) findings that simultaneous tactile events increase auditory detection thresholds. In these studies, observers tracked their auditory detection thresholds by continuously increasing and decreasing the intensity of auditory clicks in the presence or absence of tactile vibratory pulses. The observation that tactile pulses increased auditory threshold, especially when pulses and auditory clicks occurred simultaneously was interpreted in terms of crossmodal masking (i.e., the inhibition of a weak sound by a stronger tactile stimulus due to early sensory convergence at a central site). Given the methodological differences between the present Experiment 1 and the Gescheider studies, it is likely that different mechanisms are responsible for the effects obtained in these two types of tasks. In a tracking procedure such as that used by Gescheider and colleagues, factors other than crossmodal suppression of stimulus strength may have caused the observed changes in detectability. For example, more salient events in the irrelevant modality may have captured attention, such that greater intensities were required for detection of events in the relevant modality.

The results of Experiment 1 concur, however, with the findings by Odgaard et al. (2004) by Schürmann et al. (2004) in similar types of matching tasks. In forced-choice comparisons of loudness, Odgaard et al. (2004) found that observers judged bimodal visual–auditory stimuli as louder than unimodal stimuli, and as equal in loudness to physically increased unimodal auditory stimulus intensities. Similarly, Schürmann et al. (2004) found that observers chose lower auditory intensities when matching a probe sound to a faint reference sound when receiving tactile vibrations at the same time. Our Experiment 1 showed that observers are more likely to correctly choose an interval containing a faint sound in the presence of synchronous relative to asynchronous touch. Similar to the findings by Odgaard et al. and Schürmann et al., this effect is likely to reflect early-stage sensory interactions between auditory and tactile modalities, which lead to the enhancement of auditory intensity by concurrent tactile stimuli.

The enhancement of perceived auditory intensity by synchronous touch found in Experiment 2 is also in line with the tactile enhancement of low auditory intensities observed by Schürmann et al. (2004), and extends these findings to show that such enhancement effects occur over a wide range of auditory intensities. The enhancement of perceived loudness by visual stimuli that was previously observed by Odgaard et al. (2004) appears to be largely independent of criterion shifts, and is therefore likely to be based on early-stage multisensory interactions. The results from the present Experiment 1 provide evidence that tactile stimuli can affect auditory processing at early sensory stages. This is because the design of Experiment 1 was criterion-free and thus precludes any effect of response bias. The resulting increase in stimulus strength that was reflected by improved auditory detection performance might also account for the enhancement in perceived auditory intensity by synchronous touch found in Experiment 2.

Crossmodal enhancements of perceived loudness might operate on the basis of different mechanisms than crossmodal enhancements of perceived brightness and tactile intensity. Odgaard et al. (2003) found that the auditory enhancement of perceived brightness, as previously demonstrated by Stein et al. (1996), was not robust to changes in the observers' response criterion. Furthermore, when the intensity of unimodal visual stimuli was increased to the level reported during bimodal trials in a separate experiment, these stimuli were judged as brighter when directly compared with bimodal events. These findings suggest that the presence of a sound may not increase perceived visual intensity by physically altering the visual information. Along similar lines, Gescheider et al. (1974)

argued that auditory enhancement of perceived tactile intensity is based on unspecific facilitation of neural activity in the tactile system, which effectively leaves perceptual sensitivity unchanged. In contrast, the present results and the previous results by Odgaard et al. (2004) suggest that crossmodal enhancements of perceived auditory intensity is, at least in part, based on interactions at a sensory–perceptual level.

### 4.2. *The neural basis of auditory–tactile enhancement*

Multisensory neurons responding to both auditory and tactile events can be found in auditory association cortex in the superior temporal gyrus (Schroeder et al., 2001; Fu et al., 2003; Kayser et al., 2005; Foxe et al., 2002). These neurons are typically located within areas that are involved in the largely automatic and pre-attentive detection and discrimination of sound intensities (Belin et al., 1998; see also Zatorre et al., 1999). Tactile information may be sent to these regions in a primarily feedforward manner (Schroeder et al., 2001; Kayser et al., 2005) via direct and indirect connections with somatosensory areas (Schroeder et al., 2001, 2003), and can therefore lead to changes in the processing of auditory stimuli in these areas. In an fMRI study, Foxe et al. (2002) showed that this area may be involved in integrating auditory and tactile signals for the perception of textures. Observers listened to sounds likened to the rubbing of sandpaper, felt sandpaper rolled over the tips of their fingers, or both. Bilateral regions in superior temporal gyrus were activated significantly more during bimodal than during summed unimodal presentation conditions. This enhancement found for bimodal stimulation suggests that auditory and tactile signals may become integrated on the basis of a multisensory mechanism, resulting in an increase in signal strength.

If the enhancement effects observed in the present study are primarily generated at an early sensory–perceptual stage, it is tempting to assume that they might directly reflect integration in multisensory neurons in auditory association areas. The strongest indication for this was shown in Experiment 1. Not only did co-occurring tactile stimuli enhance perceived auditory intensity (as also shown by Schürmann et al., 2004), but this enhancement resulted in a clear behavioral gain, as the concurrent presence of tactile stimuli facilitated auditory detection. A processing gain has previously only been reported in terms of a reaction time advantage for bimodal auditory–tactile stimuli over summed unimodal auditory and tactile stimuli (Murray et al., 2005). The fact that the effects found in the present study were strongly dependent on the exact temporal alignment of auditory and tactile stimuli suggests that they are based primarily on an early sensory enhancement rather than on decisional processes occurring at later stages. It is possible that unspecific temporal alerting effects may have contributed to auditory detection (Experiment 1), as performance was sometimes also enhanced by tactile events preceding tones compared to those following tones (see also Correa et al., 2005, 2006). Tactile enhancement of perceived loudness (Experiment 2) was, however, only found for synchronous events. It is therefore unlikely that the effects reported here are primarily due to unspecific temporal alerting.

### 4.3. *The rules governing auditory–tactile multisensory integration*

Although auditory–tactile integration may be largely automatic, tactile effects on auditory signal strengths follow rules that demonstrate their adaptive value for behavior. Electrophysiological investigations of auditory–tactile integration in superior colliculus (see Stein and Meredith, 1993, for a review) have demonstrated that multisensory interactions are maximized when there is an overlap between the peak discharge periods in the neural activity that results from stimuli of different sensory origins (Meredith et al., 1987; see also Stein et al., 2004). Strongest enhancement of neural activity is observed for weaker stimuli (e.g., Meredith and Stein, 1986a).

The auditory–tactile interactions reported in the present study adhere to the temporal and inverse effectiveness rules of multisensory integration. The synchronicity of tactile and auditory stimulus presentation turned out to be a necessary condition for tactile enhancements of auditory detection or perceived loudness, thereby demonstrating that the temporal rule of multisensory integration governs these auditory–tactile interactions. The detection of weak auditory events was most strongly facilitated by synchronous touch (Experiment 1). Tactile enhancement of perceived loudness was strongest for the weakest tone, and declined systematically with increasing auditory stimulus intensity (Experiment 2). These results demonstrate that the multisensory gain from the presence of a tactile stimulus is most prominently revealed when the auditory information that is available to the perceptual system is relatively weak, and sensory signals that are hard to detect benefit most from the presence of a sensory event in another modality. Auditory–tactile integration appears to result in an increase in the intensity of auditory stimuli, thus facilitating their detection and affecting perceived loudness. When auditory intensity is very low (such as for intensity 1 in Experiment 1), however, signals may be masked by noise to such an extent that coincident touch fails to affect discrimination performance. Maximal enhancement should take place when the two stimulus components are themselves weakly effective, which indicates that a minimal amount of auditory stimulus energy must be present for tactile enhancement to occur. It could be that auditory strength for intensity 1 was below this minimum. An alternative possibility is that the presence of crossmodal enhancement effects is determined by whether stimuli are subthreshold or suprathreshold. Inverse effectiveness in crossmodal interactions has so far only been observed when stimuli are suprathreshold (e.g., the present Experiment 2; Diederich and Colonius, 2004). Related to this, a recent study has found that the olfactory enhancement of perceived sweetness in taste is affected by odorant concentration at suprathreshold but not at subthreshold levels (Labbe et al., 2006).

In superior colliculus, maximal integration occurs when there is an overlap between the receptive fields in the population of multisensory neurons on which different signals converge (Meredith and Stein, 1986b; see also Stein et al., 2004). Thus, multisensory integration in this structure is strongly governed by the spatial relationship between stimuli. However, this spatial rule may not necessarily apply to auditory–tactile integration in auditory association areas. The present Experiment 2 has found that tactile enhancement of perceived auditory intensity was independent of the spatial alignment of auditory and tactile stimulus events. Along similar lines, Murray et al. (2005) showed that redundancy gains in response speed as a result of presenting bimodal auditory–tactile signals were not constrained by the spatial relationship between auditory and tactile stimuli. Murray et al.'s electrophysiological findings strongly supported the possibility that the modulation of cortical responses, and speed of responding, to bimodal signals in spatially aligned and nonaligned locations may be mediated by the same spatiotemporal mechanism.

Our observation that the spatial relationship between auditory and tactile stimuli does not modulate tactile enhancements of auditory intensity judgments is perhaps less surprising that appears at first. Auditory–tactile interactions may, by their nature, be less spatial than crossmodal interactions that include the visual modality (Murray et al., 2005; Zampini et al., 2005). Zampini et al. (2005) showed that auditory–tactile temporal order judgments were unaffected by the spatial alignment of stimuli. Both Zampini et al.'s and Murray et al.'s (2005) findings stand in marked contrast to the importance of spatial factors observed for visual–auditory and visual–tactile combinations of modalities in comparable studies (e.g., Gondan et al., 2005; Spence et al., 2003; Zampini et al., 2003a,b). This difference may reflect the inferior spatial resolution of auditory and tactile modalities, when contrasted with vision (see Hötting et al., 2004), and may be related to the fact that auditory and tactile stimuli are represented more bilaterally than visual stimuli (cf. Zampini et al., 2005). Murray et al. (2005) suggested that auditory–tactile integration sites contain not only somatosensory receptive fields representing the contralateral hand, but also auditory receptive fields representing both contralateral space and locations within ipsilateral space, a pattern consistent with the findings of studies of auditory spatial function (e.g., Woldorff et al., 1999; Recanzone et al., 2000). In addition, effects of spatial congruency may have been absent because the judgment of sound intensities as employed in Experiment 2 imposed no demands on spatially selective processing. Murray et al. (2005) argued that auditory and somatosensory receptive fields of multisensory neurons may become dynamically modified via top-down influences in response to the specific demands of a task situation. That is, early sensory mechanisms may be reconfigured to minimize spatial tuning. The possibility of such reconfiguration may be necessary given the flexibility with which we are able to move our limbs relative to our ears in order to effect events that produce auditory feedback. The fact that auditory intensities had to be rated regardless of their location in the present Experiment 2 may therefore have rendered the spatial alignment of sounds and tactile events irrelevant for crossmodal enhancement.

In summary, the present study has provided compelling evidence for a central role of the temporal coincidence between auditory and tactile events during the tactile enhancements of auditory detection and perceived intensity. In addition, these effects also adhere to the principle of inverse effectiveness. However, spatial alignment does not appear to be a necessary requirement for such enhancement effects to occur, thus suggesting that the spatial rule may not apply to all types of multisensory interactions.

## 5. Experimental procedures

### 5.1. *Experiment 1*

#### 5.1.1. *Participants*

Twenty-five consenting volunteers (16 female, one left-handed) aged 20 to 38 (mean 28.2 ± 5.1) were paid to complete a testing session lasting 1 h. All participants reported to have normal hearing and normal or corrected-to-normal vision.

#### 5.1.2. *Stimuli and apparatus*

Digit labels "1" and "2" marking the temporal intervals were presented in white on a black computer screen about 500 mm in front of the participant. Auditory stimuli were presented via a speaker about 320 mm below ear level, about 390 mm to the left of the vertical midline and about 500 mm in front of the participant. Adjacent to it on the left, about 490 mm from the vertical midline, another speaker played continuous white noise to partially mask tones. Tactile stimuli were presented via a purpose-built solenoid attached to the inside second segment of the left index finger. The solenoid drove a metal rod with a blunt conical tip against the finger whenever a current was passed through it. Tactile stimulation was initiated with trigger pulses sent from the parallel computer port. The interval between trigger pulse onset and full rod protrusion was 5 ms. Rod displacement had a maximal length of 3 mm and a maximal force of 1 N. The left hand with the solenoid was placed ulnar side down directly in front of the loudspeaker presenting auditory stimuli. The right hand rested on two keys marked "1" and "2" on a computer keyboard, which was used to collect responses.

The auditory target stimulus was a 466.2 Hz sine wave sound presented for 50 ms at three different intensities (intensities 1, 2 and 3, corresponding to 31, 32 and 33 dB SPL, as measured by a digital sound level meter (DAWE Instruments, Model D-1422C) in the absence of white noise at the ear level of a seated participant). The irrelevant tactile stimulus was a 50-ms suprathreshold square-wave pulse. White noise was played continuously throughout the experiment to mask tones as well as any noise originating from the operation of the solenoid. White noise volume ranged between 53.5 and 60.2 dB SPL at the start of the experiment, and was subject to adjustment throughout (see below).

#### 5.1.3. *Design and procedure*

Target tones were presented in a 2-alternative forced choice task. Each trial consisted of two 750-ms temporal intervals separated by a 500-ms empty interval (pause). The first interval began when a "1" appeared on the computer screen and ended when this was replaced by an empty black screen indicating the pause. The second interval began when a "2" appeared, and ended when this was replaced by an empty black screen. After 400 ms, a "?" prompted the participant to respond. The next trial began 1500 ms after one of the two response buttons (marked "1" or "2") was pressed. The target tone was centered in one of the two intervals (350 ms after the beginning of the interval). Task-irrelevant tactile stimuli were delivered in both intervals. Synchronous touches (0 ms SOA) occurred centered in both intervals (350 ms after the beginning of each interval) for 50 ms, and were thus presented simultaneously with the target tone in one of these intervals. Asynchronous early touches (−200 ms SOA) occurred after 150 ms for 50 ms in each interval, asynchronous late touches (+200 ms SOA) after 550 ms for 50 ms. Trials with synchronous, asynchronous early and asynchronous late touches were equiprobable, and were randomly distributed in each block.

Participants were instructed to make a non-speeded forced-choice response, indicating whether a tone occurred in the first or second interval by pressing the corresponding key (1 or 2) on the keyboard. They were told that tactile stimuli were completely uninformative with respect to this task, and thus could be ignored. There were 54 trials in each block (six trials for each combination of auditory intensities and SOA, presented in random order). Each participant completed six blocks. Between blocks, performance feedback (percent correct responses for each auditory intensity) was given, and white noise volume was adjusted if necessary.

Before the start of the experiment, the target tone was presented repeatedly at each of the three intensities. After ensuring that participants could hear each intensity, white noise was introduced and its volume adjusted until participants reported to be able to hear with certainty only the loudest tone (intensity 3). Depending on performance in an experimental block, the volume of the white noise was increased or decreased by 1 dB SPL in the next block. If accuracy was below 75% for intensity 3, white noise level was decreased. White noise level was increased if accuracy was above 95% for intensity 3, indicating that participants were performing at ceiling in this condition, or above 60% for intensity 1, indicating that this intensity was above threshold. For 18 participants, the initial setting of the white noise volume was increased by 2 dB SPL or less in the course of the experiment. For the remaining seven participants, it was increased by 3 or 4 dB SPL. For 14 participants, white noise was not decreased at any point. For eight participants, it was decreased by 1 dB, and for the remaining three participants, by 2 dB.

### 5.2. *Experiment 2*

#### 5.2.1. *Participants*

Twenty paid and consenting volunteers (10 female, two left-handed) aged 22 to 39 (mean $26.3 \pm 4.3$) participated in a testing session lasting 1 h. All reported to have normal hearing and normal or corrected-to-normal vision.

#### 5.2.2. *Stimuli and apparatus*

The apparatus was the same as that used in Experiment 1, with the following exceptions. Two loudspeakers, situated about 290 mm to the left and to the right of the vertical midline, were used to present auditory stimuli on the left or on the right side. White noise (63 dB SPL) was played from a speaker placed centrally behind the computer screen. Responses were collected from keys marked 1 to 9 on a computer keyboard.

Auditory stimuli were 210 ms sound file recordings of the synchronous tactile stimulus (see below) mounted on a wooden table. Sound files were presented at seven different intensities: (1) 64, (2) 65, (3) 66, (4) 69, (5) 72, (6) 75 and (7) 78 dB SPL, measured as before. In a preliminary pilot study, these intensities yielded a linear increase in judged loudness as a function of actual intensity on the nine-point scale used in Experiment 2. The synchronous tactile stimulus consisted of 14 square wave pulses (3 ms duration) at 12 ms separations, yielding a suprathreshold vibration with an overall frequency of approximately 67 Hz and a duration of 210 ms. The asynchronous tactile stimulus consisted of two such vibrations (420 ms each) separated by a 210 ms gap during which the auditory stimulus was presented. Tactile stimulus presentation was otherwise identical to Experiment 1, except that the left or right hand was stimulated in different blocks (see below).

#### 5.2.3. *Design and procedure*

Asynchronous touch trials began with a tactile vibration (420 ms duration), followed by the presentation of the tone (210 ms), and a second ms tactile vibration presented for 420 ms. The trial ended when a "?" appeared on the computer screen prompting a response. Synchronous touch and no touch trials began with an empty interval of 420 ms, followed by the presentation of the tone. In synchronous touch trials, tones were accompanied by a tactile vibration. The "?" appeared after another empty interval of 420 ms. The next trial began 1500 ms after one of the nine response keys (marked "1" to "9") was pressed. Synchronous touch, asynchronous touch and no touch trials were equiprobable, and randomly distributed in each block. There were 84 trials in each block (twelve trials for each auditory intensity). Tones were presented in random order and with equal probability from the left or right loudspeaker.

Participants completed six blocks. They were instructed to make a non-speeded intensity judgment in response to the auditory stimulus, indicating its intensity by pressing the corresponding key on a nine-point scale, while ignoring tactile stimuli if present. Although the identification of intensities along such pre-defined intensity categories may not yield a psychophysically exact picture of the experienced loudness, it provides an effective way of measuring the effect of touch on loudness judgments across different auditory intensities. To assess effects of spatial coincidence between auditory and tactile stimuli, tactile stimuli were presented to the left hand in three consecutive blocks, and to the right hand in the remaining three blocks. The order in which the two hands were stimulated was counterbalanced between participants. The hand to which tactile stimuli were delivered was placed ulnar side down directly in front of the loudspeaker in the same hemifield. Tactile stimuli, when presented, were thus spatially aligned with tones presented via this speaker, but not with tones presented via the other speaker. The other hand was placed on the keyboard, and was used to indicate perceived auditory intensity by pressing one of the nine response keys.

Before the start of the experiment, the range of auditory intensities was demonstrated, accompanied by verbal labels shown on the computer screen. (1) was shown as "very low intensity", (3) as "low / medium intensity", (5) as "medium / high intensity" and (7) as "very high intensity". Participants then completed a short training block (20 trials selected at random from an experimental block). Performance feedback was provided after training and after each experimental block. This consisted of the percentage of tones (averaged over all auditory intensities) correctly identified according to the following criteria. For (1), correct responses were 1 and 2. For (2), correct responses were 2 and 3. For (3), correct responses were 3, 4 and 5. For (4), correct responses were 4, 5 and 6. For (5), correct responses were 5, 6 and 7. For (6), correct responses were 7 and 8, and for (7), correct responses were 8 and 9. This procedure was used to simplify feedback without drawing observers' attention to the fact that seven auditory intensities were used.

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