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Research Report

Improvement of visual contrast detection by a simultaneous sound

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ABSTRACT

Combining input from multiple senses is essential for successfully mastering many real-world situations. While several studies demonstrate that the presentation of a simultaneous sound can enhance visual detection performance or increase the perceived luminance of a dim light, the origin of these effect remains disputed. The suggestions range from early multisensory integration to changes in response bias and cognitive influences—implying that these effects could either result from relatively low-level, hard-wired connections of early sensory areas or from associations formed higher in the processing stream. To address this question, we quantified the effect of a simultaneous sound in various contrast detection tasks. A completely redundant sound did not alter detection rates, but only speeded reaction times. An informative sound, which reduced the uncertainty about the timing of the visual display, significantly improved detection rates, which manifested as a significant shift of the contrast detection curve. Surprisingly, this improvement occurred only in a paradigm were there was a consistent timing relation between sound and target and disappeared when subjects were not aware of the fact that the sound offered information about the visual stimulus. Altogether our findings suggest that cross-modal influences in such simple detection tasks are not exclusively mediated by hard-wired sensory integration but rather point to a prominent role for cognitive and attention-like effects.

1. Introduction

During everyday experience, auditory and visual stimuli are not separated into independent modalities but usually appear in close coordination. A snake wriggling through the grass makes a typical rustling sound, and thunderstorms impress both by lightning and thunder. In general, combining sensory information can enhance perceptual clarity and reduce ambiguity about the sensory environment (Ernst and Bulthoff, 2004; Stein and Meredith, 1993). For example, it has been demonstrated that combined sensory information can speed reaction times (Gielen et al., 1983; Hershenson, 1962; Posner et al., 1976), facilitate learning (Seitz et al., 2006) and change the qualitative sensory experience (Jousmaki and Hari, 1998; McGurk and MacDonald, 1976; Shams et al., 2000). Although many of these cross-modal phenomena are attributed to high-level cognitive processes, others are thought to arise from early and hard-wired sensory integration (Stein, 1998).

In particular, such early sensory integration is thought to mediate cross-modal improvement of low-level detection

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tasks. For example, a simultaneous tone improved detection of a dimly flashed light (Frassinetti et al., 2002a,b; McDonald et al., 2000; Teder-Salejarvi et al., 2005), enhanced the discriminability of briefly flashed visual patterns (Vroomen and de Gelder, 2000) or increased the perceived luminance of light (Stein et al., 1996). While these studies suggest that early sensory integration serves as basis for the improved visual performance, other studies propose that the observed effects result from biases of the cognitive decision process related to the particular paradigms employed (Doyle and Snowden, 2001; Odgaard et al., 2003).

One could conceive that cross-connections between early sensory areas, as for example demonstrated from the auditory to the visual cortex (Falchier et al., 2002; Rockland and Ojima, 2003), facilitate processing in one sense by input from another. It could also be that the superior colliculus, a subcortical structure containing many neurons responding to bi- or trimodal stimuli, is mediating cross-modal improvements in simple detection tasks (Stein, 1988; Stein and Meredith, 1993). However, many behavioral protocols used previously do not allow clear dissociation between early sensory integration and cognitive effects related to changes in decision making (Odgaard et al., 2003). For example, subjects could explicitly combine the information they gather from each sense and adjust their behavioral strategy depending on whether or not it seems advantageous on a cognitive level.

To address this controversy, we systematically quantified the effect of a simultaneous sound on a contrast detection task. We compared different paradigms based on the following reasoning: An early and automatic auditory influence on vision should occur regardless of whether the sound provides additional information about the visual stimulus or is redundant with the visual display. In addition, such an influence should not depend on the subjects' knowledge about the informative relation between both stimuli. A cognitive effect, however, should manifest only when the sound provides additional information over the visual stimulus, and even then, only when subjects are aware of the additional information.

To distinguish between these two possibilities, we manipulated the informative content of the sound. In different paradigms the temporal uncertainty of the visual stimulus was reduced by either the sound ("informative sound"), or by a visual cue that appeared simultaneously with target and which made the sound redundant ("redundant sound"). Additionally, we manipulated the subjects' knowledge about the informative content of the sound by randomizing the stimulus onset asynchrony. Our results demonstrate that a behavioral benefit of the sound occurs only in the "informative sound" condition, and only when the sound has a reliable and fixed timing relative to the visual target.

2. Results

2.1. *Redundant sounds do not improve visual detection*

We measured contrast detection curves in a paradigm where the timing of the visual target varied randomly from trial to trial. On half the trials, a sound was presented in synchrony with the target, informing the subject about the time point of target presentation. In the first experiment (Fig. 1A), an additional visual cue also indicated the timing of the target and rendered the sound uninformative, i.e. redundant with the visual display. Comparing the subjects' performance on trials with and without sound allowed us to quantify its effect on detection rates and response latency.

As shown by the contrast response curve in Fig. 1B, detection rates increased with increasing contrast, varying from poor performance at low contrast to near-perfect performance at high contrast values. However, detection rates were comparable between the sound and the no-sound conditions (ANOVA: $F=0.97$, $p=0.33$). The absence of any effect of the sound was confirmed by signal detection analysis: neither response bias (Fig. 1C; $F=2.30$, $p=0.13$) nor discriminability (Fig. 1D; $F=0.18$, $p=0.67$) showed a significant difference. Only reaction times revealed an influence of sound, with subjects responding significantly faster on trials with sound presentation (Fig. 1E; $F=19.4$, $p<10^{-3}$). Post-hoc analysis showed that this effect was only prominent at low contrast values, where subjects reported the absence of the stimulus (see significances in Fig. 1E). This leads us to conclude that a redundant, uninformative sound does not influence the detection of visual targets.

In the above paradigm, subjects were instructed to respond as "fast and accurately as possible." As speeded responses might bias the subjects toward a quick and incomplete analysis of the visual stimulus, we repeated this paradigm by instructing subjects to respond 'as accurately as possible'. Again, there was no effect of sound on detection rates ($F=0.42$, $p=0.51$), discrimination ($F=2.73$, $p=0.10$), or response bias ($F=0.86$, $p=0.35$). These results confirm the above finding that redundant sounds do not enhance contrast detection.

2.2. *Informative sounds improve visual detection*

In the second experiment, no visual cue indicating the timing of the target was presented. Here, the sound provided additional information about the timing of the target that was not contained in the visual display (Fig. 2A). Although subjects were not given instructions about the sound, they became aware of the temporal alignment of sound and target, as indicated in post-experiment reports by the subjects.

In this paradigm, responses significantly differed between sound and no-sound conditions. Prominently, detection rates were significantly improved by the sound (Fig. 2B; $F=32$, $p<10^{-6}$). In addition, the false alarm rate was also increased (t test; $t=2.2$, $p<0.05$). Together, this led to enhanced detection and d' was significantly higher in the sound condition (Fig. 2C; $F=6.3$, $p<0.05$). The strength of this effect is further evidenced when considering only the intermediate range of contrasts, for which behavioral performance is not saturated toward either extreme (6–12.5% contrast, $p<0.01$). In addition, there was a significant decrease of response bias across all contrasts (Fig. 2D; $F=19.2$, $p<10^{-4}$). This change of response bias indicated a more liberal response strategy during these trials, resulting in an improved detection of the visual target.

One might criticize this result, as the experimental paradigm did not allow a bias free assessment of the subjects' performance. To exclude this possibility, we repeated the same

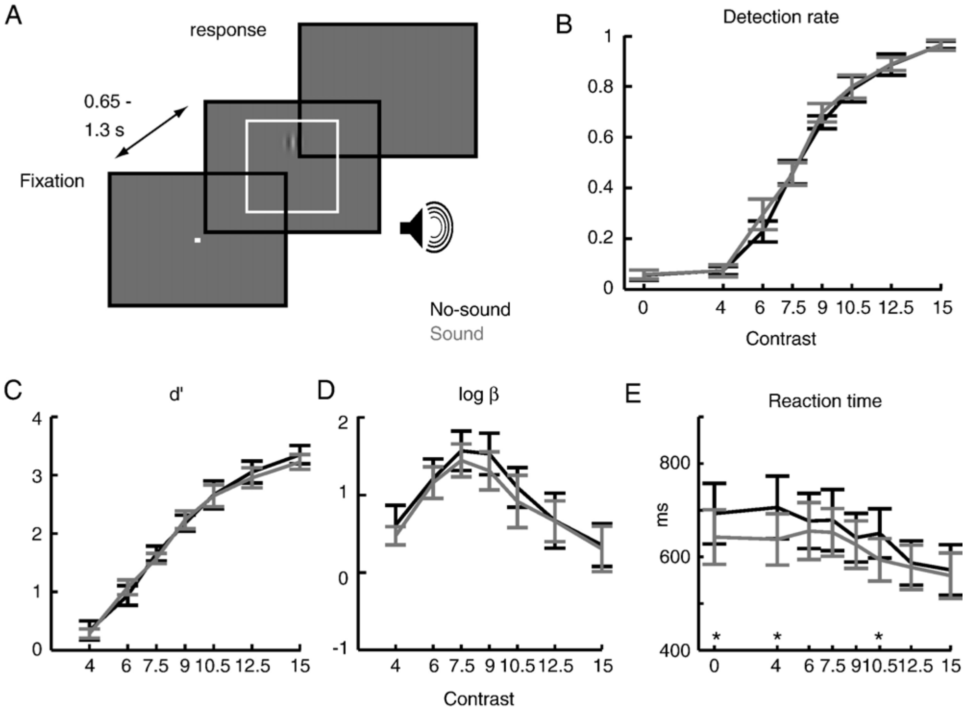

Fig. 1 – Contrast detection with uninformative sound. (A) Experimental paradigm. Visual targets were presented at random times during each trial while subjects fixated the center of the screen. On half of the trials, a sound was presented simultaneously with the target. In addition, in Experiment 1, a grey visual frame was presented around the target locations, which indicated the time point of target presentation to the subjects (and rendered the sound information redundant). (B–E) Detection rate, discriminability (*d′*), bias (log *ß*) and reaction time as a function of contrast for the sound and no-sound conditions (10 subjects, mean and SEM). Stars indicate significant differences between the sound and no-sound conditions (paired *t* test, $^{*}p<0.05$).

stimulation paradigm during a two-alternative forced-choice (2-AFC) task (Fig. 2E). In this experiment, the subjects' task was to indicate whether the visual target appeared above or below the fixation dot; hence, the task was orthogonal to the presence of the sound. The results again reveal a significant improvement of performance during the sound condition ($F=16$, $p<10^{-6}$). Hence, we can conclude that the improvement of visual target detection by a simultaneous sound is not limited to a specific task or the result of a response bias.

These findings allow two interpretations. First, direct sensory integration might enhance the subjects' percept of the visual stimulus and facilitate its processing in a bottom-up manner. Second, subjects could have used knowledge about the timing of the auditory stimulus to focus processing on the particular instant of time highlighted by the sound. In this top-down scenario, explicit knowledge about the timing relation of sound and visual stimulus is essential.

To distinguish between these two possibilities, Experiment 3 was performed in which the stimulus onset asynchrony of sound and visual display was randomly varied from trial to trial. On a subset of trials, both stimuli were synchronous and the sensory stimulation was the same as in the above experiment. On the other trials, however, the temporal relation between sound and visual target differed, and subjects could not be sure that the presentation of the sound yielded information about the timing of the visual stimulus; this uncertainty of the subjects toward any relation between visual and auditory stimuli was confirmed by post-experiment reports by the subjects. Consequently, any behavioral improvement seen in this paradigm should be the result of automatic, low-level sensory interactions, and cannot result from cognitive top-down effects.

We tested subjects on intermediate contrast values that were detected only on a fraction of trials (77±6%, mean±SD over subjects). Comparing the no-sound with the synchronous sound–target condition did not reveal any effect of the sound on detection rate (mean and SEM 0.45±0.04 and 0.44±0.04; $t=-0.15$, $p=0.87$), bias (1.71±0.07 and 1.68±0.10; $t=0.35$, $p=0.71$) or discriminability (1.74±0.10 and 1.74±0.11; $t=0.28$, $p=0.77$). We conclude that the sound does not elevate contrast detection performance in a paradigm where it does not reliably yield information about the visual display. This supports the hypothesis that the enhancement seen in Experiment 2 is not due to an automatic integration of auditory and visual information.

2.3. *Sound shifts contrast threshold*

To better understand the observed effects of an informative sound on detection rates, we examined the shape of the contrast detection curves obtained in Experiment 2 in more detail (Fig. 3A). Each subject's contrast detection curve was fit with a standard model containing three parameters (Martinez-Trujillo and Treue, 2002; Reynolds et al., 2000): the gain of the curve, its slope parameter (*n*) and the contrast threshold

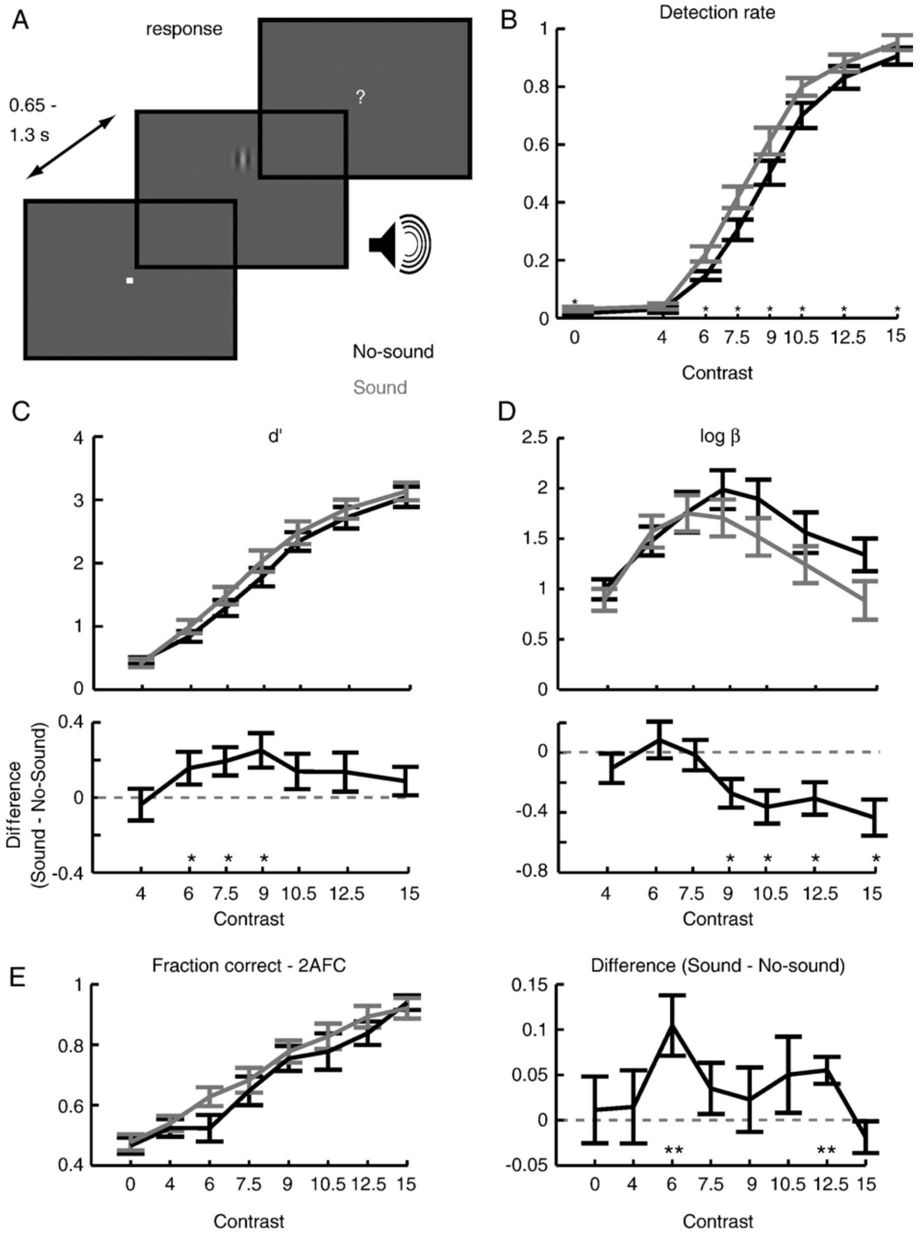

Fig. 2 – Contrast detection with informative sound. (A) Experimental paradigm. In Experiment 2, no visual cue (the grey frame in Experiment 1) was indicating the target presentation to the subjects; only the sound provided additional information about the stimulus timing. After a random interval following the target, a question mark appeared on the screen instructing the subject to make a response. (B–D) Detection rate, bias (log *ß*) and discriminability (*d′*) as a function of contrast for the sound and no-sound conditions in the *contrast detection task* (24 subjects, mean and SEM). Stars indicate significant differences between the sound and no-sound conditions (paired *t* test, $^{*}p<0.05$). (E) Data from the two-alternative forced-choice task (2-AFC). The left panel shows the average fraction of correct responses for both conditions ($n=10$ subjects, mean and SEM), and the right panel shows the average of the difference between conditions (mean and SEM, two-sided *t* test, $^{**}p<0.01$).

(c_{50}, the contrast value reaching 50% performance). Comparing the sound and no-sound conditions did not reveal any effect on the gain or slope parameter ($p=0.6$ and $p=0.2$, Wilcoxon rank-sum tests), which would indicate an increase in perceptual sensitivity. The contrast threshold (c_{50}), however, was significantly lower in the sound condition ($p<0.01$). Hence, the sound did not affect the shape of the contrast response curve, but shifted its position along the contrast axis.

To better understand how this shift of the contrast detection curve might arise, we employed a simple model based on signal detection theory (Green and Sets, 1966) (Fig. 3C, left panel). The model assumes that each target contrast is mapped on an internal representation of perceived contrast in the form of a Gaussian distribution. By applying a decision threshold, the model classifies stimuli as present or absent, resulting in a sigmoid-like contrast response curve, as found in

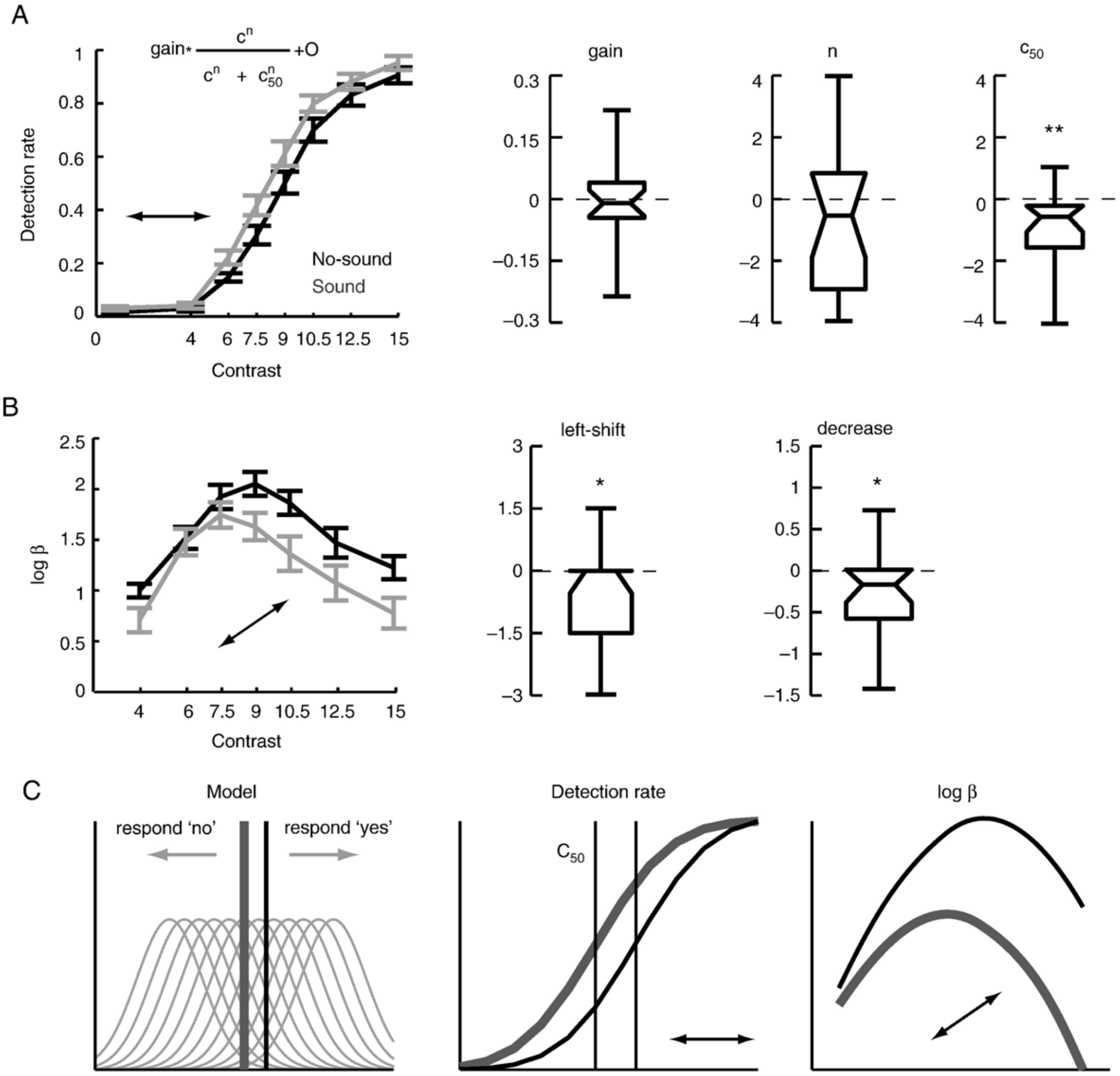

Fig. 3 – Shifts of the contrast detection curve and predictions of a model. (A) Contrast detection curves of each subject were fit with a standard shape (equation). Relevant parameters, i.e. gain, slope (*n*) and contrast threshold (c_{50}) were compared between sound and no-sound conditions across subjects. Only the contrast threshold showed a significant effect (lower threshold during the sound condition). Boxplots display difference between conditions (median, 25% and 75% quartile as well as the data range across subjects) and *p* values reflect the significance from a Wilcoxon rank-sum test (*$p<0.05$, **$p<0.01$). (B) The bias curve of each subject was examined for a left–right shift (position of peak) and an overall decrease (mean value). Both quantities differed significantly between conditions. Boxplots and statistics are the same as in A. (C) Model describing the subjects' decision behavior (left panel). Each contrast value leads to an internal representation of perceived contrast in the form of a Gaussian distribution and the decision threshold (vertical bar) separates detected from not-detected targets. Different decision thresholds lead to detection rates that are the same in shape but differ in contrast threshold (middle panel) and lead to a left–right shift and a change of overall response bias (right panel).

the experiments. The important observation from this model is that changing the decision threshold leads to a left–right shift of the contrast detection curve, in a manner similar to how the sound shifts the subjects' detection curves in the experiment. Interpreting the experimental findings in the context of this model thus suggests that the sound may have changed the subjects' response criterion, which then manifested as a higher detection rate and a more liberal response bias (Fig. 3C shows that the shift of the bias curve is in accordance with this model).

3. Discussion

Cross-modal interactions between sensory systems can occur at many stages of sensory processing and by virtue of several mechanisms. Previous studies proposed that early and hard-wired sensory interactions form the basis of improved performance in low-level visual tasks such as the detection of briefly presented targets or judgments of perceived brightness (Frassinetti et al., 2002a,b; Stein et al., 1996; Teder-Salejarvi et al., 2005;

Vroomen and de Gelder, 2000). Our results contrast this notion and rather support the hypothesis that enhancement of visual detection by a simultaneous sound arises from cognitive rather than early and automatic effects.

The assumption that our brain forms hard-wired and automatic sensory associations is well supported by the finding of multisensory neurons in structures like the superior colliculus (Stein, 1988; Stein and Meredith, 1993). These neurons respond specifically to combinations of sensory stimuli, and do so even in the absence of a particular task or behavior; e.g. in anesthetized animals. However, it is not clear whether these neurons are central to cross-modal behavioral advantages seen in low-level detection paradigms such as those used here. Our findings suggest that contrast detection is not automatically affected by acoustical information. In the present study, subjects showed an improved performance only when the sound carried additional information about the visual target that was not obtainable from the visual display and only in a paradigm where subjects could be certain about the systematic relation between sound and target, i.e. when they reported to have realized that sound and target were temporally aligned.

This proposal is in accordance with two previous studies that reached similar conclusions. Odgaard et al. (2003) asked subjects to rate the perceived brightness of a dim light that was accompanied by a simultaneous sound on a fraction of the trials. By manipulating this fraction, and by using different paradigms, these authors concluded that the sound only affects higher decision stages and alters the subjects' response bias. In another study, Marks et al. (2003) used a brightness discrimination task in conjunction with signal detection analysis to reach similar conclusions. Differently from these two studies, which linked observed effects to a more general response bias, our results demonstrate a benefit of the sound also in a paradigm where the presence of the sound was orthogonal to the subjects task (the 2-AFC task) and pinpoint the subjects' "knowledge" about the relation of sound and visual target as a crucial factor that determines their combined impact. This cognitive factor seems to have a stronger impact on the sensory interaction than the physical association between the stimuli.

Our data demonstrate that sound improved visual detection by shifting the subject's contrast detection curve. Similar decreases of contrast threshold have been observed in studies on visual attention. Focusing attention on a particular location was shown to decrease contrast thresholds (Lee et al., 1999; Zenger et al., 2000) and electrophysiological studies demonstrated shifts of individual neurons' contrast response function following shifts of attention (Martinez-Trujillo and Treue, 2002; Reynolds et al., 2000). The observation that the behavioral benefit of a sound on visual detection manifests in a similar way as attentional modulation is in good agreement with previous studies demonstrating that attention can mediate cross-modal interactions by priming a particular location or to facilitates detection at the same instance with a different sense (Driver and Spence, 1998, 2000; Spence et al., 2001). This suggests that attention could play a role in the observed auditory enhancement of visual detection and promotes future studies to understand whether attentional modulation and cross-modal interactions rely on the similar neuronal mechanisms (Talsma and Woldorff, 2005).

Although the present and previous results (Marks et al., 2003; Odgaard et al., 2003) suggest that sounds do not enhance basic visual detection by means of early sensory integration, this still could be true in the reverse direction, or for other sensory combinations. For example, in a recent study, Odgaard et al. (2004) studied the influence of an additional light on the perceived loudness of sounds and found results that are well compatible with early integration effects (and see (Lovelace et al., 2003) for similar results). Together, the various studies suggest either that there are differences in the directionality of sensory interactions, or that the tasks used to test the different senses do not match in terms of cognitive demands. Definitely, future studies are required to address whether different sensory systems are similarly affected by cognitive biases and attentional processes.

4. Experimental procedures

Volunteer subjects (20–36 years, both sexes) received a financial compensation for their participation and gave written informed consent before the experiment. All had normal or corrected-to-normal vision and were naïve about the aim of the study.

Experiments were conducted in a dark and sound-attenuated room. Stimulus presentation and data acquisition were controlled using a real-time operating system (QNX, QNX Software Systems Ltd). Visual stimuli were presented on a CRT-monitor (19 in., 85 Hz refresh rate), which was gamma-corrected to ensure a linear transfer using a Minolta CA-100 CRT color analyzer. The background luminance was set to 2.7 cd/m^2 and was perceived as neutral grey. Auditory stimuli were delivered through two miniature speakers to the left and right of the monitor at 70 dB(A) SPL. To ensure correct timing of auditory and visual stimuli, the system was tested using a photodiode and microphone, with a Tektronix TPS2014 digital oscilloscope. Calculated correction intervals were implemented in software. Participants viewed the monitor from a distance of 57 cm, with their head placed on a custom-made chin rest. Responses were obtained with a two-button response box connected to the PC.

Visual targets consisted of vertical Gabor gratings (2° diameter, 2 cycles/degree), which could appear 6° above or below the fixation point (equal probability). The contrast of these ranged from 0 to 15% in units of Michelson contrast ((max − min)/(max + min)), with max and min being the maximal and minimal values of the Gabor patch, and different contrast values were equally likely. Additional auditory stimuli consisted of 40-ms band-passed noise (1 kHz bandwidth, centered at 2 kHz, 10 ms cosine on- and off-ramp). Each trial started with the presentation of a fixation spot at the centre of the screen, followed by a random interval (650 to 1300 ms) and the visual target (23.5 ms = 2 frames at 85 Hz duration). Subjects were instructed to fixate during the entire trial.

4.1. *Experiments and tasks*

4.1.1. *Experiment 1—Uninformative sound*

The sound was presented on 50% of the trials and was always in synchrony with the visual target grating. In addition, a visual cue indicating the timing of the target grating was presented simultaneously with the target (a thin light grey frame, 15 × 15 degrees wide, 1/30 degree thick; see Fig. 1A). Importantly, this cue also appeared on trials with zero contrast target gratings, and was clearly visible to the subject. As a result, both the visual cue and the sound provided information about the timing of target presentation (both reduced temporal uncertainty), and hence, were redundant, providing no unique information. Subjects ($n=10$) were instructed to indicate whether they perceived the target stimulus by pressing a "yes" or "no" button and to respond "as fast and accurately as possible." Each contrast level was tested 40 times (20 times with and 20 times without sound). In a second experiment, another set of subjects ($n=10$) performed the same experiment, but with the instruction to respond only "as accurately as possible" to check whether subjects trade speed for accuracy; here at the end of each trial a question mark appeared on the screen (400–700 ms after target presentation) indicating the subjects to respond.

4.1.2. *Experiment 2—Informative sound (detection task)*

This experiment was identical to Experiment 1, except that the visual cue (grey frame) indicating stimulus timing was not presented. In this paradigm, the timing of stimulus presentation could only be obtained from the target grating itself or from the sound. As a result, the sound provided additional information, which (for weak stimuli) was not obtainable from the visual display. Subjects ($n=24$) were instructed to respond "as accurately as possible," and each contrast level was tested 40 times (20 times with and 20 times without sound).

4.1.3. *Experiment 2—Informative sound (2-AFC task)*

This version of Experiment 2 employed the same stimulation as the above detection task. However, in this two-alternative forced-choice task, subjects ($n=10$) had to indicate (as accurately as possible) whether the target appeared above or below the fixation dot. As a result, the subjects' task (up vs. down) was orthogonal to the presence of the sound.

4.1.4. *Experiment 3—Different SOA*

This experiment was the similar to Experiment 2, but the stimulus onset asynchrony (SOA) between sound and target was varied (−400 ms, −150 ms, 0 ms, +150 ms and +400 ms and no sound, each with equal probability, randomly in each trial). This experiment tested only one intermediate contrast level (usually 7.5% or 9%) that was determined based on the subject's contrast detection curve (at about 75% correct detection). Each subject ($n=13$) was tested 60 times at each SOA condition. As a result, the statistical power in this paradigm was higher than in Experiment 2; this was done to increase confidence in the negative result of this experiment. In the present analysis, only the no-sound and the simultaneous sound–target conditions (SOA=0) were of interest, as on these trials, the stimuli were identical to Experiment 2. The other SOA conditions were interspersed merely to prevent the subject from forming cognitive rules connecting the two stimuli.

In all experiments, subjects were instructed on the visual task, but remained naïve to the relevance of sound. Each experiment began with a short practice session for the subject to accommodate to the paradigm and task. After completing all trials, subjects were questioned about the sound and especially whether they were aware of any fixed relationship between sound and visual target.

Data were analyzed in Matlab (The MathWorks Inc., Natick, MA, USA). Detection rates and response latency were compared using an ANOVA with subjects as random effects and contrast as factor. Signal detection theory was used to analyze stimulus discriminability (d') and response bias (β). In the formulas below, H corresponds to the hit rate, F to the false alarm rate (detection rate for zero contrast) and Φ^{-1} to the inverse of the normal cumulative distribution function. β denotes to the likelihood ratio of the signal and noise distributions and indicates whether subjects' responses are free of a bias ($\log \beta=0$), conservative ($\log \beta>0$) or more liberal ($\log \beta<0$). Both characteristics were computed for each (non-zero) contrast level using the detection rate of that particular contrast as hit rate.

$$d' = \Phi^{-1}(H) - \Phi^{-1}(F)$$

$$\log \beta = \frac{[\Phi^{-1}(F)]^2 - [\Phi^{-1}(H)]^2}{2}$$

In addition to using the parametric approach to signal detection theory (Green and Sets, 1966), we also computed non-parametric measures for discriminability and bias (A' and B') (Grier, 1971; Snodgrass and Corwin, 1988). Analysis of these led to the same conclusions as obtained from the parametric measures d' and β.

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