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Brief Reports

Effects of redundant auditory stimuli on reaction time

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Auditory redundancy gains were assessed in two experiments in which a simple reaction time task was used. In each trial, an auditory stimulus was presented to the left ear, to the right ear, or simultaneously to both ears. The physical difference between auditory stimuli presented to the two ears was systematically increased across experiments. No redundancy gains were observed when the stimuli were identical pure tones or pure tones of different frequencies (Experiment 1). A clear redundancy gain and evidence of coactivation were obtained, however, when one stimulus was a pure tone and the other was white noise (Experiment 2). Experiment 3 employed a two-alternative forced choice localization task and provided evidence that dichotically presented pure tones of different frequencies are apparently integrated into a single percept, whereas a pure tone and white noise are not fused. The results extend previous findings of redundancy gains and coactivation with visual and bimodal stimuli to the auditory modality. Furthermore, at least within this modality, the results indicate that redundancy gains do not emerge when redundant stimuli are integrated into a single percept.

When participants are required to respond as quickly as possible to the onset of any stimulus, they usually respond more quickly when two stimuli are presented than when only one stimulus is presented (e.g., Hershenson, 1962). This gain in reaction time (RT) with redundant stimuli has been termed the *redundant signals effect* (RSE), and it is a very general phenomenon. First, it has been observed with redundant stimuli within the visual modality (e.g., Corballis, 2002) and with redundant bimodal stimuli, such as a tone and a light (e.g., Giray & Ulrich, 1993; Miller, 1986) or a light and an electrical pulse (e.g., Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Gondan, Lange, Rösler, & Röder, 2004). Second, although manual responses have been used in most studies, the RSE has also been documented for saccadic responses (e.g., Colonius & Arndt, 2001). Finally, the RSE has been demonstrated not only for simple RT tasks such as those mentioned above, but also for go/no-go tasks (e.g., Egeth & Mordkoff, 1991; Miller, 1991) and for choice RT tasks (e.g., Grice & Reed, 1992; Miller, 1982).

Raab (1962) was the first to suggest a detailed model for the RSE, which is based on a simple statistical principle. According to his race model, each stimulus is detected separately. In trials with redundant stimuli, a response is triggered as soon as the first stimulus is detected. In view of that, RT is determined by the latency of a single detection process in trials with one stimulus, whereas it is determined by the faster of two stimulus detection processes in trials with redundant stimuli. Because the average time of the winner in a race is usually shorter than the average detection time of each single process, this race model predicts shorter RTs in trials with redundant stimuli than in trials with only one stimulus.

Although this race model provides a simple explanation for the RSE, further research has shown that the redundancy gain in RT is often actually larger than this simple model can predict. More specifically, accordingly to race models, the observed RT distributions should satisfy the so-called race model inequality (Miller, 1982)—that is,

$$F_r(t) \leq F_1(t) + F_2(t) \tag{1}$$

for every value of t, where F_1 and F_2 are the cumulative density functions (CDFs) of the RTs in the two single-stimulus conditions and F_r is the CDF of the RT in the redundant-stimulus condition. According to race models, $F_r(t)$ may approach $F_1(t) + F_2(t)$ for small values of t, especially when the detections times for the two single stimuli are strongly negatively correlated (Colonius, 1990). Yet

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even in this case, this inequality must be satisfied according to race models. Contrary to this prediction, observed RT distributions often violate the race model inequality for small values of t (e.g., Diederich & Colonius, 1987; Giray & Ulrich, 1993; Miller, 1982, 1986; Plat, Praamstra, & Horstink, 2000). Therefore, it has been suggested that the units of information from the redundant stimuli are somehow combined together and that this combined activation triggers the response (Miller, 1982). Several quantitative models have been developed to describe this combination of information and the facilitation in RT that results from such coactivation processes (e.g., Miller & Ulrich, 2003; Schwarz, 1989, 1994; Townsend & Nozawa, 1997).

Although numerous studies have investigated such coactivation processes within the visual modality and for bimodal stimuli, we are not aware of any study that has assessed potential coactivation processes within the auditory modality. For this modality, the outcome might depend on exactly how the redundant auditory stimuli are delivered. For example, it is well known that two identical auditory stimuli, each delivered to one ear via headphones, are not perceived as two separate stimuli but, rather, produce the phenomenal impression of a single auditory percept localized between the two ears (e.g., Leakey, Sayers, & Cherry, 1958; Odenthal, 1961, 1963; Ward, 1970). Therefore, it seems possible that redundancy gains in RT within the auditory modality may depend crucially on whether the redundant stimuli fuse into a single percept or not. The present experiments were conducted to investigate this issue.

EXPERIMENT 1

In Experiment 1, a simple RT task was used. In each trial, a pure tone was presented via headphones to either the left or the right ear or to both ears, and the participants were required to press a key when they detected any tone. In order to eliminate interstimulus contingencies (see Mordkoff & Yantis, 1991) that could influence performance in redundant trials, the probability of presenting a tone to each ear was $p = .6$, independently of whether a tone was presented to the other ear. Accordingly, responses were required on 84% of all the trials; the remainder were catch trials.

Experiment 1 included two versions. In Experiment 1A (identical frequencies), half of the participants heard a 500-Hz tone in the first half of the experiment and a 700-Hz tone in the second half of the experiment. This assignment was reversed for the other half. In Experiment 1B (different frequencies), tones of different frequencies stimulated the left and the right ears. Half of the participants always heard a 500-Hz tone in the right ear and a 700-Hz tone in the left ear, whereas this assignment was reversed for the other half. Thus, comparing the results of Experiments 1A and 1B will indicate whether redundancy gain depends on the physical identity of the two tones.

Method

Participants. In both Experiments 1A and 1B, 20 students from the University of Tübingen participated in a single 30-min session as partial fulfillment of course requirements or in return for €4, resulting in a total of 40 students (30 of them female).

Apparatus and Stimuli. The stimuli were pure tones presented via headphones (Sony MDR-CD570). The duration of each stimulus was 300 msec, and its intensity was 60 dB SPL. To avoid abrupt stimulus onsets, stimulus intensity was increased gradually with increases in time t from stimulus onset. Specifically, the envelope of the sine wave stimulus was modulated according to an exponential growth function, $f(t) = 1 - \exp(-a \cdot t)$, with $a = 0.02$ msec^{-1}. The waveform started with a zero crossing at stimulus onset. To avoid clicks produced by the activation of the sound card, tones were low-pass filtered by an external Butterworth filter with a cutoff frequency (-3 dB) of 1.25 kHz. A white plus sign (0.5º × 0.5º of visual angle) centrally presented on a blue background of a standard computer screen (viewing distance of 60 cm) served as fixation and warning signal. Responses were registered with a response key that was centrally located in front of the participants. Half of the participants responded with their left index finger, and the other half responded with their right index finger.

Procedure. A single experimental block comprised 150 trials. Tones were presented in 126 trials (go trials). A tone was presented exclusively to the left or to the right ear on 36 go trials each. On 54 go trials, a tone was presented simultaneously to both ears. The participants were asked to press the response key as soon as they detected a tone, irrespective of tone location and pitch. On 24 trials, no tone was presented (no-go trials), and in these trials, the participants were asked to withhold the response. Each participant first performed a practice block with 15 trials and then performed two experimental blocks with a random ordering of trials within each block.

Each trial started with the presentation of the fixation cross, which remained until a response was registered or for a maximum of 1,600 msec. In go trials, tones were presented 600 msec after the onset of the fixation cross for 300 msec. Following the offset of the fixation cross, feedback was provided for 1,500 msec as follows: "correct" after a hit or a correct rejection, "respond only to a tone" after a false alarm or a hit with an RT below 80 msec (anticipation), or "too late" when no response was registered within 1,000 msec after tone onset (miss). The next trial started after an intertrial interval of 900 msec. After every 50 trials, the participants received feedback about their performance in terms of accuracy.

Results and Discussion

Trials with RTs shorter than 120 msec or longer than 800 msec were considered outliers and, thus, were excluded from data analysis. The outlier rate was low for both fast responses (Experiment 1A, 0.8%; Experiment 1B, 0.4%; including anticipations) and slow responses (<0.1% and 0.1%, including misses). The same was true for the false alarm rate in no-go trials (0.5% and 0.9%). An ANOVA with the within-subjects factor of stimulus condition (stimulus presented to the left ear, to the right ear, or to both ears) and the between-subjects factor of experiment (Experiment 1A, identical frequencies, or Experiment 1B, different frequencies) was performed on RTs. When necessary, reported p values were corrected using the Greenhouse–Geisser correction. There was a significant effect of stimulus condition [$F(2,76) = 10.05$, $MS_e = 80.10$, $p < .01$]. Contrasts using the Scheffé procedure (critical value: 5.0 msec, $p < .05$) revealed that RT was shorter in the redundant-stimulus condition (250 msec) than in the right single-stimulus condition (259 msec). The left single-stimulus condition (255 msec) did not differ significantly from the two other conditions. Furthermore, there was a significant effect of experiment [$F(1,38) = 4.42$, $MS_e = 10{,}295$, $p < .05$], reflecting shorter RTs in Experiment 1A (235 msec) than in Experiment 1B (274 msec). The interaction of the two

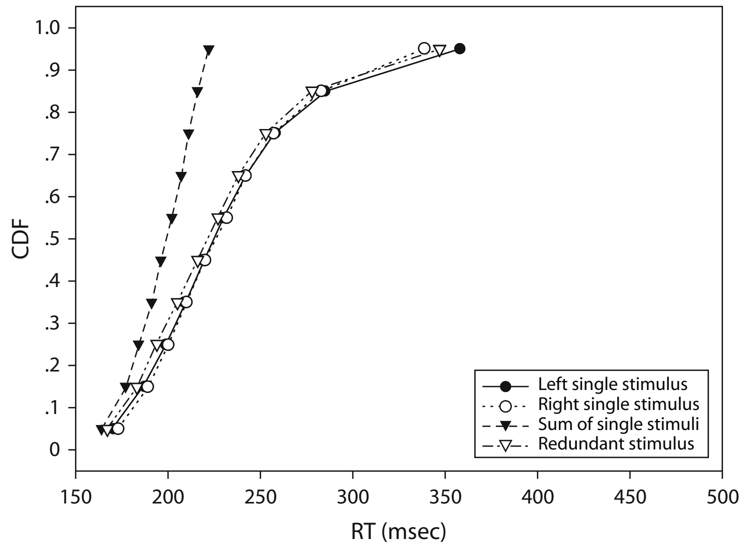

Figure 1. Estimated cumulative density function (CDF) of reaction time (RT) as a function of stimulus condition in Experiment 1A.

factors failed to reach statistical significance [$F(2,76) = 3.09$, $MS_e = 80.10$, $p = .057$]. In order to test for potential redundancy effects, we performed two additional analyses. First, we tested for RT differences between the average of the two single-stimulus conditions (257 msec) and the redundant-stimulus condition. The corresponding ANOVA revealed that the observed difference of 7 msec was significant [$F(1,38) = 24.29$, $MS_e = 39.71$, $p < .01$]. The effect of experiment was again significant [$F(1,38) = 4.16$, $MS_e = 6{,}950$, $p < .05$], and the interaction of the two factors failed to reach significance [$F(1,38) = 3.60$, $MS_e = 39.71$, $p = .066$]. Second, we computed the average of the faster single-stimulus condition across participants (251 msec) and again tested it against the redundant-stimulus condition. The corresponding ANOVA revealed that the observed difference of 1 msec was not significant ($F < 1$), suggesting that the RT advantage of the redundant condition over the average of the two single-stimulus conditions was an artifact of averaging across participants who detected the left stimulus earlier and other participants who detected the right stimulus earlier (cf. Biederman & Checkosky, 1970). Neither the effect of experiment [$F(1,38) = 3.83$, $MS_e = 6{,}948$, $p = .058$] nor the interaction of the two factors ($F < 1$) was significant. To assess potential redundancy effects at the distributional level, Vincentized RT distributions were computed for the single- and redundant-stimulus conditions (Ulrich, Miller, & Schröter, in press), and these are shown separately for

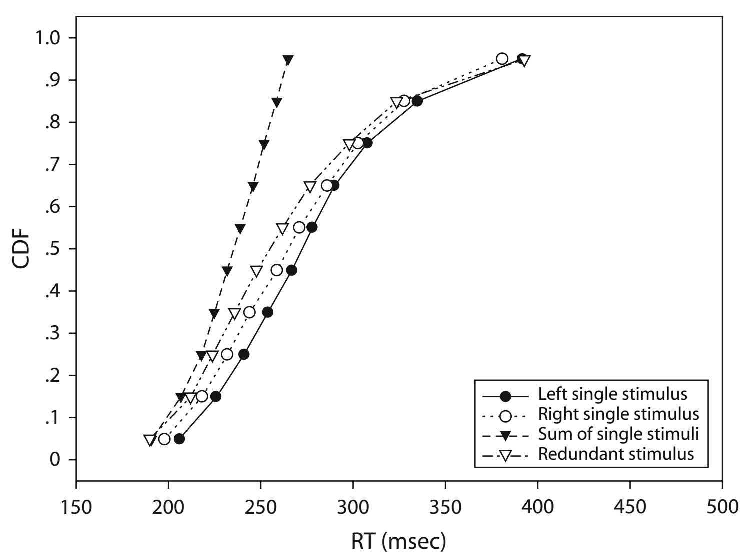

Figure 2. Estimated cumulative density function (CDF) of reaction time (RT) as a function of stimulus condition in Experiment 1B.

Experiments 1A and 1B in Figures 1 and 2, respectively. Also shown in the figures is the sum of the Vincentized single-stimulus CDFs used to test the race model inequality. As one might anticipate from the mean RT results, the present data did not violate this inequality in either Experiment 1A or 1B. Thus, even pure tones of different frequencies seem to be fused into a single percept, preventing the occurrence of a redundancy gain.

EXPERIMENT 2

This experiment was very similar to Experiment 1B, except that the auditory stimuli were made even more distinct. Specifically, a pure tone was presented to one ear, and white noise was presented to the other ear. The white noise stimulus was used so that the two stimuli in this experiment could not be fused. On the basis of Mordkoff and Yantis's (1993) conclusion that coactivation can occur only when redundant stimuli are processed in different modules, we supposed that nonfusable stimuli might elicit a redundancy gain.

Method

Twenty students from the University of Tübingen served as participants (17 of them female). The apparatus and stimuli used were identical to those in Experiment 1B, except for the replacement of the 700-Hz tone by white noise, which had the same duration, intensity, and envelope as the pure tones.[1] Again, the participants were instructed to respond to any auditory stimulus and to withhold their response when no stimulus was presented.

Results and Discussion

As in Experiment 1, trials with RTs shorter than 120 msec (0.3%, including anticipations) or longer than 800 msec (0.6%, including misses) were considered outliers and, thus, were excluded from data analysis. Again, the false alarm rate in no-go trials (1.3%) was low. The effect of stimulus condition was significant [$F(2,38) = 24.39$, $MS_e = 470.21$, $p < .001$]. Contrasts (critical value: 17.5 msec, $p < .05$) revealed that RT was shorter in the redundant-stimulus condition (302 msec) than in both the left single-stimulus condition (349 msec) and the right single-stimulus condition (332 msec). Naturally, RT in the redundant-stimulus condition was also shorter than the average RT in the two single-stimulus conditions (340 msec) [$t(19) = 11.19$, $p < .001$]. Importantly, mean RT was also less in the redundant-stimulus condition than in the faster single-stimulus condition (324 msec) [$t(19) = 6.43$, $p < .001$]. Figure 3 shows the two single-stimulus CDFs, the redundant-stimulus CDF, and the sum of the single-stimulus CDFs, used to test the race model inequality. We conducted paired t tests at each of the percentile points. To be consistent with the race model inequality, the redundant-stimulus CDF would have to be everywhere below and to the right of the sum of the single-stimulus CDFs. Paired t tests conducted at each of the 10 percentile points revealed, however, that this was not the case. RTs to redundant stimuli were reliably ($p < .05$) shorter than RTs from the sum of the single CDF curves at the 15th percentile, with $p = .055$ at the 25th percentile and $p = .19$ at the 5th percentile. Therefore, there were small but significant violations of the race model inequality at low percentiles.

EXPERIMENT 3

In Experiment 2, an RSE and evidence of coactivation were observed, suggesting that the pure tone and the white noise were not fused into a single percept. Accordingly, the absence of an RSE in Experiment 1B makes it reasonable that the two tones differing in frequency were not perceived as separate stimuli. To gain more evidence for this assumption, participants were now asked to localize one of two dichotically presented auditory stimuli.[2] If two dichotically presented pure tones of different frequency

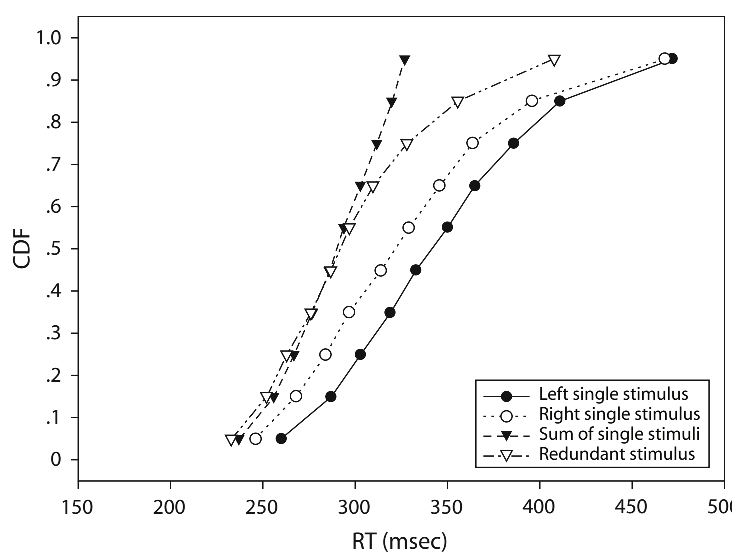

Figure 3. Estimated cumulative density function (CDF) of reaction time (RT) as a function of stimulus condition in Experiment 2.

are fused into a single percept, localization performance should be at approximately chance level. In contrast, localization performance should be clearly above chance when a tone and white noise are presented dichotically.

Method

Twelve students from the University of Tübingen served as participants (7 of them female). The apparatus and stimuli were identical to those in the other experiments, except for the following changes. The participants were asked to localize (left or right ear) one of three auditory signals (500-Hz tone, 700-Hz tone, or white noise) with a corresponding keypress of their left and right index fingers (two-alternative forced choice task). Each participant was tested in three experimental parts, with each part consisting of 100 trials. After each part, the relevant stimulus was changed, and the order of the relevant stimulus was counterbalanced across participants. In each trial, the relevant stimulus (e.g., the 500-Hz tone) was randomly presented to the left or the right ear. One of the two other signals (e.g., the 700-Hz tone or the white noise) was randomly chosen in each trial and was concurrently presented to the other ear. There was no maximal RT boundary and the participants received feedback about their mean localization performance only after each set of 50 trials.

Results and Discussion

The crucial test was the localization performance in the tone-plus-tone condition, as compared with the tone-plus-noise condition, irrespective of the relevant stimulus. In the tone-plus-tone condition, the participants correctly localized the relevant stimulus in only 61% of all the trials (chance level: 50%), with a mean RT of 1,006 msec. In the tone-plus-noise condition, however, the participants localized the relevant stimulus almost perfectly (95.2%), with a mean RT of 601 msec. We conducted t tests for both the arcsine transformed rate of correct localization [$t(11) = 9.43$, $p < .001$] and RT [$t(11) = 4.71$, $p < .01$], which revealed significant performance differences between the two conditions. These results—as well as the impressions of the participants when asked after the experiment—strongly suggest that the participants perceived the two dichotically presented tones in the tone-plus-tone condition as a single percept in most of the trials but did not fuse a tone and white noise in the tone-plus-noise condition.

GENERAL DISCUSSION

In Experiments 1 and 2, the existence of redundancy gains within the auditory modality was investigated. Most important, an RSE was observed when one stimulus was a pure tone and the other stimulus was white noise (Experiment 2). This result provides further evidence that redundancy gains are a very general phenomenon and are not limited to the visual modality (Corballis, 2002) or to combinations of different modalities (Forster et al., 2002; Giray & Ulrich, 1993; Gondan et al., 2004; Miller, 1986). Furthermore, the violation of the race model inequality observed in Experiment 2 shows that the redundancy gain is too large to be explained by mere statistical facilitation (Raab, 1962). Therefore, responses in the redundant condition seem to be triggered by combined activation of the two stimuli (Miller, 1982). To our knowledge, this is the first time that coactivation processes have been reported when both stimuli were auditory.

Identical auditory stimuli presented to both ears (i.e., diotic presentation) are fused into a single percept (e.g., Leakey et al., 1958; Odenthal, 1961, 1963; Ward, 1970). Our results suggest that the occurrence of redundancy gains depends crucially on the extent to which redundant auditory stimuli are integrated into a single percept. Consistent with this idea, diotic presentation in Experiment 1A did not result in a redundancy gain. On the other hand, the pure tone and white noise employed as stimuli in Experiment 2 (i.e., dichotic presentation) seem to differ physically enough to prevent fusion into a single percept. Importantly, the different results of Experiments 1A and 2 strongly suggest that the redundancy gain observed in Experiment 2 was not simply caused by binaural loudness summation (Marks, 1978).

Because no redundancy gain was obtained in Experiment 1B, its results suggest that a single percept was formed when the participants were presented with two pure tones differing in frequency. The results of Experiment 3 provide strong evidence for this assumption. Whereas the participants had no difficulties in localizing the relevant signal when a tone and white noise were presented dichotically, localization performance was just slightly better than chance when two tones of different frequencies were presented dichotically. This outcome is in accordance with other types of evidence suggesting that two pure tones presented dichotically to the two ears are not processed independently and, therefore, might evoke a single percept. For example, the two tones presented in Experiment 1B form a strong (dis-)harmony (a Huygens Tritonus) and, hence, a musical entity. Although early studies questioned whether musical consonance of dichotically presented tones can be perceived (Sandig, 1939), recent research suggests that the auditory system can integrate tones even when they are presented to different ears (Hall & Hess, 1984; Itoh, Miyazaki, & Nakada, 2003). If the perception of the integrated harmony dominates that of the single tones, as is suggested by the results of Experiment 3, there would be a single percept, and no redundancy gain should emerge if multiple percepts are needed for coactivation. Another type of evidence against the independent processing of dichotically presented tones is that there is a strong ear dominance for pitch. Specifically, when two tones of different frequency and a certain frequency ratio are presented dichotically, participants report the pitch of one ear, masking the pitch of the other ear, even if the latter tone is more intense (e.g., Efron & Yund, 1976; Yund & Efron, 1975). With such masking, of course, there is a single percept of the masking tone. Overall, then, the results of our experiments seem quite consistent with the idea that redundancy gain is observed with auditory stimuli only when these stimuli elicit distinct percepts. This conclusion agrees with and extends a proposal of Mordkoff and Yantis (1993), who suggested that coactivation occurs only when redundant stimuli are processed in separate modules, each producing its own percept.

Future research should investigate whether auditory coactivation processes generalize to more natural auditory stimuli, such as complex tones, environmental sounds, musical elements, and speech elements. Since binaural fusion phenomena are also evident in speech perception (e.g., phonological fusion; Cutting, 1975, 1976; Sexton & Geffen, 1981), the use of phonological elements can provide further insights concerning the hypothesis that the occurrence of redundancy gains and coactivation depends on the extent to which dichotically presented stimuli fuse into a single percept.

AUTHOR NOTE

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NOTES

1. The white noise was generated by MATLAB with a bandwidth of 0–44.1 kHz. However, it was also filtered externally by the Butterworth filter, reducing the signal strength for frequencies above the cutoff frequency of 1.25 kHz for 3 dB per octave.

2. This experiment was suggested by an anonymous reviewer.

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