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Visual–tactile integration: does stimulus duration influence the relative amount of response enhancement?

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Abstract Responses to multiple stimuli from different modalities tend to be faster compared to responses to each of these stimuli alone. Neurophysiological studies on higher mammals and behavioral studies on humans suggest that the relative amount of enhancement is inversely related to stimuli intensity. In two experiments the duration of visual and tactile stimuli was varied to investigate whether duration, as a further determinant of stimulus effectiveness, is also inversely related to the relative amount of response enhancement. Visual and tactile stimuli were presented left or right of fixation either in the same or different hemifields. Participants were required to gaze only at visual stimuli and to ignore tactile (focused attention paradigm). Saccadic reaction times were recorded. Results from both experiments show that the relative amount of response enhancement was largest for the shortest stimulus duration and decreases with increasing stimulus duration, i.e., inverse effectiveness of stimulus duration.

Keywords Multisensory integration · Visual–tactile interaction · Stimulus duration · Inverse effectiveness · Saccadic reaction time

Introduction

Complex organisms usually perceive the surrounding world through more than one sensory modality. The information delivered through separate sensory channels has to be arranged according to temporal and spatial features in order to provide a coherent picture of the environment. This process of multisensory integration may hold further benefits for the organism, as reaction

time (RT) studies have revealed. For instance, it has been demonstrated that responses to the onset of a visual stimulus are faster if the visual stimulus is accompanied by a spatially adjacent stimulus from a different modality (e.g., Diederich et al. 2003). Moreover, it was suggested that the amount of RT facilitation is determined also by their intensity (e.g., Bernstein et al. 1970). If the amount of RT reduction is sensitive to the intensity of the stimuli, can it also be influenced by the duration of the stimuli?

Almost 100 years ago, Todd (1912) reported that manual responses to stimulus onsets are faster when the target stimulus is accompanied by a stimulus of another modality compared to the presentation of the target alone, even when the participants are advised to ignore the second stimulus (focused attention paradigm, FAP). This shortening of RTs due to the presentation of additional stimuli of different modalities has been termed intersensory facilitation effect (IFE; Hershenson 1962) and was replicated for visual–auditory stimulation (Bernstein et al. 1969; Colonius and Arndt 2001; Frens et al. 1995; Gielen et al. 1983), as well as for visual–tactile stimulation (Amlôt et al. 2003; Diederich et al. 2003; Gielen et al. 1983). It has been shown that the intensities of both target and non-target have an effect on the amount of RT facilitation (Bernstein et al. 1970, 1973; Colonius and Arndt 2001).

Moreover, utilizing a redundant target paradigm (RTP; i.e., the participant is instructed to respond to any of the stimuli upon detection) Diederich and Colonius (2004) varied the intensity of tactile and auditory stimuli that were presented in addition to a visual stimulus and found larger IFE for lower intensities. In an visual–auditory RTP task, Corneil et al. (2002) varied the intensity of an auditory stimulus presented in a visual–auditory background noise and found larger response enhancement for lower signal-to-noise ratios.

Interestingly, the inverse relation between stimulus intensity and the amount of IFE reported when utilizing RTP is supported and put into a broader context by neurophysiological observations (Stein and Meredith

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1993; Perrault et al. 2005). Cell recordings from the deep layers of the superior colliculus (DLSC) of anesthetized cats revealed that the majority of multisensory neurons show enhanced responses when they get input from more than one sensory modality, compared with the input from any of these modalities alone. Note that this paradigm is formally equivalent to an RTP task in the behavioral setting, since responses are evoked by any stimulus without focusing on a certain target modality and ignoring the other. The amount of response enhancement was shown to depend on spatial and temporal disparity and stimulus effectiveness as well. The effectiveness of stimuli was varied by manipulating their size, velocity, directional preference, and intensity. In particular, it was found that the enhancement is larger when the stimuli are less effective. This principle, termed *inverse effectiveness*, culminates in the observation that two very weak stimuli of different modalities can elicit a response from a multisensory neuron, even if this neuron responds to none of these stimuli appearing alone.

If transferred to a behavioral setting, inverse effectiveness relates to the observation that combinations of weak stimuli elicit larger IFE than do combinations of more intense ones (Colonius and Diederich 2002) which is in line with the results reported by Corneil et al. (2002) and Diederich and Colonius (2004) from RTP studies.

Bernstein et al. (1970, 1973) reported that the amount of IFE (measured as the difference between RT on the target stimulus presented alone, RT_V , and RT on a bimodal condition, RT_{VA}) increased with the intensity of an auditory non-target and decreased with the intensity of the visual target. These observations make sense, because a stronger non-target can provide more response activation in order to elicit a response, whereas a stronger target would diminish the influence of the non-target because it already provides enough response activation itself (cf. Colonius and Diederich 2004).

However, Bernstein and colleagues observed inverse effectiveness only when the intensity of the visual target was decreased but not when the intensity of the auditory non-target was decreased. Note that the intensities of the target and the non-target were not varied concurrently, but each one separately. In general, increasing the intensity of one stimulus while leaving the intensity of the other stimulus constant decreases the relative effectiveness of the latter. In the FAP, the non-target enhances response activation and the more intense the stimulus the larger the possible enhancement. Therefore, the IFE is larger due to a more intense non-target, i.e., direct effectiveness. On the other hand, a less intense target increases the relative effectiveness of the non-target. Therefore, the IFE is larger due to the less intense target, i.e., inverse effectiveness.

Furthermore, stimulus effectiveness has been varied only in terms of stimulus intensity. The duration of a stimulus could be yet another determinant of the amount of IFE, because single stimulus RT studies have

revealed that the perceived intensity of a stimulus can be changed by varying its duration and an increase in stimulus duration results in a decrease in manual RT, although this holds only for very short durations (for a summary see Luce 1986). Analogous to inverse effectiveness obtained from stimulus combination with weak intensities, an inverse relation between stimulus duration and the relative amount of IFE is plausible if we assume that it is beneficial for the organism to detect minimal stimuli.

The purpose of the present study is twofold. First, to explore whether inverse effectiveness can be observed in a visual–tactile FAP task when the effectiveness of the visual target and the tactile target is varied concurrently, i.e., when both stimuli are either of shorter or longer duration. Second, to probe the influence of different stimulus durations on the amount of multisensory integration in a FAP task. We hypothesize that the presentation of shorter stimuli results in a larger IFE compared with the presentation of longer stimuli, i.e., inverse effectiveness of stimulus duration.

Experiment 1

Methods and apparatus

Participants

Four students (ages 26–27 years) served as paid voluntary participants. All of them had normal vision and right-eye dominance. All participants were informed about the procedure and gave their informed consent prior to their inclusion in the study. The experiment was conducted in accordance with the ethical standards described in the 1964 Declaration of Helsinki.

Apparatus

The experiment took place in a completely darkened room. Stimuli were presented on a black desk (180×130×75 cm) with a recess for a chair (referred to as *vertex*). A chin rest was attached to the front edge of the vertex.

Two red light-emitting diodes (LEDs; ø5 mm, 2.4 V, 0.4 cd/m²) served as visual targets. They were placed 10° to the left or right of a central fixation point marked by a third LED (fixation LED). All LEDs were arranged on a circle with a diameter of 35 cm centered on the base of the chin rest.

Tactile stimuli were vibrations (0.6 V, 50 Hz, 1–2 mm amplitude) generated by two silenced oscillation excitors (Brüel & Kjær Mini-Shaker type 4810, referred to as *shaker*) positioned 10° to the left or right of the fixation LED, 5 cm away from the visual target in the respective hemifield. They were applied to the center of the palms through wooden balls that covered the upper ends of the shakers.

The durations of both the visual target and the tactile non-target varied. The presented stimulus durations (ms) were (30/50), (60/100), (90/150), (120/200), and (500/500), where the first entry refers to the duration of the visual stimulus.¹ For convenience, the different duration combinations are labeled D1, D2, D3, D4, and D5, respectively.

Both LEDs and shakers were controlled by a PC multifunction card.

Eye movements were recorded by the infra-red light video system EyeLink (Sensomotoric Instruments, referred to as *EyeLink*) with a spatial resolution of 0.01° and a 250 Hz sampling rate.

Procedure

The participants were advised to respond only to the onset of the visual target and to pay no attention to the tactile non-target (i.e., FAP). They were instructed to gaze as quickly and as accurately as possible to the position of the visual stimulus.

Every experimental session contained two blocks of 250 trials each, separated by a break of 10 min. At the beginning of each session the participants were customized with the experimental setup (adjusting the headband of EyeLink and the position and height of the chair). Before each block, EyeLink was calibrated. For each participant the first two sessions (1,000 trials) were omitted from the data analysis (training). Afterwards a total of 1,500 trials was recorded in three regular sessions on three separate days.

Each trial started with the onset of the fixation LED. After a variable fixation time (800–1,500 ms) the fixation LED was turned off and stimulus presentation started immediately (no gap). On *unimodal* trials the visual target appeared alone, on *bimodal* trials it was accompanied by a tactile non-target that was presented simultaneously. On *bimodal-ipsilateral* trials both visual and tactile stimuli were presented in the same hemifield; on *bimodal-contralateral* trials they were presented in different hemifields. After the offset of the stimuli a pause (2–2.45 s, depending on the duration of the stimuli presented before) in complete darkness followed, before the beginning of the next trial was indicated by the onset of the fixation LED.

No stimulus onset asynchronies were introduced, i.e., the presentation of both LED and shaker started simultaneously.

For each of the 30 different conditions (five durations × three lateralities (ipsi, contra, LED-only) × two

hemifields) 50 trials were recorded. All conditions appeared randomized within a block.

Data recording and preprocessing

The EyeLink was connected to a PC used for data storage and preprocessing. Saccades were detected trial by trial using the criteria of velocity (22° s⁻¹) and acceleration (8,000° s⁻²).

Because no systematic differences between responses from the right and the left hemifield were observed, saccadic reaction times (SRT) were combined across hemifields of stimulus presentation (left or right).

For data analysis two factors were defined: *laterality* with levels LED-only, bimodal-ipsilateral, and bimodal-contralateral and *duration* with levels D1–D5.

Results

Trials with SRTs smaller than 80 ms were excluded from evaluation (anticipation errors; cf. Becker 1991), as well as ones with SRTs longer than 500 ms (misses). Also trials with saccadic amplitudes smaller than 5° or greater than 20° (50° for participant SL²) and/or direction errors (responses to the hemifield opposite to the visual target) were excluded from further evaluation (a total of less than 4.6% errors). The rate of direction errors was the same for both lateralities.³

Mean SRTs with standard errors (black vertical lines) are plotted as a function of stimulus duration and laterality in Fig. 1 (upper plot). If presentation of the tactile non-target had not affected SRT, the three curves would be identical. Furthermore, if it made no difference whether the non-target was presented ipsilateral or contralateral to the target the dotted and the slash-dotted curves would be the same. If duration of the stimulus had no effect on SRT, all curves would be aligned horizontally.

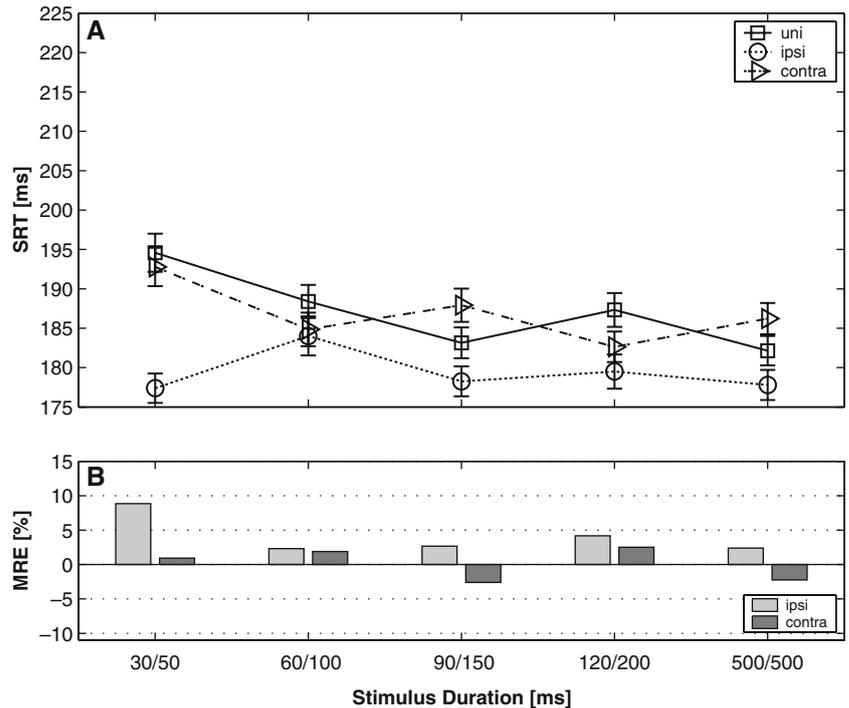
A two-way ANOVA on SRT with factors laterality and duration revealed significant results for laterality ($F_{(2,6)}=21.85$, $P \leq 0.001$), indicating that the spatial alignment of stimuli had an effect on the amount of IFE. Post hoc tests (Tukey's) showed that a tactile non-target presented ipsilateral to the visual target resulted in significantly shorter SRTs than presenting it contralateral ($P \leq 0.001$) or presenting the visual stimulus alone ($P \leq 0.001$). However, contralateral presentation of the tactile non-target did not lead to significant differences compared with presentation of the visual stimulus alone.

¹Stimulus durations were determined in unimodal pilot studies such that: (a) RT decreased monotonically with increasing stimulus duration, (b) difference in RT was as large as possible between the shortest and longest durations, and (c) steps between the lower four durations were equal in size for each modality. The longest condition (500 ms) was added to allow comparisons to earlier experiments.

²Participant SL performed saccades that systematically overshoot beyond the position of the target. This resulted in a higher mean amplitude and a larger scatter.

³This strongly suggests that participants responded according to the FAP, i.e., ignored the non-target. Otherwise, many more direction errors should have been observed on contralateral trials than on ipsilateral.

Fig. 1 Experiment 1: multisensory integration in a focused attention paradigm as a function of stimulus duration (ms) and laterality (across all participants). In each pair of durations the first entry refers to the duration of the visual stimulus. **a** Mean saccadic reaction time [SRT (ms), vertical black lines indicate standard error] decreases with increasing duration for unimodal and bimodal-contralateral presentation, but stays about the same for bimodal-ipsilateral. Unimodal mean SRTs are marked with squares, bimodal-ipsilateral SRTs with circles, and bimodal-contralateral SRTs with triangles. **b** Multisensory response enhancement [MRE (%)] is largest for ipsilateral presentation of the stimuli with the shortest durations



Moreover, the factor duration was statistically significant ($F_{(4,12)}=4.42$, $P \leq 0.001$), suggesting that different durations of stimuli led to different amounts of IFE. Mean SRT on the shortest duration D1 was significantly longer than mean SRT on durations of D3, D4, and D5, as revealed by post hoc tests ($P \leq 0.05$, $P \leq 0.05$, and $P \leq 0.01$, respectively).

A significant interaction of laterality and duration ($F_{(8,24)}=3.06$, $P \leq 0.002$) indicates that the influence of different durations varies at different conditions of laterality. Further exploration of this interaction using post hoc tests (Tukey's) revealed that significant differences were obtained only for level LED-only between durations D1 and D3, and durations D1 and D5 (both $P \leq 0.01$). Durations did not differ significantly for levels bimodal ipsilateral and bimodal contralateral.

In order to check whether or not inverse effectiveness was obtained, multisensory response enhancement (MRE) was calculated from observed mean SRT. Diederich and Colonius (2004) measured IFE in terms of MRE, a descriptive measure that relates mean RT in the unimodal condition (LED-only; i.e., RT_V), to that in the bimodal condition, (i.e., RT_{VT}):

$$MRE = \frac{RT_V - RT_{VT}}{RT_V} \times 100. \quad (1)$$

Note that this measure is applied to means tested for significant differences in an ANOVA (see above). Therefore, no further tests on this measure are necessary.

Bar plots in Fig. 1 (bottom row) show that IFE in terms of MRE was largest for ipsilateral presentation of the shortest stimuli D1.

Results of Experiment 1 show that the relative amount of IFE varied with different stimulus durations and that the shortest duration led to the largest MRE, supporting our hypothesis. However, for durations above condition D2 the amount of IFE does not appear to be influenced by stimulus duration.

Since neurophysiological studies have shown that response enhancement is greatest when stimulus intensity is near threshold (Perrault et al. 2005; Stein and Meredith 1993), evidence for inverse effectiveness might still be more convincing if stimulus duration is even shorter. This idea led us to our second experiment.

Experiment 2

The results of Experiment 1 revealed inverse effectiveness of stimulus duration only for durations below 60 ms (respectively, 100 ms for tactile stimuli). To probe whether inverse effectiveness holds for even shorter stimulus durations, a second experiment utilizing shorter stimulus durations was conducted.

Methods and apparatus

Participants

Five students (ages 20–23 years) served as paid voluntary participants. All of them had normal vision; three had right-eye and two had left-eye dominance. All participants were informed about the procedure and gave their informed consent prior to their inclusion in the study. The experiment was conducted in accordance

with the ethical standards described in the 1964 Declaration of Helsinki.

Apparatus

The experimental setup was the same as in [Experiment 1](#), except for the following differences.

Eye movements were recorded by the infra-red light video system EyeLink II (SR Research, referred to as *EyeLink II*) with a spatial resolution of 0.01° and a 500 Hz sampling rate.

To allow for the presentation of vibrations shorter than 50 ms, the shakers were operated with a higher frequency of 250 Hz. Because the shakers frequently produced noise when operated at this frequency, a background noise (white noise, 54 dB) was presented during the whole experiment, except for 10 ms of silence at the beginning of each trial for technical reasons.

Again, durations of both the visual target and the tactile non-target varied simultaneously. For both modalities the presented stimulus durations (ms) were (10, 20, 30, 40, 50, and 100 ms). Visual–tactile stimuli were presented simultaneously.

Procedure

A recording session took approximately 50 min and consisted of two blocks with 216 trials each, separated by a break of 10 min. After a training session (432 trials, excluded from analysis) four regular sessions were recorded on four separate days (1,728 trials for each participant).

Procedure and instructions to participants were the same as in [Experiment 1](#).

For each of the 36 different conditions (six durations \times three lateralities (ipsilateral, contralateral, LED-only) \times two hemifields) 48 trials were recorded. All conditions appeared randomized within a block.

Data recording and preprocessing

SRTs were collapsed across hemifields because no significant differences were observed between responses from the right and left hemifield.

For data analysis two factors were defined, laterality with levels LED-only, bimodal-ipsilateral and bimodal-contralateral, and duration with levels 10, 20, 30, 40, 50, and 100 ms.

Results

Data were tested for RT (min 80 ms; max 500 ms), amplitude [min 5° ; max 20° (50° for participant IM⁴)], and/or direction errors as in [Experiment 1](#).

⁴Participant IM performed saccades that systematically overshoot beyond the position of the target. This resulted in a higher mean amplitude and a larger scatter.

Data from participant SI were excluded from further analysis because the proportion of correct responses was below 0.4 for all lateralities. The fact that a large majority of incorrect responses failed to meet the minimum amplitude of 5° , with about half of them also being indicated as direction errors, suggests that SI had problems detecting very short stimuli.

For the four remaining participants a total of 15% of all trials were indicated as incorrect and therefore excluded from further analyses.

Mean SRTs with standard errors (black vertical lines) are drawn as a function of stimulus duration and laterality in the upper plot of [Fig. 2](#). Again, the three curves would be identical if the presentation of the tactile non-target had no influence on SRT. If the laterality of the tactile non-target had not affected SRT, the dotted and the slash-dotted curves would be the same. If there had been no effect of stimulus duration on SRT, all curves would be aligned horizontally.

A two-way ANOVA on SRT with factors laterality and duration revealed significant results for laterality ($F_{(2,6)}=56.2$, $P \leq 0.001$), indicating that the spatial alignment of stimuli had an effect on the amount of IFE. The presentation of a tactile non-target ipsilateral to the visual target led to a significant decrease in SRT compared to SRT on presentation of the visual target alone (Tukey's, $P \leq 0.001$) or the contralateral presentation of the tactile non-target ($P \leq 0.001$). SRT on contralateral presentation of the tactile non-target did not differ significantly from the SRT on presentation of the visual target alone.

Significant results were also obtained for the factor duration ($F_{(5,15)}=14.1$, $P \leq 0.001$). Post hoc tests (Tukey's) showed that SRT on the shortest stimuli (10 ms) was significantly longer than SRT on all remaining stimulus durations (all $P \leq 0.001$).

The interaction between laterality and duration was not significant (Tukey's, $F_{(10,30)}=0.71$, $P=0.714$, n.s.).

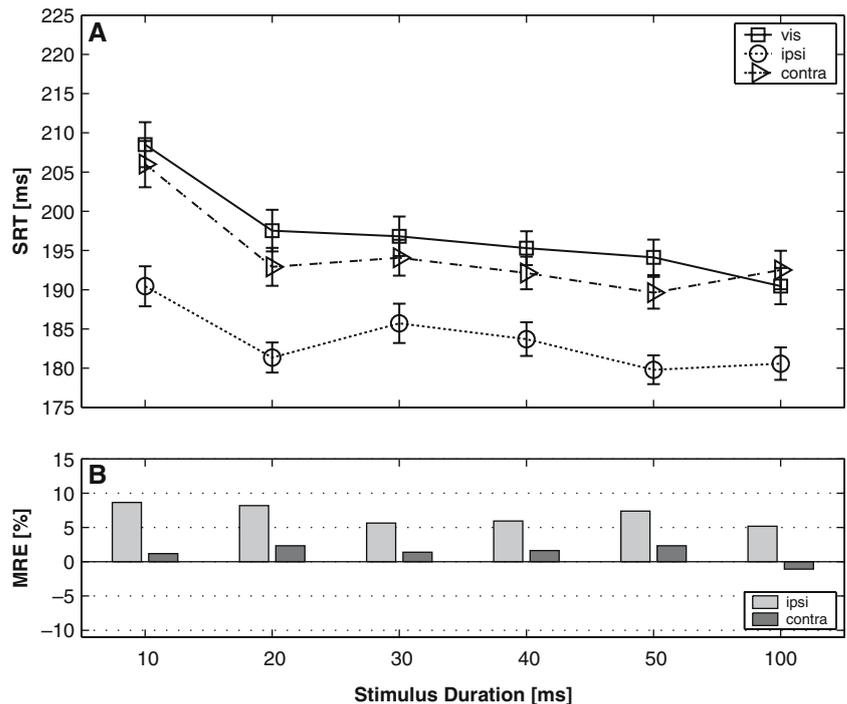
As shown in [Fig. 2](#) (bottom row), ipsilateral MRE is largest for the shortest stimulus duration (10 ms) and decreases slightly with increasing stimulus duration. For contralateral MRE no such trend is present.

Very short durations yielded reliable response enhancement, confirming the findings of [Experiment 1](#), and showing that inverse effectiveness of stimulus duration can also be demonstrated for durations below 60 ms and that ipsilateral MRE does decrease while stimulus duration increases. Ipsilateral MRE observed in [Experiment 2](#) is about the same magnitude as in the shortest condition D1 of [Experiment 1](#).

Discussion

The influence of stimulus intensity on the amount of RT facilitation in behavioral studies has been shown in studies utilizing both RTP and FAP. For RTP, larger relative amounts of IFE were observed when weaker stimuli were presented ([Corneil et al. 2002](#); [Diederich](#)

Fig. 2 Experiment 2: multisensory integration as a function of stimulus duration (ms) and laterality (across all participants). **a** Mean SRT [ms], vertical black lines indicate standard error] decreases with increasing duration for unimodal, bimodal-ipsilateral, and bimodal-contralateral presentation. Unimodal visual mean SRTs are marked with squares, bimodal-ipsilateral SRTs with circles, and bimodal-contralateral SRTs with triangles. **b** MRE (%) is largest for ipsilateral presentation of the stimuli with the shortest durations and slightly decreases with increasing stimulus duration. MRE on contralateral presentation does not appear to be influenced by stimulus duration



and Colonius 2004), a finding that is supported by neurophysiological studies on higher mammals (Perrault et al. 2005; Stein and Meredith 1993). For FAP, the pattern of results is more complicated (Bernstein et al. 1970, 1973).

The present study investigated whether duration might have a similar effect on IFE. In two experiments, utilizing an FAP with visual target and tactile non-target, we showed that this is indeed the case. In both experiments, the relative amount of IFE on ipsilateral conditions measured in terms of MRE was largest for the shortest stimulus durations and moreover, in Experiment 2, MRE on ipsilateral conditions decreased with increasing stimulus duration.

For Experiment 1, a significant interaction between laterality and duration was observed. A full exploration of the interaction revealed that stimulus duration had no effect on bimodal SRT, neither ipsilateral nor contralateral. Inverse effectiveness of stimulus duration, however, can still be postulated for the current set of data because inverse effectiveness, as defined by Stein and Meredith (1993), refers to an inverse relation between stimulus effectiveness and the relative amount of intersensory facilitation rather than between stimulus effectiveness and bimodal RT. Nevertheless, the relation between IFE and stimulus intensity, i.e., inverse effectiveness, could be explained by a ceiling effect. However, since SRT on bimodal-ipsilateral stimulation was always shorter than unimodal SRT, this possibility is ruled out for this set of data. For Experiment 2 no such interaction could be observed, ruling out the ceiling effect for our results and therefore strongly supporting the hypothesis of inverse effectiveness for very short durations. Thus, the results of Experiment 2 are consistent

with the notion that inverse effectiveness can be observed in particular when stimuli are very weak, as suggested by Perrault et al. (2005).

For Experiment 1, condition (500/500) was similar to a condition reported in Diederich et al. (2003) (the 10° conditions in all three experiments). Whereas the magnitude of MRE on ipsilateral conditions observed in our experiment was comparable to the one reported there, the magnitude of MRE on contralateral conditions was not. While Diederich et al. observed MREs between 1.8 and 4.3% for the contralateral 10° conditions, an MRE of -2.3% for the contralateral D5 condition in Experiment 1, i.e., response depression, was found. We do not have an explanation for these differing results at the moment. However, it should be noted that response enhancement and depression do not constitute distinct phenomena but rather they are two instances along the same continuum of multisensory interaction (Meredith and Stein 1986).

For both experiments, MRE on contralateral conditions seems not to be affected by stimulus duration. This suggests that inverse effectiveness of stimuli with short durations only applies if target and non-target are in close proximity. Since this effect is relatively small it might disappear with larger distances between target and non-target, as some behavioral visual-auditory studies suggest that the amount of IFE also gets smaller with increasing disparity between stimuli (e.g., Arndt and Colonius 2003; Frens et al. 1995). However, there are also studies that did not find a systematic relationship between spatial disparity and MRE (Colonius and Diederich 2004; Diederich and Colonius 2006; Diederich et al. 2003). Furthermore, neurophysiological studies on cat's DLSC neurons did not reveal a systematic relationship between

stimulus disparity and the magnitude of MRE on the level of individual neurons (cf. Kadunce et al. 2003).

The evidence from DLSC neurons is especially relevant to the investigation of SRTs, because this region has been reported not only to be an important site of multisensory integration, but also to be involved in saccade generation (Munoz and Wurtz 1995). Recently, two mechanisms facilitating shorter SRT due to multisensory integration have been revealed: the reduction of neuronal response onset latencies and an increase of premotor activity of DLSC neurons (Bell et al. 2005).

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