

Does the redundant signal effect occur at an early visual stage?

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Abstract To try and cast light on the processing locus of the redundant signal effect (RSE), i.e. the speeding of reaction time (RT) with two rather than one stimulus, we manipulated three features of redundant visual stimuli, i.e. exposure duration, intensity and interstimulus interval (ISI). We found an inverse relationship between stimulus duration or intensity and the maximum length of ISI at which an RSE occurred. These effects are broadly similar to those found in the measurement of visible persistence, i.e. the phenomenon that the sensation produced by a brief visual stimulus can outlast the duration of the physical stimulation. Therefore, we suggest that the RSE occurs at a visual processing stage. This conclusion does not rule out other subsequent stages when employing different redundant stimuli and task paradigms.

Keywords Redundancy gain · Visible persistence · Reaction time

Introduction

Reaction time (RT) to a single stimulus is typically slower than to a double stimulus, the so-called redundant signal effect (RSE). Two basic models have been proposed to explain this phenomenon, a probabilistic (Raab 1962) and a neural coactivation model (Miller 1982, 1986). The former postulates that two (or more) stimuli in a display are processed in separate channels and the fastest stimulus wins the race and triggers the response. In contrast, the coactivation

model postulates a neural convergence among the redundant stimuli. As a result, a double stimulus is processed faster than the fastest single stimulus in the pair. While for a race-model account the neural site subserving the RSE is, in a sense, immaterial, it is obviously important for the neural coactivation account. In keeping with that, Murray et al. (2001), in an event-related potential (ERP) study, found an RSE that was accounted for by probability summation and correspondingly did not find any correlated neural interactions. In contrast, in another ERP study, Miniussi et al. (1998), found a RSE explainable by coactivation and could document a neural electrophysiological correlate at the level of the P1 component. In the present study we will focus on the possible locus of coactivation and will not refer directly to RSEs attributable to probability summation.

The literature provides various examples of RSE explainable by neural coactivation, as assessed with Miller's inequality violation, that is, a mathematical means to rule out a probabilistic explanation (Miller 1982, 1986; Diederich and Colonius 1987; Schwarz and Ischebeck 1994; Miniussi et al. 1998; Cavina-Pratesi et al. 2001; Foerster et al. 2002; Savazzi and Marzi 2002; Iacoboni and Zaidel 2003; Schwarz 2006). A crucial question is whether there is a specific neural site for coactivation. In principle, stimulus convergence among redundant channels might occur at perceptual, decisional or motor stage. So far, the vast number of studies investigating the locus of the RSE with behavioural experiments in healthy or brain-damaged participants or with brain imaging experiments yielded contrasting results. As is to be expected, the results vary according to the task employed (e.g. simple versus choice RT) or the stimuli used (e.g. unisensory versus multisensory) or the technique used (behaviour, brain imaging, ERP) or, finally, according to whether healthy or brain-damaged participants have been used.

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In the present study we tested the possibility of an early visual stage of coactivation by assessing the RSE as a function of the asynchrony between two redundant stimuli (S1 and S2). Previous studies with redundant asynchronous stimuli have been mainly concerned with bimodal stimuli (Miller 1986; Diederich and Colonius 1987; Giray and Ulrich 1993; Miller and Ulrich 2003; Ulrich and Miller 1997). The finding common to all these studies was that the RSE decreases with increasing stimulus onset asynchronies (SOA). In contrast, assessment of the RSE with asynchronous unimodal visual stimuli is, to our knowledge, limited to a study by Reuter-Lorenz et al. (1995) on a patient with section of the corpus callosum. They found an average critical SOA duration of 50 ms and an RSE accountable by coactivation rather than probability summation.

Here we used unimodal visual stimuli to test the effect of stimulus duration and intensity on the temporal window over which the two asynchronous stimuli might yield an RSE. It is well known from the pioneering studies of Di Lollo (e.g. Di Lollo 1984) that the duration of visible persistence, that is, the post-offset phenomenal persistence of a visual stimulus during which information is available for encoding, is inversely proportional to the intensity and the duration of the visual stimulus. Therefore, a reasonable assumption is that the temporal window over which two asynchronous visual stimuli might summate would depend on the duration and on the intensity of the first stimulus in a pair. To test this possibility, we used an RSE paradigm with double-asynchronous stimuli and manipulated the interstimulus interval (ISI). All previous studies of the RSE as a function of temporal asynchrony between S1 and S2 used SOA rather than ISI. We preferred the latter measure because it does not include a temporal window in which S1 and S2 are physically simultaneous, albeit in different hemifields. The length of this window depends upon the exposure duration of the stimuli. Thus, if SOA is smaller than the duration of the stimuli they overlap in part. This problem is avoided when using ISI because S2 onset occurs when S1 is no longer there.

The prediction for the two experiments was that at increasing duration or intensity of S1 one should find a shortening of the temporal window compatible with a reliable RSE. In other words, the effective ISI should be longer for stimuli with lower luminance and shorter duration. A confirmation of these predictions would demonstrate that the RSE obtained with simple visual stimuli has the same constraints as the duration of visible persistence and would argue for an early perceptual locus of the RSE. Visible persistence is the result of processing at different levels in the visual system, including retinal processing but a reasonable assumption is that it represents an early perceptual operation preceding cognitive, decisional and response operations.

Experiment 1

Methods

Participants

Twelve healthy right-handed participants (three males) with normal or corrected-to-normal visual acuity took part in the experiment. Their age ranged between 21 and 34 years. All gave informed consent and the experiment was carried out according to the principles laid down in 1964 Declaration of Helsinki.

Apparatus, stimuli and procedure

The participants were seated in front of a computer screen (Nec/Multisync 5D) with their eyes at 57 cm from the centre of the screen in a dimly lit room. The refresh rate of the screen was 16 ms. A 2,000 Hz acoustic warning stimulus (200 ms duration) prompted participants to maintain fixation steady and to press the spacebar of the PC keyboard with the index finger of their right hand as quickly as possible following appearance of either a single or a double stimulus. The interval between the acoustic warning and the visual stimulus was randomised within the temporal window of 500–1,000 ms. The stimuli were luminous squares of about 1° of visual angle with a luminance of 6 cd/m². They were presented on the PC monitor at an eccentricity of 6° along the horizontal meridian either to the right or to the left of the fixation point. The background luminance was 0.001 cd/m². The participants were adapted to the room ambient light of mesopic intensity for a few minutes prior to testing. There were the following conditions of stimulus presentation: (1) single stimuli with an exposure duration of 32 (two screen refresh cycles) or 96 ms (six refresh cycles); (2) Double simultaneous stimuli with an exposure duration of 32 or 96 ms; (3) Double asynchronous stimuli with an exposure duration of 32 or 96 ms for the first stimulus (the duration of the second stimulus was fixed at 32 ms). For asynchronous double stimuli the ISI was set at 16, 32 or 48 ms (three refresh cycles); in one half of trials the first stimulus was presented to the left and in the other half to the right hemifield. The sequence of stimulus conditions and of right–left presentations was randomised. The experiment was subdivided into ten blocks of trials with an overall number of 700 presentations for each participant. There were 60 trials for each type of stimulus condition and 100 catch trials in which the target stimuli were not presented. Catch trials were introduced to discourage the participant to respond to the acoustic warning stimulus rather than to the target stimulus. Eye movements were controlled by an infrared camera. All participants included in the study had a very stable fixation.

With asynchronous stimuli RT was recorded from the onset of the first stimulus in a pair. The range of accepted RT was 140–650 ms; trials with shorter or longer RT were a minuscule minority and were not entered in the analyses. The number of omission errors was negligible.

Data analysis

For statistical analysis repeated-measure ANOVAs and Bonferroni post hoc tests were used. To rule out an explanation in terms of statistical facilitation and argue for neural coactivation, we used the formula proposed by Miller (race inequality test) which sets an upper limit for the cumulative probability of a response by any time t given redundant targets: $P(\text{RT} \leq t | T^L \text{ and } T^R) \leq P(\text{RT} \leq t | T^L) + P(\text{RT} \leq t | T^R)$, where $P(\text{RT} \leq t | T^L \text{ and } T^R)$ is the cumulative probability of a response with bilateral stimuli, $P(\text{RT} \leq t | T^L)$ is the cumulative probability of a response given a stimulus in the left visual hemifield and nothing in the right one, and $P(\text{RT} \leq t | T^R)$ is the cumulative probability of a response given a stimulus in the right visual hemifield and nothing in the left. The procedure was slightly modified for conditions with asynchronous stimuli as proposed by Miller (1986) by subtracting the relative ISI from the RT to single stimuli for any time t . When the upper bound is violated, a neural coactivation mechanism is a likely explanation; otherwise, statistical facilitation holds, although, in principle, neural coactivation cannot be ruled out. We used one-sample t tests to determine whether the inequality violations were statistically reliable.

Results

Table 1 shows mean RT for the various conditions of stimulus presentation. RT scores were statistically analysed with a two-way ANOVA with duration (32 and 96 ms) and pairing conditions (single, double simultaneous, double asynchronous with ISI of 16, 32 and 48 ms) as within factors. Both the main effect of duration [$F(1,11) = 10.989$, $P < 0.01$] and pairing conditions [$F(4,44) = 57.409$, $P < 0.001$] were significant. Also the interaction between the duration and pairing conditions was reliable [$F(4,44) = 5.302$, $P < 0.005$] indicating that the RT for the various pairing conditions differed as a function of the duration of the stimuli. Two subsequent one-way ANOVAs with pairing condition as factor were carried out separately for each stimulus duration. For the short exposure duration, pairing condition was significant [$F(4,44) = 48.637$, $P < 0.001$]. Bonferroni-corrected post hoc t tests showed that single stimuli yielded slower RT than either double simultaneous stimuli ($P < 0.001$) with a redundancy gain (RG) of 19.52 ms, or double ISI-16

Table 1 RT for single and double stimuli as a function of stimulus exposure duration in Experiment 1

	Single	Double simultaneous	Double ISI 16	Double ISI 32	Double ISI 48
32 ms	321.40	301.88	311.95	318.97	322.14
96 ms	327.93	306.06	326.99	328.08	327.89

asynchronous stimuli (RG = 9.44 ms, $P < 0.001$), whereas no reliable difference was found with respect to double ISI-32 and double ISI-48 stimuli.

For the long exposure duration, pairing condition was again significant [$F(4,44) = 32.116$, $P < 0.001$]. Bonferroni-corrected post hoc t tests showed that single stimuli yielded a slower RT only when compared to double simultaneous stimuli (RG = 21.87 ms, $P < 0.001$) whereas no reliable difference was found with respect to all double asynchronous stimuli. Figure 1a shows the RG for the two stimulus exposure durations as a function of the ISI: a reliable difference was present at ISI-16 [$t(11) = 4.254$, $P < 0.0125$] where the RG for the short exposure duration was larger than that for the long duration.

The RT data were then analysed with Miller's race inequality test to determine whether the observed RG was compatible with a race model (Miller 1982, 1986). As shown in Fig. 1b, a significant violation of the race inequality (grey rectangle) was found thus ruling out a probabilistic explanation.

The results of this experiment clearly show that the longest ISI at which a reliable RSE is still possible depends on the duration of the first stimulus in an asynchronous pair. This is in broad agreement with the properties of visible persistence (Di Lollo 1984).

Experiment 2

The general procedure and the apparatus were the same as in the preceding experiment. The only difference was that the variable of interest was stimulus intensity rather than duration. If an inverse-intensity effect holds as was the case for the inverse-duration effect found in Exp. 1 then the similarity of the temporal properties of RSE and visible persistence would be confirmed.

Methods

Participants

Ten naive healthy right-handed participants (four males) with normal or corrected-to-normal visual acuity took part in the experiment. Their age ranged between 20 and

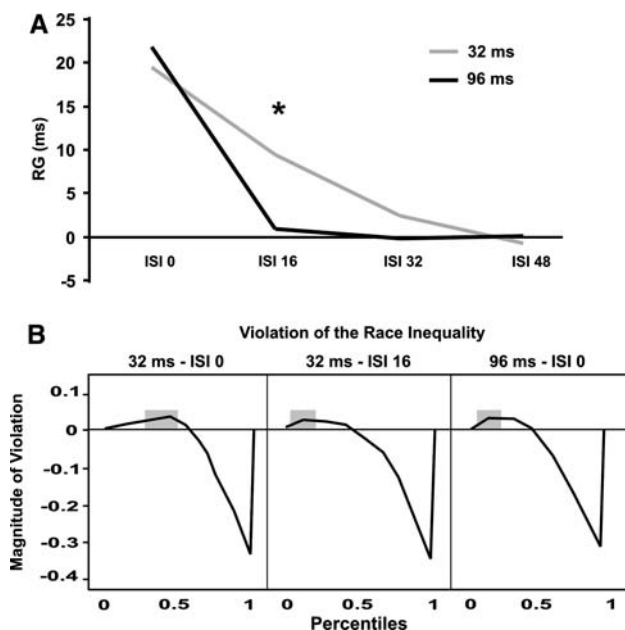


Fig. 1 Experiment 1. **a** Mean redundancy gain (*RG*), defined as RT for single stimuli minus RT for double stimuli, as a function of condition of stimulus presentation. The asterisk indicates the reliable difference in *RG* between the two conditions of stimulus duration. **b** Violation of the race inequality test for the three double-stimulus conditions. The grey rectangle marks the area in which the violation is significantly different from zero, as assessed by one-sample *t*-tests

34 years and they had normal or corrected-to-normal visual acuity. All gave informed consent and the experiment was carried out according to the principles laid out in the 1964 Declaration of Helsinki.

Apparatus, stimuli and procedure

The general procedure was the same as for Exp.1 with the difference that the stimuli had always the same exposure duration of 32 ms but different intensities. The conditions of stimulus presentation were as follows: (1) single stimuli with a luminance of 4.2 or 14.2 cd/m^2 , counterbalanced for left and right hemifield; (2) Double simultaneous stimuli with a luminance of 4.2 or 14.2; (3) Double asynchronous stimuli with a luminance of 4.2 or 14.2 for the first stimulus in the pair (the second stimulus was always kept at a luminance of 4.2 cd/m^2). The ISI between the two stimuli in a pair was set at 16, 32 or 48 ms; in one half of trials the first stimulus was presented to the left and in the other half to the right.

Data analysis

The RT data were analysed in the same way as for Exp. 1.

Results

Table 2 shows the mean RT for the various conditions of stimulus presentation.¹ The scores were statistically analysed with a two-way ANOVA with intensity (4.2 and 14.2) and pairing condition (single, double simultaneous, double asynchronous with ISI of 16, 32 and 48 ms) as within factors. Only the main effect of pairing condition was significant [$F(4,36) = 14.982$, $P < 0.001$].

Also the interaction between intensity and pairing condition was significant [$F(4,36) = 6.553$, $P < 0.001$] indicating that the RT for the various conditions was different as a function of stimulus intensity. The interaction was analysed with two one-way ANOVAs, one for each stimulus intensity with pairing condition as a factor. With lower intensity stimuli the main effect of pairing condition was significant [$F(4,36) = 13.958$, $P < 0.001$]. Bonferroni-corrected post hoc *t* tests showed that single stimuli yielded slower RT than either double simultaneous stimuli (19.64 ms, $P < 0.001$) or double ISI-16 asynchronous stimuli (13.46 ms, $P < 0.001$), whereas no difference was found at ISI-32 and ISI-48. With higher intensity stimuli, a main effect of pairing condition was again significant [$F(4,36) = 12.337$, $P < 0.001$]. However, Bonferroni-corrected post hoc *t* tests showed that single stimuli yielded slower RTs only with respect to double simultaneous stimuli (22.64 ms, $P < 0.05$) whereas no reliable difference was found with respect to asynchronous stimuli.

As for Exp. 1, we calculated the *RG* and carried out a series of Bonferroni-corrected *t* tests.

Figure 2a shows the *RG* for the two stimulus intensities as a function of ISI. *RG* turned out to be significantly different only at ISI-16 [$t(9) = 4.198$, $P < 0.0125$].

The RT data were then analysed with Miller's race inequality test. As shown in Fig. 2b, a significant violation of race inequality was found. The grey rectangle in the figure indicates the area in which the violation is significantly different from zero, as assessed by one-sample *t* tests.

As for stimulus exposure duration in Exp. 1, we found that the duration of visible persistence, as estimated on the basis of *RG*, varied as a function of stimulus intensity. Higher luminance yielded a shorter duration of VP than lower luminance. Again, this result suggests a perceptual locus for the RSE at the stage of VP.

¹ By comparing Table 2 with Table 1 one may notice that RT was overall faster in Exp. 2 even when comparing RT for the same luminance and pairing condition. Since all experimental conditions were the same in the two experiments the only conclusion is that the overall difference in RT is related to an unpredicted variability between the two groups. Clearly, this effect does not have any relevance as to the purpose of this study which is focused on a within-participant design.

Table 2 RT for single and double stimuli as a function of stimulus intensity in Experiment 2

	Single	Double simultaneous	Double ISI 16	Double ISI 32	Double ISI 48
4.2 cd/m ²	271.83	252.19	258.37	263.55	267.53
14.2 cd/m ²	270.32	247.69	269.42	268.23	267.42

Discussion and conclusions

The aim of the present study was to ascertain whether the temporal window over which a RSE occurs with asynchronous stimuli depends on the duration or the intensity of the visual stimuli. The rationale was that if the neural coactivation underlying a RSE is an early visual phenomenon, it might be affected by the same stimulus variables as those known to affect visible persistence (Di Lollo 1984) which represents an early stage of stimulus processing.

In keeping with this possibility, we found that the ISI compatible with a reliable RSE was longer for stimuli with a shorter duration or a lower intensity. According to the present results the critical window for temporal summation ranges between 16 and 32 ms, a value very similar to that found in a previous experiment with a similar paradigm but using brief light flashes as stimuli (Marzi et al. 1997). A

broadly similar mean-value (50 ms) has been found by Reuter-Lorenz et al. (1995) in a patient with total section of the corpus callosum. Clearly, these estimates are substantially shorter than the estimates of visible persistence reported in the literature. For example, Di Lollo and Bischof (1995, Fig. 1) report durations in the range 4–200 ms but these values refer to small, brief pulses superimposed on backgrounds of varying intensities while in our study only stimulus intensity was varied rather than that of the background. Further experiments are needed to relate stimulus persistence as estimated with the RSE paradigm and that estimated by classic psychophysical procedures.

A possible neural mechanism of the RSE with asynchronous stimuli is that coactivation occurs between the neural activity related to persistence of S1 and that related to S2. The neurophysiological substrate of this coactivation might be that of well established mechanisms of temporal and spatial neural summation. However, one should consider that while in visual psychophysics spatial summation is typically studied in localised areas of the visual field, here it refers to interhemispheric summation occurring in a centre which receives projections from both hemifields. Such a centre cannot typically be located in the primary visual cortex where there is a sharp retinotopic representation limited to the contralateral hemifield. It could, however, be located in visual areas with some representation of both hemifields. Clues as to the cortical site of the RSE have been provided by studies employing different methods. Miniussi et al. (1998) found an ERP correlate of coactivation at the level of the P1 component that is believed to reflect activity of extrastriate cortex. This result was corroborated by a functional magnetic resonance imaging (fMRI) study of Iacoboni et al. (2000) who found an extrastriate activation for redundant stimuli violating probability summation in an acallosal patient. Interestingly, as mentioned in the Introduction, it has been found, either in a ERP study with healthy participants (Murray et al. 2001) or in a fMRI study with acallosal patients (Iacoboni et al. 2000) that when the RSE cannot be accounted for by neural coactivation there is no neural cortical correlate of RG. In a further fMRI study Iacoboni and Zaidel (2003) found a neural correlate of the RG at premotor level and argued for a network encompassing visual extrastriate, parietal and premotor areas as a possible substrate for the RSE. In broad keeping with this possibility is the evidence provided by Turatto et al. (2004) who found that an RSE task with onset singletons as stimuli could be explained by neural coactivation while with feature singletons it was explainable by probability summation. As is well known, the magnocellular pathway is particularly sensitive to luminance changes, as is the case with onset singletons and visual motion processing

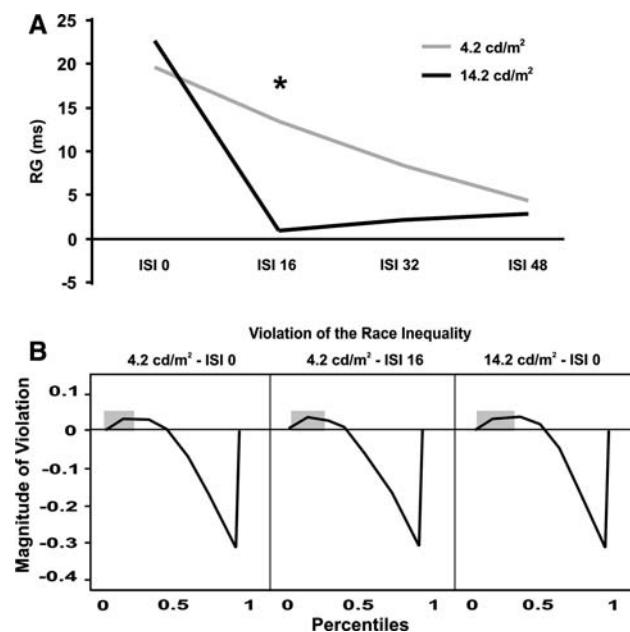


Fig. 2 Experiment 2. **a** Mean RGs as a function of conditions of stimulus presentation. The *asterisk* indicates the reliable difference in RG between the two conditions of stimulus luminance. **b** Violation of the race inequality test for the three double-stimulus conditions. The *grey rectangle* marks the area in which the violation is significantly different from zero, as assessed by one-sample *t*-tests

and is important for spatial localisation while the parvocellular pathway is mainly sensitive to form details (as is the case with form singletons) and colour and is important for object recognition. The results of Turatto et al. (2004) suggest that the neural coactivation underlying the RSE is subserved by the magnocellular system while an RSE related to probability summation is more likely to be mediated by the parvocellular system. The involvement of the magnocellular system in the RSE is in keeping with a possible important involvement in the RSE of the superior colliculus (SC), a mid-brain centre that receives a substantial magnocellular input from the retina. A role of the SC in the RSE has been suggested by two other studies with brain damaged patients. Tomaiuolo et al. (1997) found evidence of blindsight (i.e. unconscious visually guided behaviour) in two hemispherectomy patients who showed an RSE with stimuli presented across the vertical meridian despite their lack of visual awareness in one hemifield. The presence of a RSE following total removal of the visual cortex of one side strongly suggests a subcortical SC locus for coactivation. Furthermore, Savazzi and Marzi (2004) presented single or double targets to one or both hemifields in normal participants and in patients lacking the corpus callosum. Confirming previous results (see Zaidel and Iacoboni 2003 for review), they found a larger RSE in patients without callosum than in normals. Importantly, in both groups, the RSE was related to neural coactivation rather than to probability summation. The novel result was that when using monochromatic purple stimuli that are invisible to the SC (Sumner et al. 2002), they found a similar RSE in both groups but the mechanism was probabilistic rather than neural. They concluded that visual input to the SC is necessary for interhemispheric neural summation in both normals and in individuals lacking the corpus callosum while a probabilistic RSE can occur without the SC. An interesting subcortical alternative to the SC as an important site for the RSE has been suggested by Roser and Corballis (2002). They reasoned that the lack of retinotopy of the RSE is not in keeping with SC mediation but rather with a pontine or reticular site. However, one might argue that the retinotopic representation of the SC is much less precise than that of the visual cortex and might fit with the coarse retinotopy of the RSE. Clearly, Roser and Corballis' suggestion requires further experimentation.

In conclusion, we think that the site of coactivation of redundant stimuli may vary according to stimulus, task and response condition. The present results argue for a coactivation mechanism occurring at early visual stages when the RSE is tested with a simple unimodal RT paradigm.

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