

**The effects of space on multisensory integration**  
*Bachelor thesis L.M.Maasse*

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## **Abstract**

The integration of sensory signals from different modalities is sensitive not only to the spatial and temporal relationship of these sensory signals, but also to their intensity. It is said that low intensity unimodal stimuli elicit a larger integration response when presented together than high intensity unimodal stimuli do. This phenomenon is also known as inverse effectiveness. Although the mechanics of inverse effectiveness in two-dimensional space are well established, for three-dimensional space this is not so much the case.

In the present study, stimuli of different intensities were presented in near and far space in order to elicit an inverse effectiveness effect. This way a possible interaction between depth and inverse effectiveness could be examined. Integration was present in both near and far space, and stimuli of high and low intensity behaved according to the inverse effectiveness rule in both near and far space.

Although the difference in integration between high and low intensity stimuli did not differ between near and far space, an interaction effect of space with inverse effectiveness was found when comparing the near space high intensity condition with the far space low intensity condition. This outcome, together with a marginally significant main effect of distance on integration, led us to the conclusion that space on its own is too weak of a factor to significantly influence integration, but in conjunction with inverse effectiveness has an effect on multisensory integration.

## Introduction

In everyday life our senses receive a tremendous amount of sensory information, which are all processed in our brain. The sensory stimuli we experience are of many different modalities, such as the visual, auditory, and somatosensory modality. Stimuli of different modalities are processed by neurons specific to that modality, although some neurons respond to more than one modality and radically change their activity (positively or negatively) as inputs from different sensory modalities converge on such a single neuron. Such neurons where several stimuli of different modalities converge are called multisensory neurons. They make it possible for animals (including humans) to integrate different sensory stimuli as to make sense of the world around them and locate areas and objects of interest.

In the case of multisensory integration, the neuronal response of a multisensory neuron evoked when (component) stimuli of different modalities are presented simultaneously, is significantly different (as measured by number of impulses) from the response that would be created when the most effective component stimuli would be presented in isolation. This is, at the neurological level, what we call multisensory integration (Meredith & Stein, 1983).

This means that the response of individual neurons can both be inhibited or facilitated (depression or enhancement correspondingly). In practice however, when people respond to bimodal stimuli, multisensory integration often results in enhancement of the given response: the response we give to a multisensory stimulus is often greater than the response we would give to the corresponding strongest component stimulus (Stein & Stanford, 2008). Behaviorally, this is seen in the faster reaction times and more accurate responses that subjects deliver in response to multimodal stimuli versus unimodal stimuli (i.e. Giard & Peronnet, 1999). This multisensory enhancement will be the object of interest in this paper.

When the unimodal components of a bimodal stimuli are very weak in isolation (i.e. barely elicit any response at all), the integration of the corresponding neurological responses is often superadditive, so that the bimodal response exceeds the summation of the expected responses to each component stimulus in isolation. When the unimodal components are somewhat stronger in isolation, the integration of the corresponding neurological responses will be additive at best, and when even more vigorous unimodal stimuli are used the integration of the neurological responses will become subadditive. Thus, we see that multisensory enhancement is maximal when the stimuli in isolation elicit only a weak response (e.g. near threshold) (Stevenson, Fister, Barnett, Nidiffer, Wallace, 2012; Wallace et al. 1998). This inverse relation between stimulus intensity and the strength of multisensory integration is also known as inverse effectiveness (IE) (Stevenson et al., 2012).

The inverse effectiveness rule is seen in behavior of subjects as they respond to more vivid and less vivid multisensory stimuli. Because response times and accuracy for bimodal stimuli are generally better than for unimodal stimuli, it is only logical that these effects will grow accordingly as the component stimuli become less intense (and integration effects become more pronounced). Nozawa, Reuter-Lorenz, & Hughes (1994) established the relationship between reaction speed and multisensory integration: subjects gradually responded faster as multisensory stimuli with less vivid component stimuli were displayed. This is also evident in the results from other neurophysiological studies concerned with multisensory integration (e.g. Molholm, Ritter, Murray, Javitt, Schroeder, & Foxe, 2002).

Critically, for integration to occur, the two sensory cues of a bimodal stimulus need to be in close spatial and temporal proximity, enhancing the probability that they will be perceived as originating from the same event (Radeau, 1994). Because some temporal asynchrony between the two unimodal stimuli is allowed (Stevenson et al., 2012), a temporal binding window (TBW) has been defined in which there is a range of (temporal) asynchronies at which stimuli are still perceived as occurring simultaneously (Vroomen & Keetels, 2010). Several other studies have

provided conclusive evidence for such TBW; Meredith, Nemitz, and Stein (1987) showed that the strength of multisensory integration decreased rapidly as the temporal asynchrony became larger than 100 ms. For space, there is no such thing as a 'spatial binding window', although the same study (Meredith et al., 1987) also shows that at the single cell level, there is a larger integration response if the unimodal stimuli are more closely presented in space.

The fact that stimuli of different modalities need to be spatially congruent if multisensory integration is to occur (spatial rule of multisensory integration), stems from the way in which the receptive fields of multisensory neurons are organized. The receptive fields of multimodal neurons feature a central excitatory area which is surrounded by an inhibiting area. Because the auditory- and visual receptive fields of these multimodal neurons overlap, including the excitatory areas, spatially congruent stimuli fall within the corresponding excitatory areas of the same multisensory neuron, and facilitate each others activity so that multisensory enhancement can take place (Bolognini, Frassinetti, Serino, & Làdavas, 2005; Frassinetti, Bolognini, & Làdavas, 2002; Wallace, Wilkinson, & Stein, 1996).

Note however that the stimuli with different modalities (in this case visual and auditory) do not need to originate from exactly the same point in space; they just need to fall within the space where the corresponding receptive fields overlap. When two stimuli originate from different events (or in other words: locations) so that, for example, the visual stimulus falls within the excitatory receptive field of the multimodal neuron and the auditory stimulus falls outside of it (in the inhibiting region of the receptive field), the auditory stimulus will have either no effect on the neuron's response or it will lower the response to the visual stimulus (Meredith & Stein, 1996).

Such event where one component stimulus lowers the response to the other component stimulus, is called multisensory depression.

Interestingly enough, it is not always certain that multisensory enhancement will occur even though the unimodal component stimuli of a bimodal stimulus are spatially congruent, and both fall within the excitatory receptive field of a multimodal neuron. This is because the receptive fields, of neurons that encode stimuli in a reference frame according to current eye (or head/ limb) position, must shift in response to eye, head, and limb movements in order to maintain their spatial register. Although the majority of such neurons seem to lie in cortical areas such as the posterior parietal cortex (Stein & Stanford, 2008), several studies (Hartline, Vimal, King, Kurylo, & Northmore, 1995; Jay & Sparks, 1984) have pointed out that they are found in areas such as the superior colliculus as well. Although such shifts of receptive fields seem harmless at first, the fact is that receptive fields for different modalities do not always move synchronously as many multisensory neurons use different reference frames to encode visual and auditory stimuli. Schlack, Sterbing-D'Angelo, Hartung, Hoffmann, & Bremmer, (2005) showed that roughly just thirty percent of the neurons in macaque VIP encoded visual and auditory stimuli in the same reference frame, and other studies such as the ones just named (Hartline et al., 1995) are in accordance with these results.

The fact that many multisensory neurons encode stimuli of different modalities in different reference frames means that changes in, for example, eye position can change the way in which these neurons respond to bimodal stimuli, since the corresponding receptive fields do not shift equally. In theory, a center aligned eye position could cause response enhancement in the neuron while a twenty degree shift to the left or right could cause response depression, since the reference frames are different and thus the receptive fields do not move identically. It is then especially important in studies such as the current one, to keep body, head and eye alignment the same during the experiment. Otherwise, effects such as the one just described could very well be an influencing factor in the obtained multisensory integration effects.

There is also another way in which space, as a critical feature of integration, influences multisensory enhancement. According to Previc (1998), sensory information coming from different distances from the observer is processed by different regions of the brain. Some of these regions, such as the superior parietal lobule (Molholm et al., 2006) and the superior colliculus (Calvert,

Hansen, Iversen, Brammer, 2001; Meredith & Stein, 1983) are specifically involved in multisensory integration. Previc discusses four realms that together represent three-dimensional (3-D) space.

Of specific interest to the current study are near (or peripersonal) and far (or focal) extrapersonal space. The three realms that process stimuli in far space (generally the area outside of reaching distance) all share a brain region crucial to their functioning; namely the superior colliculus (Previc, 1998). Given this information that the superior colliculus is specifically involved in multisensory integration, and is a binding factor between the three realms responsible for processing stimuli in far space according to Previc (1998), it is to be expected that the same stimuli in far space elicit more multisensory integration than in near space.

To add onto this, it is worth considering the fact that stimuli located outside peripersonal space can only be perceived through some of our senses (not all of them); namely through vision, audition, and olfaction. Stimuli that are active within peripersonal space, on the other hand, can be perceived through all of our senses. It is therefore to be expected that any existing multisensory integration sites responsible for integrating multisensory information in peripersonal space, are inferior to multisensory integration sites such as the superior colliculus when it comes down to the integration of bimodal stimuli. This is because multisensory neurons responsible for integrating multisensory information in peripersonal space, will have more receptive fields compared to the multisensory neurons found in areas such as the superior colliculus. It is likely then that these multisensory neurons, responding to multimodal stimuli in peripersonal space, are consequently less activated when only a bimodal stimulus (exciting two of their possibly six (?) receptive fields) comes along, compared to their colleague neurons in the superior colliculus which have specifically evolved to process mostly bimodal stimuli.

In the present study, the role of space in multisensory integration was studied by investigating multisensory integration in four different settings: near space with stimuli presented at a low intensity (-X); near space with stimuli presented at a high intensity (-Y); far space with stimuli presented at the same low intensity (X), and far space with stimuli presented at the same high intensity (Y). All intensities are relative to the viewer; i.e. intensity X and Y for near- and far space are equal from the point of the viewer. The unimodal components of the multisensory stimuli were presented with perfect synchrony in order to maximize potential integration effects.

This setting makes for a unique situation in which we can test for the effect of space alone on integration levels by comparing the different integration values for X, and for Y (compare -X with X and -Y with Y). In addition, the role of inverse effectiveness can be ruled out since the intensities of the stimuli are the same to the observer. With no effect of inverse effectiveness, it is initially expected that space will not influence multisensory integration because there are no significant changes in the stimuli from the perspective of the viewer, between near- and far space besides those that fall under the principle of inverse effectiveness (which in this case has been eliminated).

There is some asynchrony in the time of arrival between the visual and auditory stimuli, but this asynchrony is very small (roughly 2-6 milliseconds difference for 2.2m). However, based on the earlier discussed review by Previc (1998), we may in fact expect to see faster response times in far space conditions compared to near space conditions because regions that are involved in the processing of far space stimuli have more connections to the superior colliculus.

Because we will present stimuli of low and high intensity in both near and far space, an inverse effectiveness (IE) effect will be present in each region of space (near and far). By doing this we are able to not only look for a main effect of space on integration, but also for an interaction effect of space with IE. An effect of space on integration does not necessarily have to occur through a main effect of space; this could just as well occur through an interaction effect of space with IE which is also more closely tied to real life situations, where two stimuli that are presented at different distances sporadically are of the same intensity.

We will be able to test for an interaction effect between space and inverse effectiveness by comparing the amount of integration between intensities X and Y, in near- and far space. We

hypothesized that, based on the previously discussed review by Previc (1998), space and inverse effectiveness interact in such a way that the difference in integration, between stimuli of different intensity (X and Y) in far space, is greater than the difference in integration found in near space for the same stimuli at the same intensities (a stronger inverse effectiveness effect as space is involved).

## Methods

### *Subjects*

Twenty participants were tested. All participants were in good health, did not report any hearing problems and had normal or corrected to normal vision. Before the start of each experiment, a short auditory test was carried out to see if the hearing of the participant was in order (the set up for this auditory test was equal to the set up used for the experiment, see below). Every participant could distinguish the different locations of the auditory stimuli on the short test.

Before starting the experiment, the participants were given the instructions for the test (on paper) together with an informed consent, which each participant signed. A full understanding of the task was checked by asking the participant whether everything was clear, and also by incorporating practice trials before the start of the experiment. The instructor stayed with each subject during the practice trials to make sure that the participant performed the task according to the instructions. The purpose of the experiment was unknown to the participants, and they were compensated with participant credits.

### *Stimuli and task*

Each test consisted of 720 trials, of which 360 were presented in near space and 360 were presented in far space (two blocks). Each block consisted of 180 high-intensity trials (stimuli are presented at high intensity), and 180 low-intensity trials (stimuli are presented at low intensity). Each of the 180 trials consisted of 60 auditory-alone stimuli, 60 visual-alone stimuli, and 60 auditory-visual stimuli. Each of these 60 trials consisted of 20 stimuli presented to the left of the fixation cross, 20 presented at the center of the fixation cross, and 20 presented to the right of the fixation cross, which means there were 60 stimuli presented at the center for every 180 trials. The trials in every block were presented in random order, so that participants could not predict what kind of trial would come next (auditory, visual, audio-visual; high intensity, low intensity; left, center, right).

Participants were seated in a dimly lit room in front of one of two screens. Depending on whether they would start with the task in near- or far space, targets would either be presented on the near or the far screen (see Figure 1 for setup). For near space, a white canvas was used, which was located 80 cm in front of the subject. For far space, a black canvas was used, which was located 208 cm in front of the subject. The same beamer/ projector was used for each canvas to display the screen from the computer. When targets were presented in far space, the near space screen was placed out of sight. Each trial started with the presentation of a black fixation cross ( $0.7^\circ \times 0.7^\circ$ ) at the center of the screen. After 500ms, the fixation cross disappeared and a stimulus (either auditory, visual, or audio-visual) was presented for 100ms.

For the auditory stimuli (without visual stimuli present), white noise bursts (100-ms duration,  $\pm 60$  dB SPL for low intensity and  $\pm 70$  dB SPL for high intensity, in both near and far space) were presented with one of six speakers. Three speakers in each space allowed for white noise bursts to be presented to the left, right, or at the middle of the fixation cross appearing on the screen. The speakers were placed directly behind the canvas projection screens and were set to the exact same location as where the white target dots would appear on each test. White noise bursts were used because white noise is resistant to habituation (Combs & Polich, 2006) and removes the variability of stimulus novelty (Combs & Polich, 2006).

For the visual stimuli (without auditory stimuli present), a white dot was presented ( $3^\circ \times 3^\circ$  for high intensity stimuli in both spaces,  $1.16^\circ \times 1.16^\circ$  for low intensity stimuli in both spaces). The

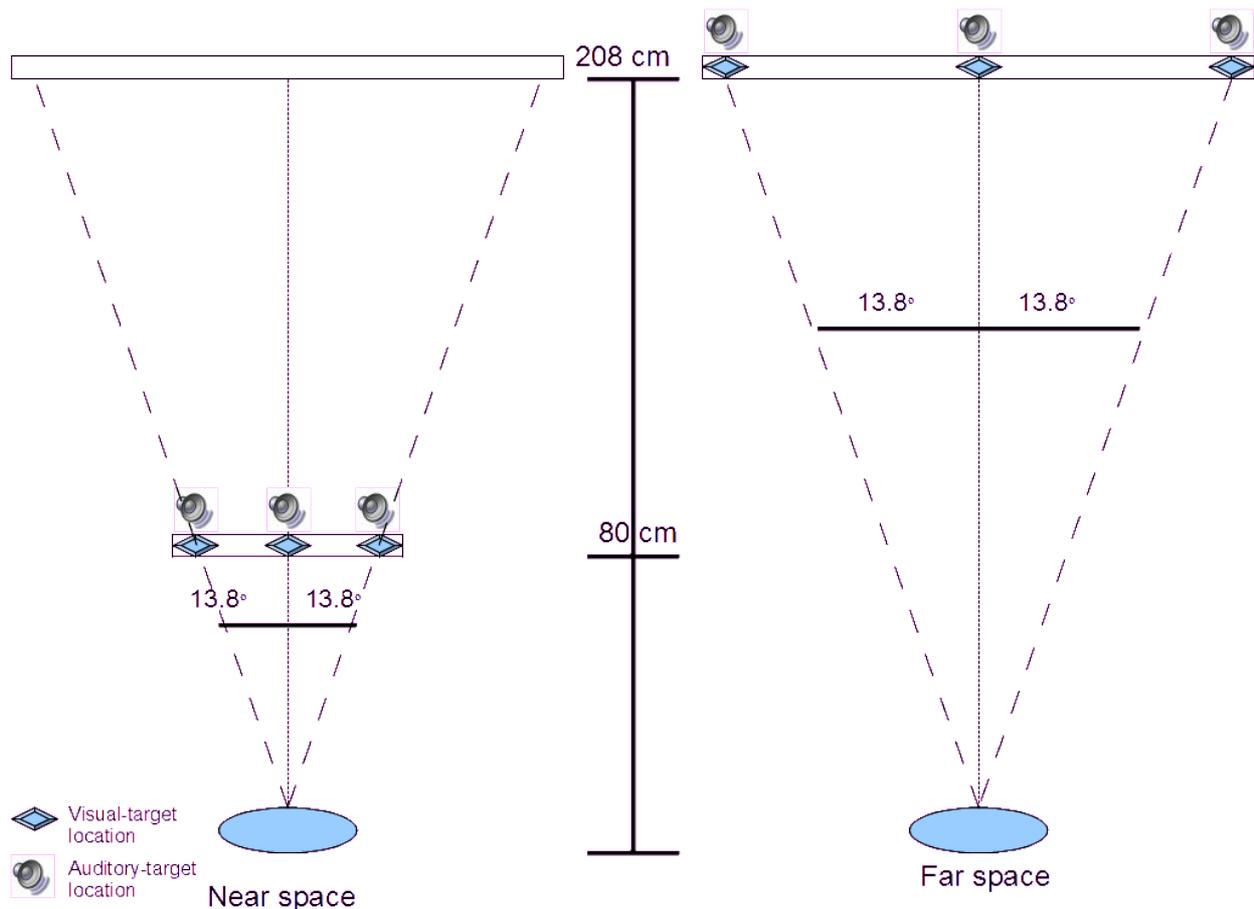
white dot was 4.22 cm in diameter for high intensity (Int.), and 1.62 cm for low intensity, in near space; and was 11.0 cm in diameter for high intensity, and 4.22 cm for low intensity, in far space. This way visual angles were kept the same for near and far space. See Table 1 for specifications.

The above described visual and auditory stimuli were presented simultaneously for the audio-visual stimuli.

Each experiment started with a short auditory localization task to make sure that the participant could distinguish between auditory cues coming from the left, middle, or right. After this auditory test, 20 practice trials were given to each participant while the researcher stayed in the room to make sure the participant understood the task. After the practice trials, the researcher left the room and the participant started the trial by pressing the space bar on a keyboard.

Participants were instructed to respond as fast and as accurate as possible to the stimuli presented to the left and the right of the fixation cross, by pressing a button on a custom made response-box. They were instructed to withhold any response when stimuli were presented at the center. The trials in which the stimuli were presented at the center functioned as catch trials (there were 60 catch trials for every 180 trials). In case of a response, or after 2000 ms, reaction times and accuracy (hit or miss) were recorded, and the experiment continued after a 1500 ms inter trial interval. Each block came with two pauses: one after 120 trials and one after 240 trials. Participants could continue with the test at any time by pressing the space bar on a keyboard. Of the twenty participants, ten started the experiment in near space and ten in far space.

Visual intensity was measured using a lux meter. Small fluctuations in the measurements are inherent to this type of device (e.g. giving a background light-intensity of 1.28 cd/m<sup>2</sup> for near space and 1.34 cd/m<sup>2</sup> for far space). This also gives room for some difference in intensity of the target between near- and far space (i.e. 6,6 cd/m<sup>2</sup> in near high vs 6,76 cd/m<sup>2</sup> in far high; 1,98 cd/m<sup>2</sup> in near low vs 1,96 cd/m<sup>2</sup> in far low). Intensity of the visual stimuli was measured on the white canvas for nearspace, and on the black canvas for far space. Intensity of the visual stimulus was adjusted in Matlab. The low-intensities and high-intensities for near- and far space were made the same by adjusting the code in Matlab.



**Fig. 1** A schematic topview of the setup for the near and the far space condition

## Data analysis

### *Preprocessing*

Data from the practice trials was left out from the analysis (both for RT and accuracy). Response times below 100 ms and above 1000 ms were filtered out. Data from participants with an accuracy lower than 70% was also removed. The assumption of sphericity was not violated for any of the significant effects. For the CDF analysis, we assumed integration was present in a condition when the CDF's of the audio, visual, and audiovisual RT's for that condition significantly violated the race model function as noted by Miller (1986):  $F(t)_{AV} \leq F(t)_A + F(t)_V$ . In other words; for any response time  $t$ , the CDF curve corresponding to the audiovisual RT's should lie below (or on top of) the race model curve which is a summation of the CDF curves corresponding to the RT's for audio and visual stimuli. When integration is present this function is violated significantly for several reaction times (see statistical analysis). Such requirement where the audiovisual RT's have to be smaller or equal to the summation of the corresponding unimodal RT's, adheres to the superadditivity requirement which takes into account that additive or subadditive audiovisual RT's could be caused by activated neighbouring unisensory neurons (Stein & Stanford, 2008).

### *Statistical analysis*

Differences in response times and accuracy, for stimuli in near- and far space and for high and low intensity, were analyzed through a 2x2x3 Repeated Measures (rm) ANOVA with the factors space (near, far), intensity (high, low), and modality (visual, auditory, audio-visual). A 2x3 repeated measures ANOVA was used to analyze the effect of space on response times and accuracy for all three modalities, and the same was done for intensity.

Table 1  
*Specifications of the visual stimuli in the four conditions*

	Measure	Degrees
High intensity in Near Space	Target-Fixation	13,8
	Target	3
	Fixation cross	0,7
	Background	
Low intensity in Near Space	Target-Fixation	13,78
	Target	1,16
	Fixation cross	0,69
	Background	
High intensity in Far Space	Target-Fixation	13,8
	Target	3
	Fixation cross	0,7
	Background	
Low intensity in Far Space	Target-Fixation	13,78
	Target	1,16
	Fixation cross	0,69
	Background	

In order to test for differences in integration between the four conditions (near space low intensity (near low), near space high intensity (near high), far space low intensity (far low), far space high intensity (far high)), cumulative distribution functions (CDF's) were generated from response times in all three modalities (audio, visual, audio-visual) in each condition (near high, near low, far high, far low), and race models by combining the CDF's of the response times to the unimodal stimuli. For integration, the CDF based on multisensory response times lies above the corresponding race model for a significant amount of response times, and is thus proof for sensory integration (Miller, 1986).

One-sample t-tests were used to test for possible violations of the race models by testing the difference between the audiovisual and race model CDF against zero, for nine bins in each of the four conditions ( $p$ -values for each bin were corrected with Motulsky's (1995) formula  $p = 1-(1-p)^n$ ). To test for the effect of space alone on race model violations (by the audio-visual CDF), we compared the average race model violation in the condition near high with race model violations in the condition far high through a paired samples t-test. We then did the same for the conditions near low and far low.

To test for our main hypothesis that the differences in integration between the high and low intensities differ between near and far space, the difference between the differences in race model violation of each participant between the conditions near high and near low, and between far high

and far low, were tested with a paired samples t-test. Depending on the results of this t-test, we were able to see if there was an interaction between space and inverse effectiveness.

Finally, a 2x7 repeated measures ANOVA was used with factors space (near, far) and bin (bins 1 to 7) to analyze a possible main effect of space and/ or bin on race-model violation, and a possible interaction between these two factors. Any other comparisons besides those made with the paired-samples t-tests just described, were done through this 2x7 repeated measures ANOVA.

## Results

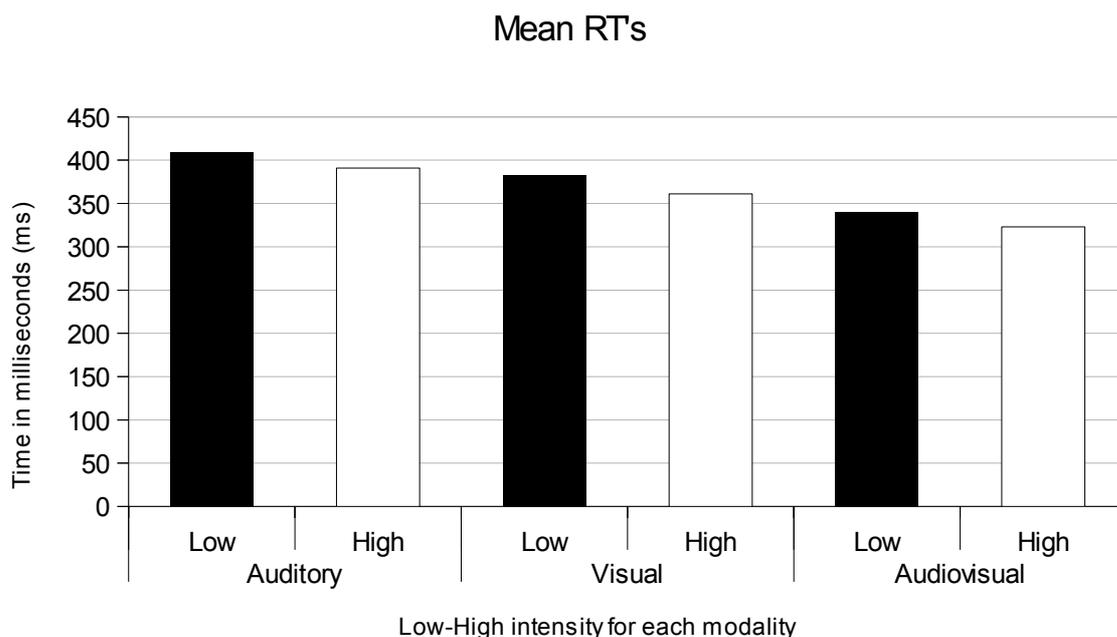
### Accuracy

The 2x2x3 repeated measures ANOVA showed no main effects of intensity, space or modality on accuracy, and showed no significant interaction effect between any of the factors. A total of three participants were removed due to poor accuracy on catch trials in several conditions (accuracies < .70). Performance for the other participants was high on target present trials (all accuracies > .85) and good on catch trials (all accuracies > .70).

### Response times

The 2x2x3 repeated measures ANOVA showed a main effect for modality [ $F(2,32) = 62.440, p < .001, \eta^2 = .796$ ]. Response times were shorter for bimodal/ audiovisual stimuli (332 ms) compared to the response times for auditory stimuli (400 ms) and visual stimuli (372 ms) (also see Figure 2). Planned pairwise comparisons indicated that response times differed significantly between the modalities of each of the three comparisons (auditory/visual: [ $F(16) = 3.900, p < .005$ ]; auditory/audiovisual: [ $F(16) = 11.756, p < .001$ ]; visual/ audiovisual: [ $F(16) = 7.592, p < .001$ ]).

Although auditory stimuli are generally processed faster by the brain than visual stimuli (Stevenson et al., 2012), auditory localization is less accurate compared to visual localization and therefore deciding between left, center or right would naturally take slightly longer for auditory stimuli. A main effect of intensity was also found [ $F(1,16) = 48.555, p < .001, \eta^2 = .752$ ], which means that response times differed significantly between stimuli of low intensity and stimuli of high intensity ( $p < .001$ ). Average response times for low intensity stimuli were larger ( $M = 377$  ms) compared to high intensity stimuli ( $M = 358$  ms). No other main effects or significant interactions were found (no main effect of space or any interaction with space was found).



**Fig. 2** The mean response times for high and low intensity grouped by modality (near and far space conditions were grouped together according to their intensity)

*Multisensory Response Enhancement*

Average multisensory response enhancements (MRE) for each condition (far space low intensity, far space high intensity, near space low intensity, near space high intensity) are shown in Table 2. No significant main effect of space or intensity was found for MRE, nor an interaction between space and intensity (all  $p > .05$ ). This indicates that the absolute amount of facilitation caused by multisensory stimulation was the same for all conditions.

*CDF Analysis*

To see if the multisensory response enhancements in each condition could be explained by an integration effect, CDF's were created from the RT data of each modality in each condition. Combining the CDF's of the RT data associated with the auditory and visual modalities generated race models. CDF's from the bimodal conditions were then compared with their corresponding race model. Differences between audiovisual CDF values and values of the corresponding race model were tested with a paired-samples t-test (for each condition).

The CDF's were partitioned into 9 bins to see at which part of the reaction time distribution the audiovisual CDF's would violate the corresponding race model. For all four conditions, at least 4 bins showed a significant race model violation (bins 1 to 4 for near space low intensity; bins 1 to 4 for near space high intensity; bins 1 to 7 for far space low intensity; bins 1 to 5 for far space high intensity,  $p < 0.05$ ). Because a significant amount of race model violation occurred in all four conditions, we concluded that multisensory integration took place in each condition.

In order to test for our first hypothesis that space influences the strength of the integration effect on its own, apart from inverse effectiveness, we compared race model violation in the near space high intensity condition with race model violation in the far space high intensity condition, and did the same for the low intensity conditions (near low and far low, see Figure 3 graphs 3 and 4), through a paired-samples t-test. The t-test showed no significant differences for

Table 2

*Mean Multisensory Response Enhancement and standard deviations for each condition*

	Mean	Std. Deviation
MRE Near Low	37,65	26,87
MRE Near High	34,29	32,88
MRE Far Low	38,71	21,17
MRE Far High	32,47	22,89

any of the 9 bins in both comparisons, indicating that space on its own has no significant effect on the amount of integration/race model violation of audiovisual stimuli.

In order to test our second hypothesis; namely that space and inverse effectiveness interact with one another so that there is a greater effect of IE in far space compared to near space, we looked at the differences in the amount of integration between conditions near high and near low, and did the same for conditions far high and far low. The difference between these two values (= the difference in integration between two conditions, being near high and near low or far high and far low) was compared with a paired-samples t-test. Across all subjects, no significant differences were found, indicating that there is no interaction effect between space and IE. One other approach we used to look for differences in integration was to test the race-model violation in each condition

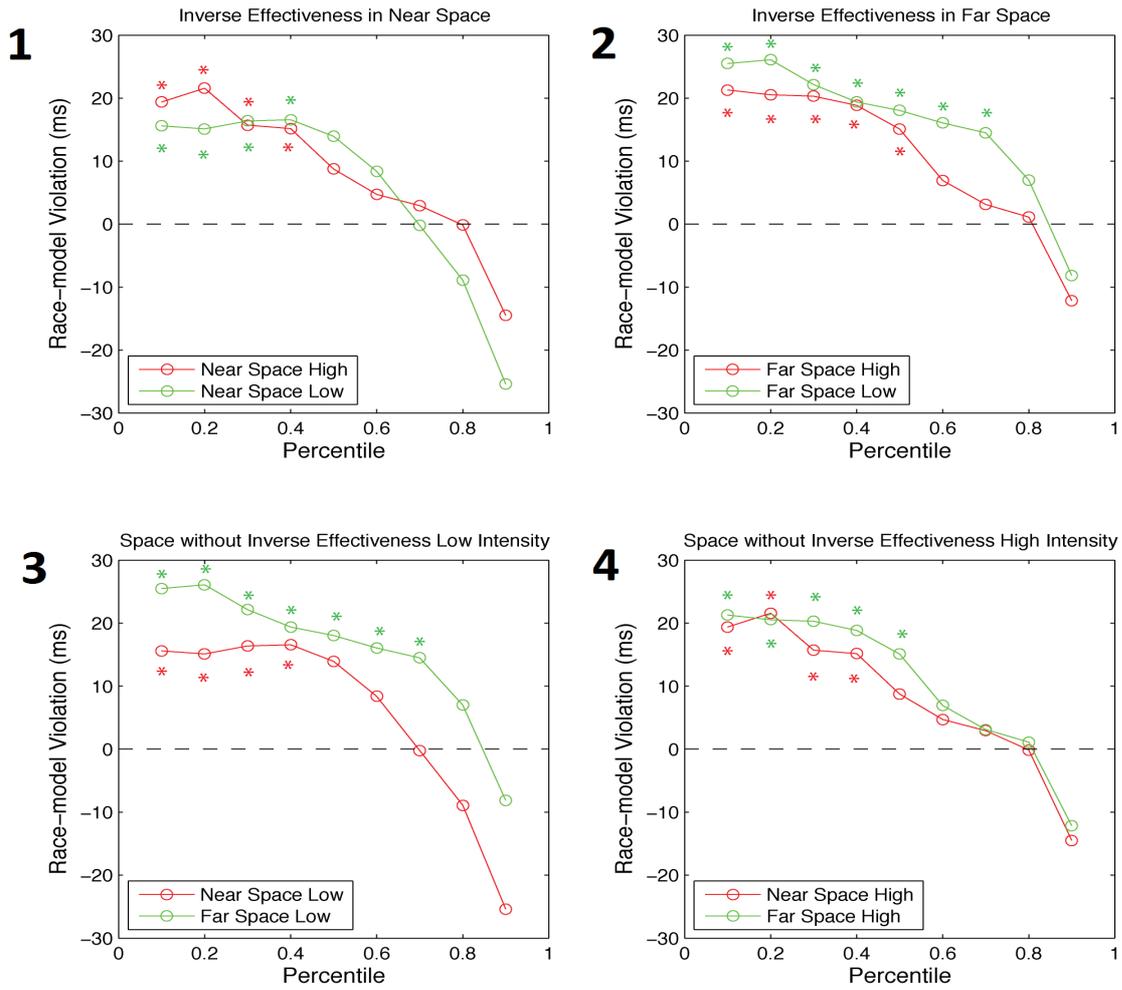
with a 2x7 repeated measures ANOVA with the factors space (near, far) and bin (1 to 7).

This 2x7 repeated measures ANOVA revealed a significant main effect of space on the amount of race-model violation between the conditions near space high intensity and far space low intensity [ $F(1,16) = 5.186, p < .05, \eta^2 = .245$ ] (Figure 4), but no main effect of space was observed for any of the other conditions (see Figure 3), although the 2x7 repeated measures ANOVA did reveal a marginally significant main effect of space on the amount of race-model violation between the conditions near space low intensity and far space low intensity [ $F(1,16) = 3.29, p = 0.088$ ]. Also a main effect of bin was found for all comparisons (including near high vs far low) ( $p < 0.001$  for all comparisons). No interaction effect between space and bin was found for any of the comparisons.

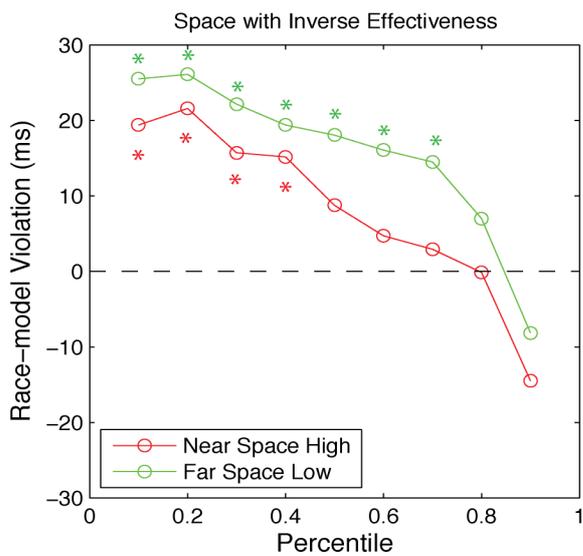
Figure 3 shows the amount of race model violation for each audiovisual CDF and shows pairwise comparisons to reveal effects of inverse effectiveness and space on the amount of integration in each condition. From looking at these graphs it is apparent that some conditions have a longer interval at which significant race-model violations still occur. This could be seen as a different measure of whether two conditions differ in the amount of integration that took place. The far space conditions in the graphs of Figure 3 and 5 have several bins more at which significant race model violation occurs compared to the near space condition, which is in line with the literature on near and far space (e.g. Previc, 1998).

By looking at these graphs, there are several arguments in favor of the idea that space on its own has an effect on the amount of integration. Graphs 1 and 2 in Figure 3 together suggest a larger IE effect in far space compared to near space, which is consistent with the idea that space interacts with IE. Graphs 3 and 4 support the idea that space on its own has an effect on integration: in each graph the near space condition has less bins at which significant race-model violation takes place compared to the far space condition. For graph 3, with the low intensity conditions, this even amounts to three more bins for the far space condition, which is consistent with the fact that low intensity stimuli elicit greater integration values and as a result will more clearly show the effects of factors such as space. Comparing the graph in Figure 4 with graph 2 from Figure 3 also hints at an interaction effect of space with IE, because IE on its own is responsible for two more significant bins while space plus IE gives three more significant bins.

Although the range of reaction times at which significant race-model violation occurs is probably a good measure to compare the amount of integration between audiovisual CDF's of different conditions, it is not clear for which difference in amount of significant bins one can say that one CDF shows significantly more integration than another CDF. For this reason, the previously described 2x7 repeated measures (rm) ANOVA with factors space (near, far) and bin (bins 1 to 7) was performed. The results of this 2x7 rm ANOVA are in line with the analysis on the range of significant race-model violation RT's just construed. The only two comparisons with a three-bin difference and a significant difference in race-model violation are the near high vs far low and near low vs far low comparisons. These were also the only two comparisons that revealed a significant and marginally significant effect of space on race-model violation respectively in the 2x7 rm ANOVA.



**Fig. 3** The CDF's of the different conditions compared with one another. Bins at which race-model violations are significant are denoted with an asterisk



**Fig. 4** showing the effect of space and IE by comparing the near high with the far low condition

## Discussion

Presenting audiovisual stimuli at different intensities at different distances and carefully matching intensities across distances in several conditions allowed us to disentangle the effects of distance and inverse effectiveness in multisensory integration. The amount of race-model violation evoked by the stimuli with high intensity presented in near space, did not differ significantly from the race-model violation amount generated by the same stimuli (same intensity) presented in far space. The same was also the case for stimuli with low intensities presented in either far space or near space, indicating that space has no effect on response times on its own (i.e. no main effect of space).

However, when both space and intensity were varied, a significant difference in amount of race-model violation was found (i.e. when the amount of race-model violation evoked by the stimuli with high intensity presented in near space, was compared with the race-model violation amount evoked by the stimuli with low intensity in far space). This means that multisensory integration is stronger when stimuli are presented further away from the observer, as long as no adjustments are made to their intensity (stimuli become naturally less intense when presented further away from the observer).

The idea that multisensory integration would be greater in far space due to an interaction between space and IE was initially rejected because the magnitude of the IE effect did not differ significantly between near and far space. However, only because both IE and space in isolation reveal no effects on race-model violation does not mean that their conjunction should not result in more prominent effects on multisensory integration. As is apparent from the just described significant difference in race-model violation when both space and intensity were varied, such conjunction of both IE and space resulting in significant effects on race-model violation backs the idea that IE and space interact.

Conclusively, it is more likely that space does influence multisensory integration, but just not so much that it has a significant effect on its own on integration values. This idea is supported by the result that space in isolation does not significantly affect integration values (the same is true of IE; see Figure 3: graphs 1 and 2 for an effect of IE, graphs 3 and 4 for an effect of space), and that a marginally significant effect of space on integration values was found when race-model violation of low-intensity stimuli was compared between near and far space. There are several points worth discussing based on the obtained results.

Although three of the four realms discussed by Previc (1998) that together represent distant 3D space all share a brain region crucial to integration (the superior colliculus, as shown by Calvert et al., 2001), the same article also discusses the superior parietal lobule which is also shown to be involved in multisensory integration (also see Molholm et al., 2006). As is described by Previc (1998), Brain (1941) noted that inferior and superior parietal lobe lesions in humans increasingly affected perceptual-motor operations used within grasping distance and walking distance respectively. Although Previc later notes that the posterior parietal lobe is crucial to the realm responsible for near space or grasping space (the PrP system) (not the superior part), and that the same brain area is also crucial to one of the far space realms, it is likely that the PrP system is not completely deprived from brain areas responsible for multisensory integration. For instance, the posterior parietal lobe consists of several subregions, of which one is the ventral intraparietal area (VIP). The VIP has been shown to be a site where multisensory integration takes place (Avillac, Hamed, Duhamel, 2007).

Increasing amounts of empirical studies reveal that the operations executed in previously defined unisensory areas are essentially multisensory (Ghazanfar & Schroeder, 2006), meaning that multisensory integration is more prevalent than we first thought in areas such as lower-order regions of sensory cortex and large parts of the neocortex. Further evidence for this comes from a study by Talsma & Woldorff (2005). In this study, ERPs to multisensory stimuli were recorded. The multisensory ERPs consisted of contralateral occipital P1 and N1 components, as well as a

fronto-central N1 component. Multisensory integration effects were measured as early as 100 msec after stimulus presentation (under the influence of spatial attention). Multisensory ERPs were first elicited in the frontal scalp, and activity then spread towards more centrally located areas (centro-medial scalp). Seeing as the superior colliculus lies deep inside the brain, it is unlikely that this area would have generated these multisensory ERPs. The same study proposes other areas that are more likely to be responsible for the ERP effects found, including the superior parietal lobula, which Previc (1998) denotes as an area especially important to the PrP system.

So even though it is clear that the far space realms have a well established brain region responsible for multisensory integration working for them, it is likely that some (if not most) of the brain areas comprising the PrP system also play a role in multisensory integration, supporting the result that space does influence integration, but not as much as would be expected when only looking at some of the highly specialized brain areas (i.e. superior colliculus) comprising the far space realms. It is valuable in this regard to look more into the neural correlates of the PrP system to see exactly what brain areas are involved and how much they are involved in multisensory integration.

It is also worth considering the used set up in this experiment, because it differs a lot from other experiments studying multisensory integration. The setup used by Lovelace, Stein, and Wallace (2003) involved an adaptive staircase to determine at what intensity level the stimuli were just detectable. This seems like a good strategy to ensure a maximal difference in the IE effect in our experiment, because the difference in intensity between the high intensity and low intensity stimuli will be greater (depending on the intensity of the high intensity conditions).

The multisensory integration strength in the low intensity conditions would be greater than it is now with the current set up, and so we could expect a bigger difference in integration between the high and low intensity conditions, as well as a bigger difference when comparing the difference in integration between the near and far space conditions. This could in turn influence the result we got on our second hypothesis, namely that the difference in integration, between the high and low intensity stimuli conditions in far space, is greater than the difference in integration found in near space for the same stimuli at the same intensities. The idea here is that a greater difference in integration makes more room for significant differences in integration strength to occur.

The decision to present the stimuli at a visual angle of roughly fourteen degrees should possibly be reconsidered. It was decided to present stimuli in the periphery to maximize multisensory integration effects, based on the idea that stimuli that are presented more off-center become less intense for the observer. According to inverse effectiveness, this should elicit greater multisensory integration effects, and thus result in faster reaction times to the bimodal stimuli.

However, as is shown in several studies (i.e. Giard & Peronnet, 1999), multisensory integration occurs earlier in time when the bimodal stimuli are presented centrally (and not peripherally). As is discussed by Talsma, Doty, and Woldorff (2007), their study (Talsma & Woldorff, 2005) in which stimuli were presented in the periphery, featured a delayed onset of multisensory ERP effects compared to that of Giard & Peronnet (1999). The difference was fifty milliseconds, which is huge in terms of reaction times to bimodal stimuli. Of course, it is highly unlikely that a difference of fifty ms in the onset of multisensory ERP effects would translate in a fifty ms difference in reaction times between stimuli presented centrally as opposed to peripherally. It does however raise the question whether our presently used setup is the best one when space as an influencing factor on multisensory integration is examined.

The current result, that space in conjunction with inverse effectiveness has an effect on multisensory integration, leads to implications for other research areas. One of these research areas is concerned with patients that show neglect for often the left side of space relative to the body. Frassinetti, Pavani, & Làdavas (2002) showed that in patients with neglect, detection of previously neglected visual stimuli could be influenced positively by the simultaneous presentation of a spatially congruent auditory stimulus. More specifically, they showed that multisensory

enhancement was greatest for peripheral stimuli locations (those areas showing the most neglect) and that in those areas the spatial rule of multisensory integration had to be respected if multisensory enhancement was to occur (which is characteristic of multisensory integration).

Conclusively, taking into account the results from the current study that space does influence multisensory integration, further research in this area should include space as a possible influencing factor. For instance, if stimuli in far space show more multisensory integration, visual stimuli that are neglected in near space even with the congruent presentation of an auditory stimulus, could become detectable in far space with all else kept the same. This area of research is already growing, showing that distance specific neglect is real and that standard neglect tests that only happen in near space are therefore insufficient (Van der Stoep, Visser-Meily, Kappelle, de Kort, Huisman, Eijsackers & Nijboer, 2013).

Another area of research for which the results of the current study can be interesting, is spatial attention. In recent decennia there has been a vast increase in the number of studies concerning attention, with more recent studies focusing on possible interactions of multisensory integration with attentional properties. Spence & Driver (1999) used an orthogonal spatial cueing paradigm in which exogenous cues could be either unimodal (visual or auditory) or bimodal (audiovisual). They found that the bimodal cues were no more effective at capturing the attention of the participant than the unimodal cues; the bimodal cues sometimes were even less effective.

Although studies such as these suggest no facilitating relationship between visual attention and multisensory integration, others have obtained results in favor of such a relationship. One such study is concerned with the effects of multimodal cues (instead of unimodal cues) in exogenous spatial cueing under the presence of a concurrent visual monitoring task (Santangelo & Spence, 2007). The study showed that multisensory (exogenous) spatial cueing effects were left unaffected by a concurrent task that otherwise caused unisensory spatial cueing effects (on capturing spatial attention) to completely disappear. However, the study also showed that for the no-load condition, bimodal exogenous spatial cues caused significantly less spatial cueing when compared with data from Santangelo, Olivetti Belardinelli, and Spence (2007) on unimodal cues.

Since all the stimuli were presented in near space (visual and auditory stimuli were presented 40cm in front of the participant) it is worth questioning what the results by Santangelo & Spence (2007) would look like if the same experiment was run in far space. Greater spatial cueing effects for the bimodal cues in a far space set up (across several perceptual-load conditions), when compared with the data from the study by Santangelo & Spence (2007), would back the result of the current study that space has a modest effect on multisensory integration. In this respect it would also be worthwhile to change the setup of the current study. Small adjustments would have to be made so that the stimuli used in the current experiment would be presented as exogenous spatial cues. Spatial cueing effects would be measured across the four conditions, and additional factors such as a concurrent visual monitoring task could be implemented. Such a setup would create a new opportunity to test for the effects of space on multisensory integration.

Studying the effects of space on multisensory integration comes with its possible downsides too, however. Exogenous attentional shifts depend on the activation of areas of the superior colliculus (SC) (Stein & Stanford, 2008); and as we already know from Previc (1998), this area is crucial to the functioning of all three far space regions, and an area with a high concentration of multisensory neurons. It seems initially plausible that activation of neurons in the superior colliculus by multisensory integration could facilitate the activity of SC neurons crucial to exogenous attentional shifts, and vice versa. Further study would have to rule out such facilitating effects before carrying out any of the just described experiments.

Most importantly, Santangelo & Spence (2007) show that making a more realistic set up (more closely tied with real life situations) can reveal new insights in how things such as multisensory integration and attention influence each other. Several other studies which suggest that multisensory integration has no effect on attention, employed a setup in which the cue and target

were the only stimuli presented to the participants, which is a completely unrealistic setting. Besides being unrealistic, such setups do not take into account the fact that attention can improve performance through either signal enhancement, noise reduction, or both (Carrasco, 2011).

Similarly, if multisensory integration draws its behavioral effects (i.e. faster RTs) partly from having the observer focus his/her attention to the bimodal stimulus, including noise in the setup may be necessary to fully display the effects of integration on behavioral output. Subsequently, the use of a concurrent visual monitoring task in the setup of the present study could be beneficial to the obtained results. The idea that a lingering effect of space on integration values cannot be fully appreciated in an unrealistic environment where the target stimuli are the only stimuli present, is an attractive one and triggers more ideas for new (more 'realistic') setups in which more significant differences between multisensory integration values among near and far space could be revealed.

Evidently, based on the just discussed literature, attention may very well be an inherent part of multisensory integration. Indeed, Talsma, Doty, & Woldorff, (2007) showed that very early (roughly fifty ms after stimulus display) multisensory integration only occurs when both modalities (visual and auditory) are attended. When only one modality was attended to, multisensory integration still occurred but at a much later time. Apparently, attention can be a modulating factor influencing the speed with which unimodal stimuli are integrated into a single percept. It may therefore be necessary to include the topic of visual attention in any future study on multisensory integration. The fact that the SC is both responsible for exogenous attentional shifts and for multisensory integration, supports this view (Meredith & Stein, 1986).

As a final remark, it should be noted that studies such as the ones just named employ a secondary attention demanding task, so that competition among stimuli is high (Talsma et al., 2007; display of a rapid stream of letters). When little to no competing stimuli are present during the presentation of stimuli relevant for the task, top-down attentional effects lose their influence on the multisensory process (see Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010).

## **Conclusion**

In this study we expected to find a main effect of space on race-model violation, or an interaction between space and IE. The results only supported the idea that space interacts with inverse effectiveness; a main effect of space on integration was not found. The fact that no significant differences in race-model violation were seen in the presence of just IE, or just space, but were in fact seen in the presence of both together, is a strong lead for the idea that space and IE interact with one another, which does not impeach the literature discussed by Previc (1998).

This result is backed very well by a biological or evolutionary viewpoint, because in everyday life stimuli further away (space factor) from us are also less intense (IE factor). Thus, when stimuli (of low intensity and outside grasping space) of different modalities are just on the edge of drawing enough attention and have good spatial and temporal proximity, the event of them happening simultaneously and at the same location must be important and so we take notice of it through the process of multisensory integration. Stimuli with sufficient spatial and temporal proximity which are observed within grasping space, are naturally more intense in isolation and consequently need not depend on multisensory integration nearly as much to be noticed by the observer. Further research on multisensory integration aiming to employ more realistic setups should incorporate secondary tasks that compete for resources with the main task, in order to simulate real life situations where bimodal stimuli are rarely seen in isolation (i.e. without the presence of other distracting stimuli). The influence of attentional effects in such experiments should be taken into consideration as they can determine the outcome of multisensory integration processes (facilitation vs interference/ depression), see Talsma, Doty, & Woldorff (2007).

## **Relevance of the current study for the Cognitive Artificial Intelligence (CAI) research field.**

Studying the functioning of the human brain, especially when looking at processes in the brain involved in sensory processing, is of great significance for development in CAI research. More intelligent robots/ autonomous computers are denoted as such when they can independently figure out what is important to process and what isn't, and the current study can consequently add to the development of more intelligent robots. As we have seen in the discussion, the influence of space on multisensory integration is backed by an evolutionary viewpoint since the chance of two unimodal stimuli in far space happening at the same time and at the same location is more exceptional, and so the event must have a higher significance than other ordinary stimuli taking place. Taking notice of such bimodal stimuli in far space, and treating it differently (i.e. making it more intense or important possibly through some process similar to multisensory integration) than other bimodal stimuli without proper temporal and spatial alignment, is intelligent behavior for an autonomous computer/ robot that has to plan its next best action in some partially observable environment. So, in other words, new insights in how the human brain works can be of great value to the ongoing development of more intelligent computers/ robots in the CAI research field. After all, a great deal in the quest of making computers more intelligent is trying to make them more similar to us humans. It seems that we often use our own capabilities as a measure of what is intelligent, so adding to the knowledge of what we are capable of also modifies what we think is intelligent, and so influences the development of autonomous agents.

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