Paying Attention to Working Memory: Similarities in the Spatial Distribution of Attention in Mental and Physical Space

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Abstract

Selective attention is not limited to information that is physically present in the external world, but can also operate on mental representations in the internal world. However, it is not known whether mechanisms of attentional selection in mental space operate in a similar fashion as in physical space. We studied the spatial distribution of attention for items in physical and in mental space by comparing how successfully distracters were rejected at varying distances from the attended location. The results indicate very similar distribution characteristics of spatial attention in physical and mental space. Specifically, we found that performance monotonically improved with increasing distracter distance relative to the attended location suggesting that distracter confusability is particularly pronounced for nearby distracters relative to further away distracters. The present findings suggest that mental representations preserve their spatial configuration in working memory, and that similar mechanistic principles underlie selective attention in physical and mental space.

Keywords: spatial attention, working memory, mental representations, distracter confusion, distribution, orienting

Humans constantly form mental representations of the external world and keep them active in working memory for further cognitive elaboration. Recent accounts of working memory describe the process of actively maintaining mental representations as selective attention that is directed towards internal representations (Awh & Jonides, 2001; Oberauer, 2009; Postle, 2006). Moreover, it has been claimed that selective attention directed towards internal representations depends heavily on resources that are shared with selective attention directed towards external stimuli (Kiyonaga & Egner, 2013). Accordingly, a growing number of studies has shown that orienting attention in mental space is characterized by the same behavioural patterns and recruits the same neural systems as orienting attention in the external world (Gazzaley & Nobre, 2012).

Most studies investigating orienting of attention in working memory use a variant of the retro-cueing paradigm developed by Griffin and Nobre (2003). This paradigm closely matches the attentional pre-cueing paradigm (Posner, 1980) and allows a direct comparison of the effects of attentional orienting in sensory and in representational space. During the retention interval in which a visual array has to be remembered, a retro-cue is presented that points towards a location in the array. Subsequently, a probe is presented at a location in the array and participants have to indicate whether the probe matches the item that was displayed at that location. As with pre-cues, cue validity effects are observed (facilitation when the retro-cue points to the location of the probe and interference when a different location is cued), suggesting that attention has shifted to the cued location in mental space.

An important remaining question is how exactly information processing at the attended location is prioritized compared to unattended information. Although the field has largely accepted the view that attention operates similarly in working memory as in perception, studies have mainly shown this in terms of the orienting of attention (Awh &

Jonides, 2001; Gazzaley & Nobre, 2012), but it is not known whether also the mechanisms of attentional selection show similar characteristics for mental and physical space. A study of how attention is distributed across distracter locations might provide direct evidence for a similar selection mechanism in mental and physical space. The present paper addresses this unexplored issue.

We directly compared the characteristics of the spatial distribution of attention in mental and in physical space under highly comparable conditions by investigating the faith of unattended locations. If there is a similar attentional selection mechanism for both mental and physical space, then the distribution characteristics in physical space should also apply to mental space. For this purpose, we developed a variant of the pre- and retro-cueing paradigm (Griffin & Nobre, 2003). Crucially, we manipulated the distance between the attended location and the location at which the proposed probe was originally presented. We investigated how this distance determined the accuracy of rejecting a distracter probe (i.e. a probe not occurring at the indicated location). The distance functions induced by pre- and retro-cueing were compared.

While it is generally agreed that attention enhances processing at the focus of attention relative to the unattended locations, theories differ with respect to how exactly attention is divided across the unattended locations. The spotlight (Posner, 1980) and zoom lens models (Eriksen & Yeh, 1985) assume a focal all-or-nothing attentional distribution with a sharp boundary between information inside or outside the focus of attention. These models predict no effect of distance. The gradient model (Downing & Pinker, 1985) assumes a monotonic distribution with activation decreasing with increasing distance from the focus of attention. This model predicts that distracters close to the focus of attention are more difficult to reject than more remote distracters. Finally, center-surround models (Hopf et al., 2005;

Störmer & Alvarez, 2014; Tsotsos et al., 1995) postulate a non-monotonic distribution with enhancement turning into inhibition for the area surrounding the focus of attention. This inhibition then gradually diminishes with further distance. Consequently, a non-monotonic effect of distance is predicted with the highest level of distracter activation at distances far away from the target.

Experiment 1

Method

Participants. Nineteen Ghent University students (3 males, *M*=23.7, *SD*=5.24) participated in return for financial compensation. One participant was excluded from the analysis because performance was close to chance level (55.5%). The research complied to the guidelines of the Independent Ethics Committee of the Department of Psychology and Educational Sciences of Ghent University. All participants gave written informed consent.

Task and Design. Participants viewed a stimulus array composed of five coloured discs that were placed on an imaginary circle. They had to memorize the discs in order to make a delayed decision about a probe that occupied one of the five locations in this stimulus array. Participants had to decide whether the colour of the probe stimulus presented at a certain location matched the colour of the item from the stimulus array (figure 1). The probability of match trials was 50%. In case of a non-match, the colour was randomly chosen from the other four locations of the stimulus array. The non-match trials allowed to study the distribution of attention across the stimulus array by comparing the distance effect between the probed location and the location from which the colour was drawn (Distances 1, 2, 3, 4). Stimuli were either presented unilaterally in the upper left or upper right quadrant with 50% probability each. Two cue type conditions were used that only differed regarding the time at which they appeared in the trial sequence. In the pre-cue condition the cue was presented before the stimulus array, while in the retro-cue condition the cue was presented after the stimulus array. The probe appeared at the cued location in 80% of the trials (valid cue) while in 20% of the trials the probe appeared on a different location than the cued location (invalid cue).

Stimuli and Procedure. A white exclamation mark (!) announcing a new trial was presented against a black background in the middle of the screen for 500 msec. This was followed by a random interval ranging from 400-600 msec. A white pre-cue was presented 1500-2500 msec before the stimulus array for 100 msec in pre-cue blocks, while a fixation cross (0.34° x 0.34° visual angle) was presented for 100 msec instead in the retro-cue trials. The stimulus array of five discs appeared then for 250 msec. The discs (radius 0.5°) were placed on an imaginary circle at 4° eccentricity. This configuration resulted in 0.34° tangential distance between the edges of each neighbouring disc. The colours (red, green, blue, yellow and pink) were randomly assigned to the discs. A white retro-cue was presented 1500-2500 msec after the stimulus array in retro-cue blocks for 100 msec, while a white fixation cross was presented for 100 msec instead in the pre-cue trials. Cues were administered in a non-coloured array by highlighting the circumference of one of the five discs that were simultaneously presented in white. After another random interval ranging from 500-1000 msec, one of the five locations in the empty array was randomly probed for 100 msec. A colour was randomly drawn from the disc locations of the stimulus array in the non-match trials, while in match trials the colour of the probe corresponded to the colour of the disc in the stimulus array. A 1600 msec response deadline was imposed.

Pre- and retro-cue blocks of the task were tested in different sessions on two consecutive days, with the order counterbalanced across participants. Each session comprised 400 trials and lasted for one hour. Each session was divided in 16 blocks of 25 trials. Responses were registered via a Cedrus RB-730 response box with the index fingers of the left and right hand, with response mappings counterbalanced across participants. Instructions emphasized both speed and accuracy. Participants were informed about the dependency between the cue, stimulus and probe arrays.

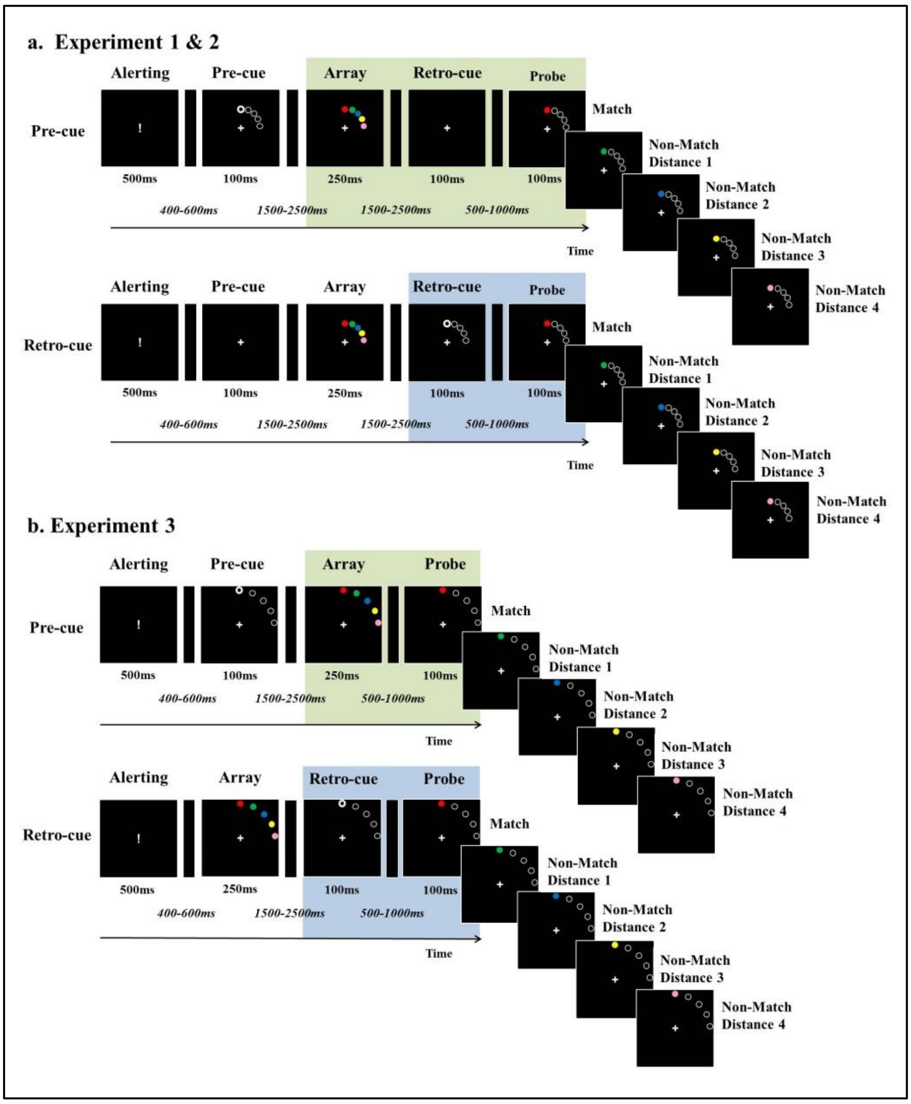

Figure 1. Experimental paradigm. Participants memorized a stimulus array coloured discs in order to make a delayed decision about a probe (i.e. a delayed match-to-sample task). The task was to decide whether the probe stimulus matched the stimulus at the location in the original array. The task in Experiment 2 was the same as in Experiment 1 except for the spacing between the discs (a). The task in Experiment 3 was the same as in Experiment 2 except for timing differences in the trial sequence. The 1500-2500 msec intervals before the stimulus array and after the stimulus array respectively in retro- and pre-cue conditions were removed (b). Green and blue areas indicate the time intervals between attentional selection and response execution respectively in pre- and retro-cue conditions. Notice that the green area in Experiments 1 and 2 are shortened in Experiment 3 to match the blue area. Italicized ranges of times relate to interstimulus intervals.

Data Analysis. Mean accuracy and reaction times in the non-match condition with valid cues were analyzed using a Repeated Measures ANOVA with *Cue Type* (pre- or retro-cue) and *Distance* (1 to 4) as within-subject factors. Reaction times below and above 2.5*SD* from the means were discarded. Multivariate test results for repeated measures are reported. To quantify the distance effect, regression analyses were performed to test for linear effects of distance conditional to *Cue Type* (following Lorch & Myers, 1990). Differences in slopes between cue types were tested by two-tailed paired *t*-tests. An alpha level of .05 was applied and Bonferroni correction was used on multiple tests to control for false-positives.

To exclude the possibility that the results were driven by the largest distances, which are limited to the outer edges of the array, we repeated all analyses with distance 4 excluded. Very similar results were obtained, so we do not report these analyses.

Additional analyses were performed as a manipulation check for attentional cueing in working memory (Supplementary Material).

Results

Accuracy. The analysis revealed a main effect of *Cue Type* [$F(1,17)=13.683$, $p=.002$, $\eta_p^2=.446$] with higher accuracies in pre-cue trials compared to retro-cue trials. Furthermore, a main of effect of *Distance* [$F(3,15)=26.530$, $p<.001$, $\eta_p^2=.841$] was obtained. The analysis also revealed a significant *Distance* by *Cue Type* interaction [$F(3,15)=4.217$, $p=.024$, $\eta_p^2=.458$]. Crucially, regression analyses revealed an accuracy increase with increasing distance in the retro-cue condition (slope=5.57, $SE=.8$; $t(17)=6.965$, p<.001, *95% CI*=[3.61,7.54]) and in the pre-cue condition (slope=3.4, $SE=.51$; $t(17)=6.635$, p<.001, *95%CI*=[2.14,4.66]), although the increase was larger in the retro-cue condition than in the pre-cue condition ($t(17)=-2.43$, $p=.026$, *95%CI*=[-4.05,-.29]). See figure 2.

Reaction Times. The analyses only revealed a significant *Distance* by *Cue Type* interaction [$F(3,15)=6.464$, $p=.005$, $\eta_p^2=.564$]. Regression analyses showed that while reaction times remained stable in the retro-cue trials (slope=3.1, $SE=4.23$, $t(17)=.728$, $p=.954$, *95%CI*=[-7.3,13.5]), they decreased with distance in the pre-cue trials (slope=-18.7, $SE=5.41$; $t(17)=-3.47$, $p=.006$, *95%CI*=[-32,-5.4]). The decrease in RTs in pre-cue condition significantly differed from the RT pattern in retro-cue condition ($t(17)=-3.205$, $p=.005$, *95%CI*=[-36.17, -7.5]).

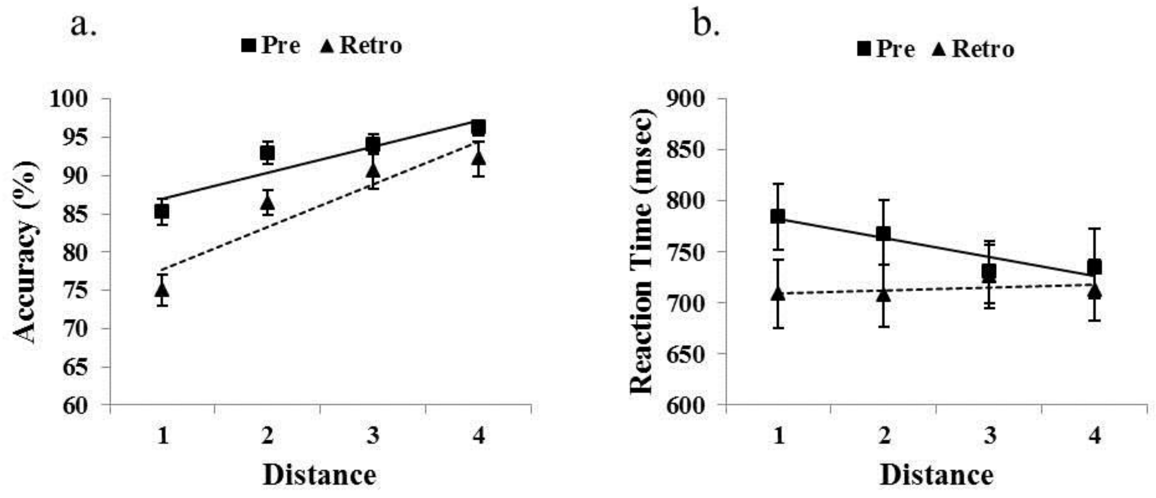

Figure 2. Accuracy (a) and reaction time (b) by *Distance* and *Cue Type* from Experiment 1. Note that distance relates to non-match trials. The regression lines for the pre- and retro cue conditions are respectively plotted in solid and dashed lines. In all cases, the error bars show the standard errors of the mean .

Discussion

The main purpose of this experiment was to study how attention is distributed across mental space and directly compare this to the attentional distribution in physical space. Results showed a clear effect of distance in physical space, in the sense that items that were located close to the target location were rejected with more difficulty (slower and less accurate) than items that were located further away. Using retro-cues, the same pattern was observed. This suggests that the mechanisms of attentional prioritizing are similar for mental and physical space.

There are, however, two issues that have to be dealt with before accepting this conclusion. First, since the items in the visual arrays were densely spaced, it is possible that the observed effects emanate from crowding rather than attentional selection. Second, the distance-related gradual performance differences in the retro-cue condition were only observed for accuracy but not for reaction times. These issues will be further explored in Experiment 2 and 3, respectively.

Experiment 2

In principle, the findings of Experiment 1 could have emerged from visual crowding as a result of the dense configuration of the discs covering a small portion of the visual field (Levi, 2008). Indeed, when neighbouring items are spaced less than one tenth of the eccentricity at which they are presented, discriminability of individual discs may become degraded (Levi, 2008). With an eccentricity of 4° and inter-item gap of 0.34° the visual arrays of Experiment 1 fell within this critical range. To rule out a crowding effect, we repeated Experiment 1 with inter-item spacing that was clearly above the crowding threshold.

Method

Participants. Twenty other Ghent University students (2 males, *M*=19.6y, *SD*=2.4) participated for course credits. One participant was excluded from the analysis because performance was close to chance level (46.5%).

Stimuli, Design and Procedure. Parameters were the same as in Experiment 1 except for the spacing between the discs which was increased. The tangential distance between discs in the array was set to 1.50° by increasing the eccentricity of discs to 8°. These parameters clearly exceed the critical spacing measures (~0.1 x eccentricity) and therefore exclude crowding effects (Levi, 2008).

Results

Accuracy. The analyses revealed a main effect of *Cue Type* [$F(1,18)=15.570$, $p=.001$, $\eta_p^2=.464$] with higher accuracies in pre-cue trials compared to retro-cue trials. Furthermore, a main of effect of *Distance* [$F(3,16)=14.917$, $p<.001$, $\eta_p^2=.737$] was obtained. Finally, the analysis also revealed a significant *Distance* by *Cue Type* interaction [$F(3,16)=4.821$, $p=.014$, $\eta_p^2=.475$]. As in Experiment 1, regression analyses revealed an accuracy increase with increasing distance for retro- (slope=4.98, *SE*=1.06; *t*(18)=4.68, *p*<.001, *95%CI*=[2.38,7.58]) and pre-cue condition (slope=2.67, *SE*=.56; *t*(18)=4.77, *p*<.001, *95%CI*=[1.30,4.04]). This increase was larger in the retro-cue condition than in the pre-cue condition (slope=2.67, *SE*=.56 ; *t*(18)=-2.3, *p*=.034 , *95%CI*=[-4.42,0.20]). See figure 3.

Reaction Times. The analyses revealed a significant effect of *Distance* [*F*(3,16)=8.293, *p*=.001, η_p^2=.609]. Although the *Distance* by *Cue Type* interaction did not reach significance at 5% alpha level, it was marginally significant [*F*(3,16)=2.981, *p*=.063, η_p^2=.359]. Regression analyses showed that while reaction times remained stable in the retro-cue trials (slope=-1.987, *SE*=5.07; *t*(18)=-.391, *p*=.70, *95%CI*=[-14.41,10.43]), they decreased with increasing distance in the pre-cue trials (slope=-19.185, *SE*=3.86; *t*(18)=-4.97, *p*<.001, *95%CI*=[-28.63,-9.74]).

When directly comparing the two experiments against one another, none of the within-subjects factors interacted with *Experiment*, nor was there a main effect of *Experiment* (all *Fs* < 1), neither on reaction times nor on accuracies.

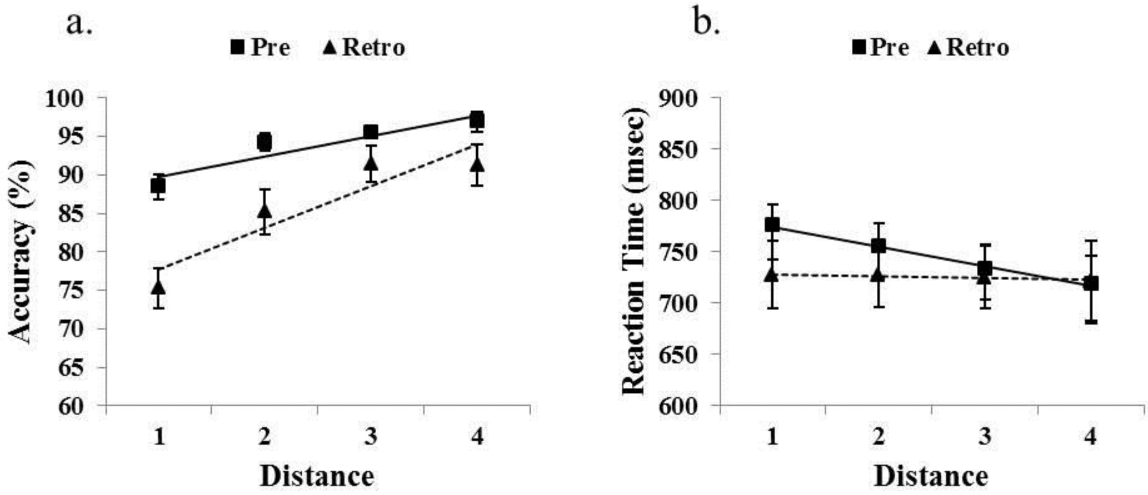

Figure 3. Accuracy (a) and reaction time (b) by *Distance* and *Cue Type* from Experiment 2. Note that distance relates to non-match trials. The regression lines for the pre- and retro cue conditions are respectively plotted in solid and dashed lines. In all cases, the error bars show the standard errors of the mean .

Discussion

The purpose of Experiment 2 was, as in Experiment 1, to investigate how attention is distributed in mental space and whether this spatial attention gradient follows a similar pattern as in physical space. Crucially, the main objective was to test whether crowding effects were underlying our findings rather than spatial attentional mechanisms per se. Key findings of Experiment 1 were replicated, namely performance gradually improved with increasing distracter distance in mental and physical space. Moreover, no *Experiment* effects were found indicating that attentional selection mechanisms brought about the results in both experiments, rather than being driven by crowding effects in Experiment 1.

Experiment 3

Although the findings from Experiment 1 and 2 converge and generally confirm that spatial attention is distributed similarly in mental and physical space as reflected in accuracy, it is not clear why reaction time measures reveal a different pattern. Reaction times do not gradually decrease when retro-cues are administered but remain stable and are overall faster compared to the pre-cue condition. A possible explanation could be the difference in duration of the interval between the moment of attentional selection and the response execution. Experiment 1 and 2 were designed such that array and probe display were temporally aligned in the pre- and retro-cue conditions. Combined with the fact that the pre-cue was delivered before the array and the retro-cue after the array, this implies that the time between attentional selection and the presentation of the probe lasts longer for the pre-cue than for the retro-cue condition. In Experiment 3, the trial events were timed such that the interval between attentional selection and the delivery of the probe was the same in these two conditions.

Method

Participants. Twenty other Ghent University students (6 males, *M*=18.3y, *SD*=0.57) participated for course credits.

Stimuli, Design and Procedure. All parameters were as in Experiment 2 except for stimulus onsets in the trial sequence (see figure 1). The 1500-2500 msec intervals before the stimulus array and after the stimulus array respectively in retro- and pre-cue conditions of this experiment were removed. These manipulations enabled the pre-cue trials to closely match retro-cue trials with respect to the timing of the critical attentional selection and probe events during the trial sequence.

Results

Accuracy. The analyses revealed a main effect of *Cue Type* [$F(1,19)=33.066$, $p<.001$, $\eta_p^2=.635$] with higher accuracies in pre-cue trials compared to retro-cue trials. Furthermore, a main of effect of *Distance* [$F(3,17)=25.749$, $p<.001$, $\eta_p^2=.820$] was evidenced. To further examine the main effect of distance, a regression analysis was performed to test for linear effects of distance. The mean accuracies linearly increased with distance (slope=3.24, $SE=.40$; $t(19)=8.102$, $p<.001$, *95%CI*=[-2.41,4.08]). The *Distance* by *Cue Type* interaction was marginally significant [$F(3,17)=2.834$, $p=.069$, $\eta_p^2=.333$]. Regression analyses revealed an accuracy increase with increasing distance for the retro- (slope=4.32, $SE=0.69$; $t(19)=6.20$, $p<.001$, *95%CI*=[2.62,6.02]) and the pre-cue condition (slope=2.09, $SE=.39$; $t(19)=5.35$, $p<.001$, *95%CI*=[1.14,3.03]), with the increase being larger in the retro-cue condition compared to the pre-cue condition ($t(19)=-2.87$, $p=.010$, *95%CI*=[-3.87,0.60]). See figure 4.

Reaction Times. The analyses revealed a marginally significant effect of *Distance* [$F(3,17)=2.923$, $p=.064$, $\eta_p^2=.340$]. Neither was there a main effect of *Cue Type* [$F(1,19) = 1.524$, $p = .23$, $\eta_p^2=.074$] nor a *Cue Type* by *Distance* interaction [$F(3,17)=1.163$, $p=.35$, $\eta_p^2=.170$] that reached significance. Regression analyses showed that the slopes in pre- and retro-cue condition did not differ from each other ($t(19)=-.861$, $p=.40$, *95%CI*=[-15.5,6.46]).

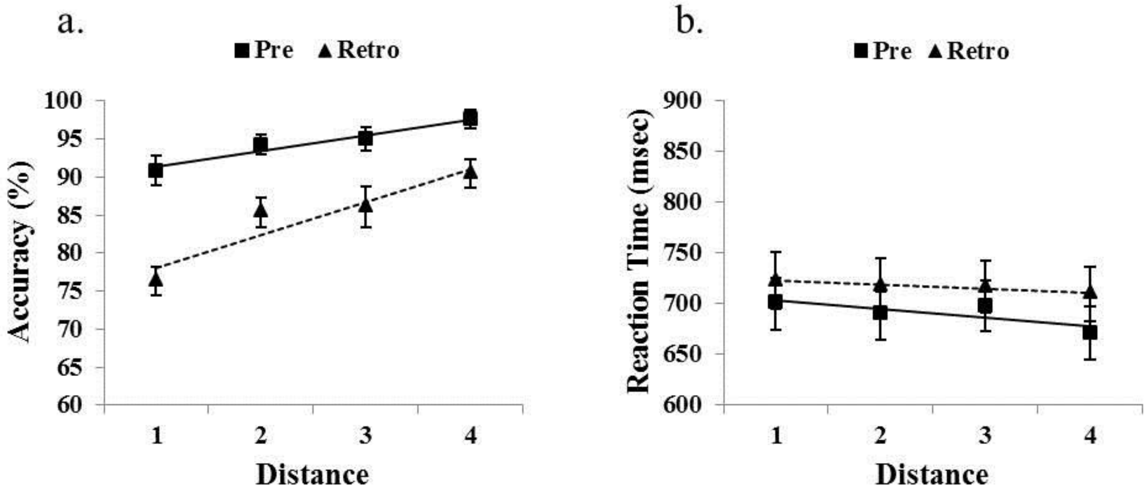

Figure 4. Accuracy (a) and reaction time (b) by *Distance* and *Cue Type* from Experiment 3. Note that distance relates to non-match trials. The regression lines for the pre- and retro cue conditions are respectively plotted in solid and dashed lines. In all cases, the error bars show the standard errors of the mean .

Discussion

The present data resolve the remaining ambiguity from Experiments 1 and 2 where the attentional distribution reflects the same distance-related pattern for pre- and retro-cue conditions, as measured by accuracy but not by reaction time. In Experiment 3, with the same duration of the interval between attentional selection and probe, the difference in reaction time patterns between the two cueing conditions disappeared.

General Discussion

Selective attention reduces the load on limited-capacity cognitive systems by not only filtering irrelevant distracters in the external visual space but also filtering irrelevant distracters within the internal mental space (Rowe & Passingham, 2001). What has not been shown yet is whether attentional selection of internal and external information relies on similar spatial mechanisms. It has been shown that orienting the focus of attention in mental space is similar to orienting attention in physical space (Griffin & Nobre, 2003). However, these findings do not clarify how unattended information at different locations outside the focus of attention is dealt with. Are unattended locations in mental space merely discarded from memory regardless of their location? Or are they instead subjected to a spatial gradient based on their relative distance to the focus of attention, very much like what is usually observed for spatial attention to physical space?

Across three experiments it was found consistently that selective attention modulates the strength of internal representations in mental space in the same way as in physical space. Crucially, our findings demonstrate that attention is distributed across unattended locations in mental space with similar distributional characteristics as attention in physical space. More precisely, performance was marked by a gradual improvement when the focus of attention was probed with a distracter item that originated from more remote locations in a mentally represented or physically present stimulus array.

Without additional assumptions, the observation that performance gradually improved with increasing distracter distance is not compatible with spotlight (Posner, 1980), zoomlens (Eriksen & Yeh, 1985) or centre-surround models (Tsotsos et al., 1995). In contrast, it is completely in line with the predictions from the gradient model (Downing & Pinker, 1985).

Our results can be naturally accommodated within the resource allocation theory of working memory (Bays & Husain, 2008), as this theory assumes flexible assignment of resources to items to be remembered. Thus far research within this framework has primarily focused on the allocation of resources as a function of the number of items to be remembered; however it has recently also been established that an attended item receives more resources than an unattended item (Pertzov, Bays, Joseph, & Husain, 2013). Our findings add to this by providing strong indications that the resources that are allocated to the unattended items are distributed as a function of the distance to the attended item. This view has also been implemented in other computational models (e.g. Kahana & Sekuler, 2002; Sederberg, Miller, Howard, & Kahana, 2010).

It is noteworthy that the gradual performance increase was more pronounced in the retro-cue condition than in the pre-cue condition. One could argue that this is indicative of different selection mechanisms. However, this is unlikely given that the distribution patterns of attention in mental and physical space match in terms of their shape. Instead, the slope differences may emerge due to differences in visual resolution between mental representations and perceptual stimuli. As visual resolution decays in memory, the confusability for distances near the focus of attention may be higher in mental space than in physical space (Ma, Husain, & Bays, 2014).

In summary, the present data suggest that the distribution of attention follows a similar pattern in physical and mental space with information close to the focus attention inducing more confusion than more distant information. Whether this means that attentional selection in physical and mental space involve the same system (e.g. Awh & Jonides, 2001) or, alternatively, engage independent systems (e. g. Hedge, Oberauer, & Leonards, 2015) with similar properties is matter for further research.

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