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BRIEF REPORT

Endogenous temporal and spatial orienting: Evidence for two distinct attentional mechanisms

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Abstract The requirement to orient attention in space and time usually occurs simultaneously. Previous reports were indecisive regarding possible interactions between temporal and spatial orienting. The present study examined whether temporal and spatial orienting can operate simultaneously and independently in the framework of a detection task. Participants completed three consecutive target detection tasks: in the first two tasks a central cue provided predictive information regarding either the temporal delay of the target or its spatial location. In a third task the temporal and spatial cues from the first two tasks were combined into a single cue. Temporal and spatial information provided by the combined cue could be valid or invalid for each type of information separately. Results from the combined temporal-spatial task revealed that at a short cue-to-target interval temporal validity effects were significant at the attended and unattended spatial locations and were not modulated by spatial validity conditions. Spatial validity effects were also significant and comparable between the valid and invalid temporal conditions. Moreover, temporal and spatial validity effects in the combined task were equivalent to those attained in the separate tasks. At a long cue-to-target delay, spatial validity effects were significant and were not modulated by temporal validity but there were no temporal validity effects. Overall, the results suggest that participants were able to extract temporal and spatial information provided by a single cue simultaneously and independently. We conclude that temporal and spatial endogenous orienting function orthogonally in a task that does not require demanding perceptual discrimination.

Keywords Attention · Temporal orienting · Spatial orienting · Endogenous orienting

The attention system is responsible for selectively allocating resources for information processing. This ability is crucial when considering the amount of information we encounter at each moment. Decades of research demonstrated how attention can prioritize processing of information automatically or voluntarily. In the present study we focused on the ability to voluntarily allocate attention in space and time. Research shows that attention can be guided flexibly and dynamically to specific locations in the visual field (i.e., endogenous spatial attention) and also to particular moments in time (i.e., endogenous temporal attention). Naturally, in a complex dynamic environment, spatial attention and temporal attention often operate simultaneously. In the present study we investigated whether endogenous orienting of attention to space and time is carried out by a single or multiple attentional mechanisms.

Endogenous spatial attention

Shifting spatial attention endogenously is a goal-directed behavior that involves top-down volitional processes and conscious awareness (for review see Chica, Bartolomeo, & Lupiáñez, 2012). Endogenous spatial attention is often measured using Posner's cueing task (Posner, 1980). In this task participants are presented with a central cue that predicts with high certainty (e.g., 75 % of the trials) the spatial location of the upcoming target. Trials in which the target appears at the

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predicted location are considered valid trials, and, conversely, invalid trials when the target appears at the opposite location to what was predicted (e.g., 25 % of the trials). Reaction times (RTs) are faster for valid compared with invalid trials. This effect is named the 'validity effect' and is used as a measure of the ability to orient attention to a spatial location endogenously.

Endogenous temporal attention

In the last decade there has been growing interest in the way attention can be allocated voluntarily to specific moments in time. Based on spatial cueing tasks, temporal orienting tasks were developed (Correa, Lupiáñez, Milliken, & Tudela, 2004; Coull & Nobre, 1998; Kingstone, 1992). In one of those tasks (Correa et al., 2004), which is similar in design to the endogenous spatial cueing task, a central cue predicts the time interval in which the target will appear. For example, a red rectangle can be used to predict with 75 % probability that the target will appear early (e.g., following 400 ms), and a blue rectangle can be used to predict that the target will appear later (e.g., following 1,400 ms). The cues are considered valid when the target appears at the predicted time (e.g., 75 % of the trials), and invalid when the target appears at a temporally unexpected time (e.g., 25 % of the trials). Temporal orienting effects are generally indexed by the validity effect only at a short interval (Correa, 2010; Lawrence & Klein, 2013). At the late interval, temporal validity effects are more fragile and are usually not reported. This is due to the fact that when the short interval has passed, participants already know with high certainty that the target will appear at the late interval (Coull & Nobre, 1998), so the temporal cue is no longer informative for the late interval. Inclusion of catch trials in which the target does not appear can diminish to some extent the certainty for target appearance at the late interval and therefore can occasionally reinstate the validity effect at late temporal intervals (Correa, Lupiáñez, & Tudela, 2006).

How do endogenous spatial and temporal orienting work together?

Endogenous spatial and temporal orienting involve voluntary shifts of attention and are both resource-consuming processes. In everyday situations these mechanisms often work together as we need to direct attention in space and time simultaneously. However, not many studies examined if and how these two systems interact. The existing literature provides some conflicting evidence.

MacKay and Juola (2007) explored whether temporal and spatial attention can function independently at the behavioral level. In their study participants performed a rapid serial visual presentation (RSVP) task in which they searched for one of two target letters. In separate blocks, different types of cues could appear prior to the target, indicating the spatial location of the upcoming target, the temporal lag in which it would appear (i.e., in how many frames following the cue), or both. They showed that the benefits from the spatial and temporal cues combined additively when the cues were presented together and suggested that spatial and temporal attention function independently. However, there were some limitations to their design. First, the spatial cue used involved exogenous properties (peripheral color change), making it difficult to dissociate between voluntary and involuntary shifts of attention. Secondly, all the cues were 100 % valid so validity effects could not be measured. Validity effects provide a good insight into how participants use the information provided by the cue.

In a design offered by Coull and Nobre (1998), validity effects for temporal and spatial orienting were examined within a single task. The design included conditions in which spatial or temporal cues were presented separately and simultaneously, creating a spatial-temporal cue. The neural correlates of temporal and spatial attention were examined. The results revealed many common brain regions associated with spatial and temporal orienting along with distinct neural activity. Behaviorally, it was hard to assess the independent nature of temporal and spatial orienting because validity was not manipulated independently for each type of orienting. For example, there was no condition in which one type of orienting delivered valid information and the other did not. What happens when a single cue provides valid spatial information but invalid temporal information and vice versa? It would seem inefficient to direct attention to the correct location but not at the right time, as it would be less useful to direct attention to the right time but not to the correct location. Support for distinct temporal and spatial orienting would be indicated by validity effects for each type of orienting that are not modulated by the other orienting type. However, a recent study that manipulated validity of temporal and spatial information independently did report an interaction (rather than independence) between the two types of orienting (Rohenkohl, Gould, Pessoa, & Nobre, 2014).

Rohenkohl and colleagues (2014) had participants perform a demanding perceptual task (i.e., discriminating the orientation of a Gabor patch). Prior to the target, a colored arrow cue appeared. The arrow direction predicted the location of the upcoming target (80 % validity) and the color indicated the interval for target appearance (80 % validity). The results showed that when the target appeared at the unattended spatial location, temporal information had no impact on visual discrimination (i.e., no temporal validity effect). However, when the target appeared at the predicted spatial location, the benefits of temporal and spatial information combined to improve perceptual discrimination. It was suggested that temporal information has no impact when the target appears at an unattended spatial location.

The authors based this argument on previous findings of an event-related potential (ERP) study showing that temporal expectation modulates response-specific components but not early perceptual components in the absence of spatial attention (Doherty, Rao, Mesulam, & Nobre, 2005).

It is still not clear whether temporal information can improve performance even at unattended spatial locations when the task does not rely heavily on perceptual processes, for example, in a simple detection task. Research has shown that attentional effects can change dramatically as a function of task requirements (e.g., Al-Janabi & Finkbeiner, 2014; Berger, Henik, & Rafal, 2005; Bridwell, Hecker, Serences, & Srinivasan, 2013; Chica, Lupiáñez, & Bartolomeo, 2006). A previous study by Correa et al. (2004) showed that temporal orienting effects are less stable in the framework of a discrimination task (with no spatial uncertainty) due to competition over shared resources with the stimulus-response mapping process. Similarly, Gabay and Henik (2008) reported that temporal information did not modulate an exogenous spatial attention effect in a target detection task but it enhanced it in a discrimination task (Gabay & Henik, 2010). In light of this literature, it is important to examine if and how endogenous temporal and spatial attention interact under a low demanding task that could amplify their influence on performance and reveal whether these two processes are fundamentally orthogonal.

The current study

The goal of the present study was to directly examine whether pure endogenous temporal and spatial attention can operate simultaneously and independently in the framework of a simple detection task. Participants performed three consecutive tasks. The first two tasks were typical temporal and spatial orienting tasks that were introduced in different blocks. Participants were required to respond as fast as possible upon detection of a target letter that could appear in one out of two possible spatial locations (i.e., left or right) and time intervals (i.e., 400 ms or 1,400 ms). In the temporal orienting task, an arbitrary central cue (shape or color) predicted with 75 % certainty the time in which the target would appear but was not predictive of its spatial location (Fig. 1a). In a spatial orienting task, an arbitrary cue predicted with 75 % certainty the spatial location of the target but was not informative of its temporal appearance (Fig. 1b). The critical task was the third task in which the temporal and spatial cues from the two separate tasks were integrated into a single cue (a colored shape, Fig. 1c). This resulted in four types of cues (temporal valid-spatial valid, temporal valid-spatial invalid, temporal invalid-spatial valid, or temporal invalid-spatial invalid). This allowed examining whether participants were able to extract and use each type of information separately and independently. Catch trials were included in all tasks to reduce anticipatory responses and to allow examination of temporal orienting effects at the late time interval (Correa et al., 2006).

According to the additive factor method (Sternberg, 1969), when two factors impact RTs independently we can assume that they represent two functionally distinct and separately modifiable processes (Sternberg, 2013). Thus, an indication that endogenous temporal and spatial orienting are two functionally distinct processes would be that their effects on RTs can be viewed independently when activated simultaneously by a single cue. That is, spatial validity effects should be similar irrespective of whether the temporal information was valid or invalid and vice versa.

Methods

Participants Forty undergraduate students from the Department of Psychology at Ben-Gurion University of the Negev took part in this experiment (nine males, aged 20–28 years) for course credit. All participants reported normal or corrected-to-normal vision. All participants gave informed consent prior to inclusion in the study. A power analysis using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that the current sample allowed for examination of temporal and spatial validity effects at a power >90 % to test medium to large effects size with a Type 1 error ($\alpha < 0.05$). Data collection was stopped only upon achieving the intended sample size of 40 participants.

Apparatus Data collection and stimuli presentation were controlled by a DELL OptiPlex 760 v Pro computer with an Intel core 2 duo processor E8400 3 GHz. Stimuli were presented on a DELL E198PF 19-in LCD monitor. E-Prime software (Psychology Software Tools, Pittsburgh, PA,USA) was used for programming, presentation of stimuli, and timing operations. Responses were collected through a keyboard.

Stimuli The display consisted of three white square boxes (5.2° each side from a viewing distance of 60 cm); one located at the center of the screen and the other two located 6.5° to the left or right of the center. A '+' fixation subtended a 0.5° visual angle. The target was the letter 'X' (1°) that appeared in one of the peripheral boxes. In the separate temporal and spatial orienting tasks, a central cue appeared that was either a shape (triangle or circle in a neutral white color, 2.5°) or a color (blue or red neutral rectangle shape, 2.5°). The assignment of color and shape for temporal and spatial cues was counterbalanced between participants. This was to ensure the cue was arbitrary and therefore purely endogenous. In the temporal-spatial orienting task, the cue was a combination of the previously

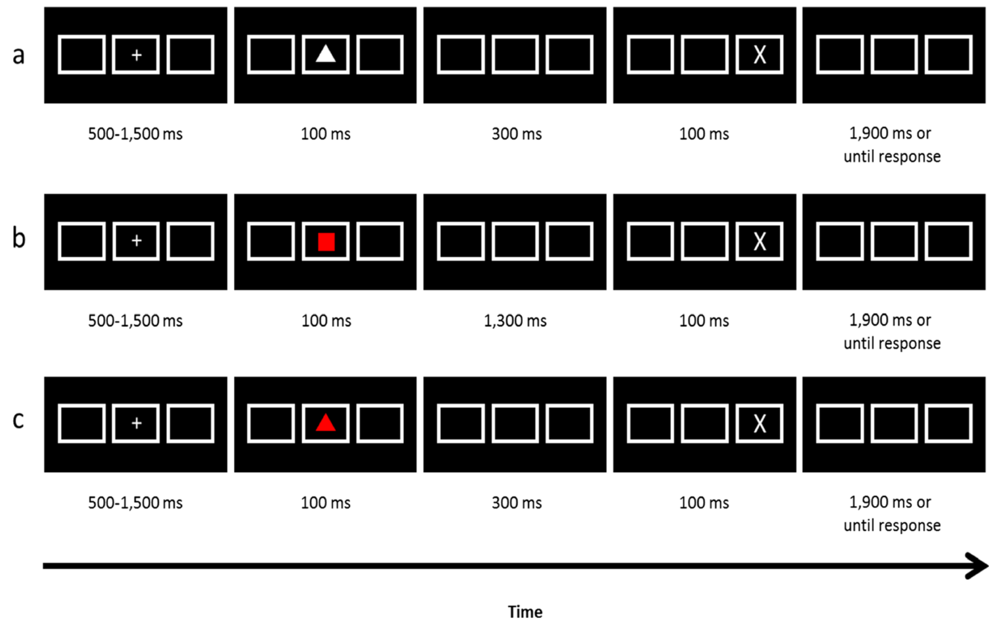

Fig. 1 Examples of typical trials in each task. **a** An example of a valid trial in the temporal orienting task with a triangle predicting target appearance at a short 400-ms stimulus onset asynchrony (SOA). **b** An invalid trial in the spatial orienting task with the color red predicting that the target would appear in the left spatial location. **c** An example of a trial in the combined temporal-spatial task in which a red triangle predicts that the target would appear shortly (400 ms) in the left spatial location. In this example the cue is valid for the temporal information but invalid for the spatial information. In the actual experiment the assignment for colors and shapes for temporal and spatial cues was counterbalanced between participants

presented colors and shapes (i.e., blue circle, blue triangle, red circle, and red triangle).

Procedure and design Participants were seated approximately 60 cm from the computer screen. All participants completed three consecutive tasks: a temporal orienting task, a spatial orienting task (the order of these tasks was counterbalanced between participants), and a combined temporal-spatial orienting task that always followed the two previous tasks.

Participants were instructed to maintain fixation at the center of the screen and to press the space bar as quickly as possible upon detection of the target. The time frame was similar for all tasks. A fixation was presented for a random interval between 500 and 1,500 ms and was replaced by a cue that lasted 100 ms. Following the cue, a blank screen was presented for either 300 or 1,300 ms. Then the target appeared for 100 ms in the left or right box and was followed by a response window for an additional 1,900 ms or until response.

In the temporal orienting task, participants were told a cue would predict with high certainty that the target would appear at a short (i.e., 400 ms) or long (i.e., 1,400 ms) time interval. The cue predicted the onset of the target at the predicted time in 75 % of the trials (valid trials). In the remaining trials, the target appeared at the unpredicted time interval (invalid trials). The cue was not informative regarding the spatial location of the target because the target appeared in half of the trials in the left box and in half of the trials and in the right box (see example of a typical trial in Fig. 1a).

In the spatial orienting task, participants were informed that a central cue would predict the spatial location of the target (left or right) with 75 % certainty. In the remaining trials the target appeared at the opposite location to what was predicted by the cue. The temporal onset of the target could not be predicted because the target appeared 50 % of the time after the short interval and 50 % after the long time interval (see Fig. 1b).

Each of the separate temporal and spatial tasks consisted of one block of 64 target trials (48 valid and 16 invalid). In addition, eight catch trials were included in which the target did not appear (i.e., catch trials/experimental trials ratio of 1:8, based on findings by Correa et al., 2006).

In the temporal-spatial cueing task, participants were shown a list of four cues (combination of the cues presented in the two earlier tasks) that would hold information regarding both the time interval and spatial location of the target (see Fig. 1c). The temporal and spatial information of the cue was predictive in 75 % of the trials, for each type of information separately. This resulted in four types of validity conditions (i.e., temporal valid-spatial valid, temporal valid-spatial invalid, temporal invalid-spatial valid, and temporal invalid-spatial invalid). This task consisted of two blocks of 192 target trials each. In addition, 24 catch trials were included in each block. Prior to the task, 12 practice trials were introduced.

Throughout all the tasks, anticipatory responses were monitored and feedback was given in case of a response before the target appearance.

Results

Separate spatial and temporal orienting tasks Trials in which RTs were less than 100 ms or greater than 1,000 ms were excluded (1.1 %). False alarms (i.e., response during catch trials) were rare (2 % and 1 % for the spatial and temporal tasks, respectively). Figure 2 shows mean RTs and standard errors per condition. A three-way analysis of variance (ANOVA) that included orienting (spatial or temporal) stimulus onset asynchrony (SOA) (400 ms or 1,400 ms) and validity (valid or invalid) was conducted (see Table 1 in Supplementary Material for full ANOVA results). The ANOVA revealed that in the spatial orienting task, there was a significant spatial validity effect at the short 400 ms SOA (35 ms), $F(1, 39) = 22.6$, $p < 0.0001$, $\eta^2_p = 0.36$, and at the long 1,400 ms SOA (25 ms), $F(1, 39) = 15.57$, $p < 0.001$, $\eta^2_p = 0.28$. In the temporal orienting task, the temporal validity effect was also significant at the short SOA (19 ms), $F(1, 39) = 10.92$, $p < 0.01$, $\eta^2_p = 0.21$, and at the long SOA (24 ms), $F(1, 39) = 13.89$, $p < 0.001$, $\eta^2_p = 0.26$.

Combined temporal-spatial orienting task. Trials in which RTs were less than 100 ms or greater than 1,000 ms were excluded (1.4 %). There were 3 % false alarm responses during catch trials. Figure 3 shows mean RTs and standard errors per condition. A three-way ANOVA with SOA (400 ms or 1,400 ms), temporal validity (temporal valid or temporal invalid), and spatial validity (spatial valid or spatial invalid) was carried out (see Table 2 in Supplementary Material for full ANOVA results). The three-way interaction was not significant, $F(1, 39) = 2.47$, $p = 0.12$, $\eta^2_p = 0.05$. At the short SOA,

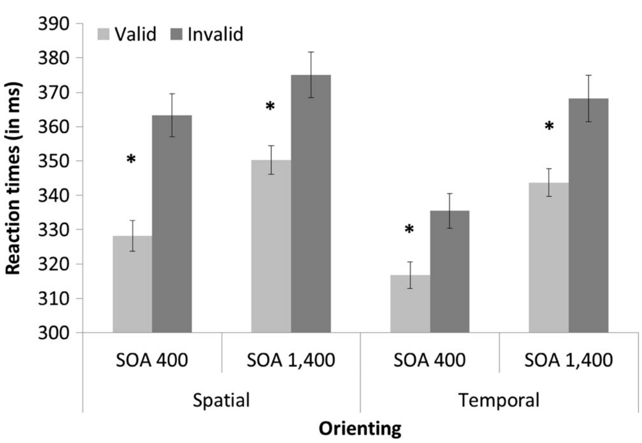

Fig. 2 Mean reaction times (RTs) as a function of orienting task, stimulus onset asynchrony (SOA) (ms), and cue validity. Error bars represent within-participants confidence intervals. * $p < 0.05$

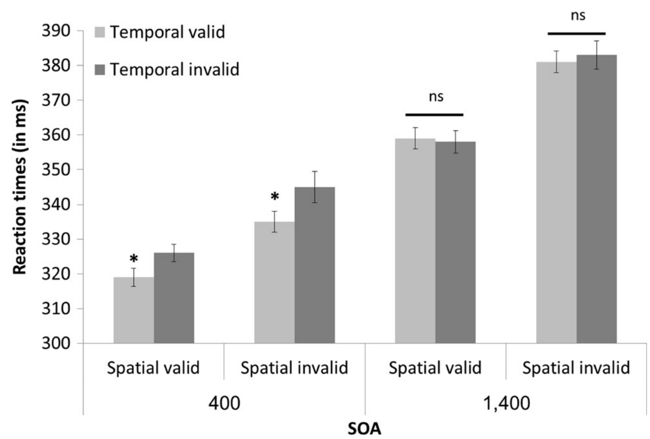

Fig. 3 Mean reaction times (RTs) as a function of temporal validity, spatial validity, and stimulus onset asynchrony (SOA). Error bars represent within-participants confidence intervals. * $p < 0.05$

the spatial validity effect was significant when the temporal information provided by the cue was valid (19 ms), $F(1, 39) = 27.18$, $p < 0.0001$, $\eta^2_p = 0.41$, and when the temporal information was invalid (27 ms), $F(1, 39) = 18.93$, $p < 0.0001$, $\eta^2_p = 0.32$. Similarly, the temporal validity effects were significant both in the valid (12 ms) and the invalid (20 ms) spatial conditions, $F(1, 39) = 9$, $p < 0.01$, $\eta^2_p = 0.18$, and $F(1, 39) = 13.32$, $p < 0.001$, $\eta^2_p = 0.25$, respectively. More critically, the temporal validity effects were not modulated by the spatial validity conditions and vice versa, $F(1,39) = 2.74$, $p = 0.10$, $\eta^2_p = 0.06$.

At the long SOA, the spatial validity effects were significant both in temporal valid (34 ms) and invalid (28 ms) conditions; $F(1, 39) = 20.7$, $p < 0.0001$, $\eta^2_p = 0.34$, and $F(1, 39) = 16.46$, $p < 0.001$, $\eta^2_p = 0.29$, respectively. In contrast, the temporal validity effects at the long SOA were not significant in the spatial valid (7 ms) and invalid (1 ms) conditions; $F(1, 39) = 2.53$, $p = 0.11$, $\eta^2_p = 0.06$, and $F < 1$, respectively. More importantly, the spatial and temporal validity conditions at the long SOA did not interact, $F < 1$[1].

Temporal and spatial validity effects in the combined vs. separate tasks In order to conduct an analysis comparing validity effects between the combined and separate tasks, further calculations were required. In the combined task, we averaged the spatial validity effect in the temporal valid and invalid conditions in order to get a measure for spatial validity, irrespective of temporal validity (and the same for temporal validity across spatial validity conditions). This averaging is based on the fact that there was no interaction between spatial validity and temporal validity effects at the short and long SOAs.

[1] The order of the separate tasks (spatial first/temporal first) and type of cue (color/shape) main effects were not significant and did not interact with the effects described.

We performed a four-way ANOVA with task (combined or separate), mode of orienting (spatial or temporal), SOA (400 or 1,400 ms), and validity (valid or invalid). A main effect for task revealed that RTs were slower in the combined compared with the separate tasks, $F(1, 39) = 8.05$, $p < 0.01$, $\eta^2_p = 0.17$. The four-way interaction was significant $F(1, 39) = 8.47$, $p < 0.01$, $\eta^2_p = 0.17$. In order to examine the source of the interaction we compared spatial and temporal validity effects between the combined and separate tasks for each SOA. Temporal validity effects were not different between the combined (16 ms) and separate task (19 ms) at the short SOA, $F < 1$), but they differed significantly at the long SOA (4 ms in the combined and 24 ms in the separate task; $F(1, 39) = 9.29$, $p < 0.01$, $\eta^2_p = 0.19$). This is because the temporal validity effects were absent at the long SOA in the combined task but not in the separate task. In contrast, spatial validity effects did not differ between the combined and separate task, either at the short SOA (23 ms in the combined and 35 ms in the separate task; $F(1, 39) = 2.43$, $p = 0.12$, $\eta^2_p = 0.05$), or at the long SOA (30 ms in the combined and 25 ms in the separate task; $F < 1$).

Discussion

The results of the present study revealed that participants were able to extract and use temporal and spatial information that was combined in a single cue simultaneously and independently. Specifically, spatial validity effects were significant, irrespective of whether the target appeared at the predicted time interval or not. The spatial validity effect in the temporal valid condition was comparable to the spatial validity effect in the temporal invalid condition. This was true for both short and long SOAs. Moreover, spatial validity effects in the combined temporal-spatial task were comparable to those reported in the separate spatial orienting task.

Temporal validity effects were also significant at the attended and unattended spatial locations. However, these effects were limited to the early SOA. At the early SOA, temporal validity effects did not differ between the spatial valid and invalid conditions. Moreover, the temporal validity effect at the short SOA in the combined task was equivalent to that at the short SOA in the separate temporal orienting task. At the long SOA, temporal validity effects were absent. This is in contrast to the significant temporal validity effect at the long SOA of the separate temporal task.

Note that the absence of temporal validity effects at the long SOA in the combined temporal-spatial task does not point to an interaction with spatial attention because spatial validity did not modulate the temporal effect (i.e., temporal validity was absent in the valid and invalid spatial condition). A possible explanation for the absent temporal validity effect in the combined task is related to increased working memory load in this task. Earlier work showed that increased working memory load disrupts temporal orienting effects (Capizzi, Sanabria, & Correa, 2012). In the combined task, participants were required to memorize four cue conditions. This also resulted in slower RTs in the combined compared to the separate tasks. Because temporal validity effects at long SOAs are fragile and rarely reported to begin with (Correa, 2010; Lawrence & Klein, 2013; see also introduction section), it is not surprising that increased load would impair these effects, sparing the more stable temporal validity effects at the short SOA.

Overall, the results indicate that temporal and spatial information provided simultaneously can be handled independently. According to the additive factor method, this suggests that endogenous temporal and spatial orienting can be considered orthogonal constructs that are based upon functionally distinct processes (Sternberg, 1969; however for a debate concerning the additive factor method see Stafford & Gurney, 2011; Sternberg, 2013).

Our findings are in contrast to results reported recently in a study by Rohenkohl and colleagues (2014). In the framework of a demanding perceptual discrimination task, Rohenkohl and colleagues reported an interaction between endogenous temporal and spatial orienting that resulted from lack of a temporal validity effect at the unattended spatial location. In contrast, our experiment revealed a significant temporal validity effect even at the unattended spatial location.

A possible reconciliation of the discrepant results between the studies can be reached when considering the different tasks used in the different studies. Rohenkohl et al. (2014) used a demanding perceptual discrimination task and argued that the lack of temporal orienting effects at the unattended locations were due to the fact that temporal expectation does not influence perceptual processing in the absence of spatial attention (i.e., under conditions of spatial uncertainty). This was previously shown in an ERP study by Doherty et al. (2005) that reported no influence of temporal attention on early perceptual components in the absence of spatial attention. In the absence of spatial attention, temporal expectation only modulated response-related components. In our study we used a simple detection task that did not rely heavily on perceptual processing as in discrimination tasks. Our results showed that when perceptual demands were low, temporal expectation influenced performance even when spatial attention was diverted to a different location from that of the target. Moreover, the temporal expectation effect at the unattended location was equivalent to that at the attended location. Integrating our results with those of Rohenkohl et al. strengthen the notion that endogenous temporal and spatial attention are fundamentally orthogonal constructs but can interact under conditions of high perceptual demands.

Interestingly, a similar pattern of results was achieved in studies investigating interactions between temporal expectancy and exogenous spatial attention. These studies found that inhibition of return, considered to be a mostly automatic process, was not modulated by increased temporal expectancy in a detection task (Gabay & Henik, 2008) but was enhanced in the framework of a discrimination task when temporal expectancy was high (Gabay & Henik, 2010). Gabay and Henik's work provides further support that temporal and spatial orienting of attention (endogenous and exogenous) are distinct attentional processes that can also interact under conditions that require perceptual discrimination. Understanding the conditions under which attentional mechanisms work together or separately provides important insight into how attention operates unitarily in a complex environment.

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