Exogenous temporal attention varies with temporal uncertainty

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Temporal attention is the selection and prioritization of information at a specific moment. Exogenous temporal attention is the automatic, stimulus driven deployment of attention. The benefits and costs of exogenous temporal attention on performance have not been isolated. Previous experimental designs have precluded distinguishing the effects of attention and expectation about stimulus timing. Here, we manipulated exogenous temporal attention and the uncertainty of stimulus timing independently and investigated visual performance at the attended and unattended moments with different levels of temporal uncertainty. In each trial, two Gabor patches were presented consecutively with a variable stimulus onset. To drive exogenous attention and test performance at attended and unattended moments, a task-irrelevant, brief cue was presented 100 ms before target onset, and an independent response cue was presented at the end of the trial. Exogenous temporal attention slightly improved accuracy, and the effects varied with temporal uncertainty, suggesting a possible interaction of temporal attention and expectations in time.

Introduction

Continuous and rich visual input from the environment is beyond the processing capacity of our brain. Expectation and attention serve to optimize perception given these constraints. Expectation is related to event predictability, and attention is related to behavioral relevance of events. Previous studies referring to this distinction have focused on endogenous, voluntary attention across space, feature or time (Summerfield & Egner, 2009, 2016; Denison, Heeger, & Carrasco, 2017; Fernández, Denison, & Carrasco, 2019). Spatial attention can be deployed endogenously (voluntarily), goal-driven by task relevance, and exogenously (involuntarily), stimulus driven by a salient change (Carrasco, 2011, 2018). Here, we investigate exogenous temporal attention, defining it as the reflexive selection and prioritization of moments following salient temporal cues, and address the distinction between expectation and attention.

Temporal attention selects and prioritizes the most relevant information at specific moments, and leads to perceptual benefits in accuracy of discrimination, detection and temporal resolution, as well as response time at the attended moments (Nobre, 2001; Coull, 2004; Nobre, Correa & Coull, 2007; Denison et al., 2017, 2021; Nobre & van Ede, 2017; Fernández et al., 2019). Temporal expectation, or the ability to make use of the predictability of the event timings, improves visual perception (Correa, Lupiáñez, & Tudela, 2005; Rolke & Hofmann, 2007; Rohenkohl, Cravo, Wyart, & Nobre, 2012; Shalev & Nobre, 2022). Temporal expectations reflect a hazard function. A hazard function describes the increasing probability of an event occurring given that it has not yet occurred (Nobre et al., 2007; Amit, Abeles, Carrasco, & Yuval-Greenberg, 2019; Moon, Choe, Lee, & Kwon, 2019; Badde, Myers, C.

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Greenberg, & Carrasco, 2020). When it is known that a target will appear eventually, the passage of time decreases uncertainty about when the target will appear and hence also increases expectation. Whether improved performance with temporal expectation is achieved through sensory enhancement or at the decision or motor response level has been under discussion (Bausenhart et al., 2010; Seibold et al., 2011; Jepma, Wagenmakers, & Nieuwenhuis, 2012; Cravo et al. 2013; Vangkilde, Petersen, & Bundesen, 2012; van den Brink, Murphy, Desender, de Ru, & Nieuwenhuis, 2021).

Endogenous temporal attention is the voluntary and flexible deployment of attention in time. It can be used when the stimulus timing is unpredictable and the temporal expectation is generated with temporally informational cues to guide attention (Coull & Nobre, 1998; Doherty, Mesulam, & Nobre, 2005; Correa, Sanabria, Spence, Tudela, & Lupiáñez, 2006; Denison et al., 2017; Ramirez, Foster, & Ling, 2021). Temporal attention can be deployed on top of expectations, when temporal expectation is kept constant and temporal attention is manipulated by instructing observers to selectively attend to a time point, resulting in improved accuracy, reaction time (RT), and discriminability at the attended moments, and impairments at the unattended moments (Denison et al. 2017, 2021; Fernández et al., 2019).

Exogenous temporal attention is the stimulus-driven, involuntary prioritization of specific moments in time (Coull, Frith, Büchel, & Nobre, 2000; Rohenkohl, Coull, & Nobre, 2011; Lawrence & Klein, 2013; Denison et al., 2021). Unlike endogenous temporal attention, whether exogenous temporal attention affects performance in terms of benefits and costs at the attended and unattended moments remains to be investigated. Moreover, how these effects differ with temporal expectation is not understood; previous designs have not differentiated between the two processes. The first study about exogenous temporal attention operationalized exogenous temporal attention as an unexpected presentation of the target, and hypothesized that exogenous temporal attention should be captured when the target is presented earlier or later than expected in a detection task (Coull et al., 2000). RTs were faster when the target was expected or when the observers could reorient attention at the unexpected moments. Another study using a discrimination task argued that rhythmic properties of a visual event should drive temporal expectations and, hence, capture temporal attention (Rohenkohl et al., 2011), and found a speeding up of the RT when the stimulus timing was predictable, but no effect on accuracy. The results from both studies showed improvements in response time related to the predictability of stimulus onset. A recent study in which exogenous temporal attention was operationalized with the rhythmicity of the auditory cue showed that rhythmicity improved RT in the correct trials (Zoroufi, Mirebrahimi, & Ghafari, 2021). However, rhythmicity often is used to manipulate expectation (Coull & Nobre, 2008; Rohenkohl et al., 2012).

A discrimination study aimed to differentiate between endogenous and exogenous temporal attention by manipulating temporal contingency between the targets and auditory signals, and the auditory signal intensity, respectively (Lawrence & Klein, 2013). Endogenous attention, deployed when the auditory signal informs the target onset, increased accuracy and decreased RTs, whereas exogenous attention, manipulated by the decibel volume change that accompanies the auditory signal without a temporal contingency for the target onset, only decreased RTs. In a follow-up study investigating the interaction of endogenous and exogenous temporal attention with a detection task, cues provided information regarding the temporal contingency between the auditory signal and the target (endogenous temporal attention), in addition to manipulating the auditory signal intensity (exogenous and endogenous temporal attention), as in the previous experimental design (McCormick, Redden, Lawrence & Klein, 2018). They found slight improvements in the RT with exogenous temporal attention driven by auditory intensity change, as well as with endogenous temporal attention, when the target appeared at the expected time point.

In sum, previous experimental designs have not differentiated between exogenous temporal attention and temporal expectation. Moreover, only RT benefits, but no accuracy benefits, have been reported. RT effects can be due to many factors, for example changes in discriminability or criterion, speed of processing or motor preparation (e.g., Wickelgren, 1977; Carrasco & McElree, 2001; Correa, 2010; Vangkilde et al., 2012; Thomaschke & Dreisbach, 2013; Grubb, White, Heeger & Carrasco, 2014).

A normalization model of temporal attention was developed and used to model behavioral data from an endogenous temporal attention experiment (Denison et al., 2021). Exogenous temporal attention was included in the model for theoretical reasons but existing psychophysical data do not strongly constrain its role. Therefore, we decided to investigate its role with an empirical study.

In the present study, we asked whether exogenous temporal attention improves visual performance, and whether such an effect will vary with temporal expectation. To manipulate exogenous temporal attention, we used task-irrelevant cues; to manipulate temporal expectation, we varied temporal uncertainty of the stimulus onset via hazard function.

Methods

Observers

Twelve observers (9 females; age range, 24–37 years), including an author (A.D.), participated in the experiment. The participants were recruited from New York University, all had normal or corrected-to-normal vision. The study was approved by the New York University Institutional Review Board, and all participants signed an informed consent before participation.

The initial sample size was computed as 12 using G*Power (Faul, Erdfelder, Lang & Buchner, 2007). We set the effect size as $\eta_G{}^2 = 0.12$ based on voluntary temporal attention literature (Denison et al., 2017), and evaluated the sample size at 80% desired power. We confirmed the required sample size by using an independent pilot data set ($n = 3$) that we collected with the same design, but with a different target location on the lower right quadrant of the fixation. Observers and trials from the corresponding observer's dataset were bootstrapped (McConnell & Vera-Hernández, 2015), and a four-way analysis of variance (Target × Precue × Temporal uncertainty × T1–T2 stimulus onset asynchrony [SOA]) was performed. We calculated the power at 0.05 alpha level, by computing the proportion of p values corresponding with the main effect of cue validity smaller than the alpha level. We started with a sample size of 3, and increased the number for random sampling with replacement until sufficient power (80%) was achieved.

Apparatus

Stimuli were generated on an Apple iMac (3.06 GHz, Intel Core 2 Duo) using MATLAB 2012b (Mathworks, Natick, MA, USA) and the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007), and displayed on a color-calibrated CRT monitor (1,280 × 960 screen resolution, 100-Hertz refresh rate). Observers were seated 57 cm away from the display, and head movements were restricted using a chinrest. Eyelink 1000 eye tracker (SR Research, Ottawa, Ontario, Canada) was used for eye position recording and online eye tracking to ensure central fixation throughout the trials. In case of a fixation break owing to a blink or if the eye position deviated for more than 1° from the screen center between the ready cue and the response cue, the trial was aborted and repeated at the end of each experimental block. Eye movements and blinks were allowed while giving a response and between trials.

Stimuli

Stimuli were presented on a uniform medium gray background. A fixation circle (subtending 0.15° dva) was presented at the center of the screen. The placeholders were four small black circles (0.2°) placed at corners of an imaginary square (side length = 2.2°) centered at the screen center.

Target stimuli were Gaussian-windowed (standard deviation of 0.3°) sinusoidal gratings with random phase presented at full contrast. Each target was tilted clockwise or counterclockwise from the vertical or horizontal axis. The tilt was titrated for each observer and for each target independently.

All auditory stimuli were presented through the speakers positioned behind the monitor. The ready signal was an auditory tone generated by superimposing 800 and 440 Hz sine waves, and presented for 100 ms. The response cue was a 300-ms auditory tone, a sinusoidal wave with high or low frequency. A high-frequency tone (800 Hz) indicated the first target, and a low-frequency tone (440 Hz) indicated the second target.

Experimental procedure

We used a two alternative forced-choice orientation discrimination task to assess visual performance as a function of involuntary temporal attention and temporal uncertainty. The experimental protocol is shown in Figure 1.

Each trial began with an auditory ready signal, indicating that the trial was starting and observers had to fixate. Two Gabor stimuli were presented sequentially in each trial, and temporal uncertainty of the target timing was manipulated by systematically varying the SOA between the ready signal and the first target (T1); it was either 1 or 2 seconds, randomly selected at each trial. In the beginning of each trial, temporal uncertainty is high, as it is unknown whether T1 will be presented sooner (1 second) or later (2 seconds). As time passes and if T1 is not presented at 1 second, temporal uncertainty decreases and observers will expect T1 to be presented at 2 seconds. We refer to the trials where T1 was presented at 1 second as high-temporal uncertainty trials, and the other trials at 2 seconds as low-temporal uncertainty trials.

The two targets were presented consecutively at fixation for 50 ms, and to introduce temporal uncertainty for the second target (T2), the SOA between the two targets was randomly assigned as 250, 300, or 350 ms.

We tested attentional selectivity by randomly cueing either of the targets (T1, T2) or both targets (neutral, as a baseline). Observers were instructed to report

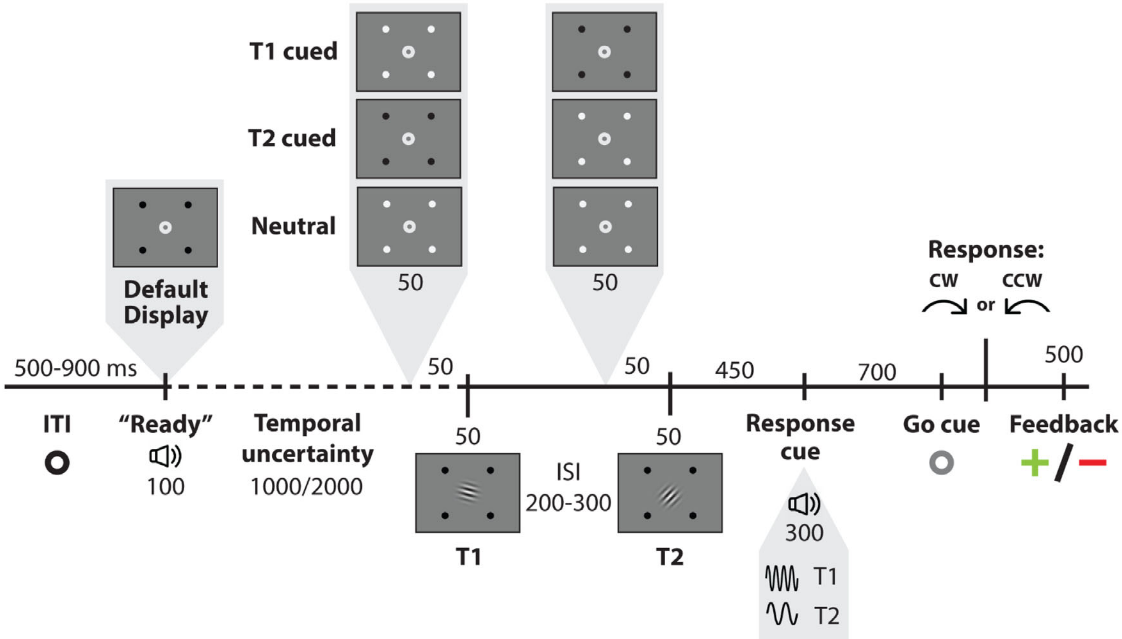

Figure 1. Psychophysical procedure to test visual performance at the attended and unattended time points with variable temporal uncertainty. Each trial started with a "Ready" tone and the fixation color turned into a bright gray. The first target (T1) was presented either at 1,000 or 2,000 ms, determining the overall temporal uncertainty of the trial, followed by the second target (T2) presented 200, 250, or 300 ms after the T1 offset. T1, T2, or both targets were cued each trial, with a brief luminance change of the placeholders. After both targets disappeared, an auditory response cue was presented to indicate which target to respond. Observers were allowed to respond after the go cue, indicated by the change in the fixation color to a dim gray. The task was to report the orientation of the target, and observers received feedback at the end of each trial. The intertrial interval (ITI) was randomly jittered between 500 and 900 ms.

the orientation of the grating that was indicated by an auditory response cue at the end of each trial. The match between the precue and the response cue determined the cue validity; when they matched the cue was valid, when they mismatched it was invalid. In neutral trials, we cued both targets, and tested either of them, as indicated at the end of the trial by a response cue. This cueing protocol is conceptually similar to the one used to manipulate neutral, valid and invalid cue conditions in exogenous spatial attention experiments (e.g., Pestilli & Carrasco, 2005; Barbot, Landy & Carrasco, 2012; Dugué, Merriam, Heeger & Carrasco, 2020; Fernández, Okun, & Carrasco, 2021; Jigo, Heeger & Carrasco, 2021). The placeholders turned to white color for a brief duration (50 ms) as the exogenous cue. This cue was uninformative, such that observers were motivated to attend to both targets at each trial. The exogenous cue was only informative regarding the timing, such that the targets appeared 100 ms after the cue. The targets were presented at different time points, and their spatial location was constant throughout the trial. Such temporal precues have been used in other exogenous and endogenous temporal attention studies (e.g., Coull et al., 2000; Coull & Nobre, 1998; Denison et al., 2017, 2021; Fernandez et al., 2019; Griffin, Miniussi & Nobre, 2001). Thus, temporal attention was manipulated with precues presented before the target onset, without any spatial manipulation.

The task was to report the orientation of the probed target by pressing a key on the keyboard (1 = counterclockwise, 2 = clockwise). Observers were allowed to respond after the go cue, indicated by the change of fixation color to a dim gray. Observers were encouraged to prioritize accuracy over RT, and they were allowed to respond anytime after the go cue, which was presented 1 second after the response cue onset, to prevent speed–accuracy tradeoffs. The RT was calculated relative to the go cue onset. A green "+" or a red "–" was presented at the end of each trial as feedback.

Each observer completed 7 experimental sessions, 2784 trials in total, and 928 trials of each attention condition (valid, neutral and invalid). A 64-trial practice block with neutral trials was administered before the first session, to familiarize observers with the procedure. Before each experimental session, observers completed 128 titration trials to equate performance for two targets in the neutral condition, and orientation discrimination was titrated to attain 75% accuracy separately for each target. The best PEST procedure (Lieberman & Pentland, 1982) was used in the titration blocks, and the obtained tilt angles were used throughout the following experimental session. If necessary, additional adjustments were made after each block, based on performance for the neutral condition during the experimental session.

Statistical analyses

Data analyses were performed with R (version 4.0.0; R Core Team, 2020), using generalized linear modeling using the glmmTMB package (Brooks et al., 2017). A Shapiro–Wilk test showed that residuals for accuracy were normally distributed ($W = 0.991$, $p = 0.45$). We used the median absolute deviation with a cutoff of 3 (Leys, Ley, Klein, Bernard & Licata, 2013) and detected 10 outliers, which were included in the analysis (8 accuracy values <66% and 2 values >85%).

A Wilk–Shapiro test showed that RT is not normally distributed ($W = 0.792$, $p < 0.001$), with a skewness of 1.425. We compared data with theoretical Gaussian, uniform, exponential, logistic, beta, lognormal, and gamma functions, and found that the data followed a beta distribution.

Results

We investigated the effect of expectation on exogenous temporal attention. We investigated expectation by manipulating the SOA between the ready cue and T1, and to add some uncertainty to the timing of T2, we also varied the T1–T2 SOA between 250 and 350 ms. Thus, we first had to ensure that this slight variation in T2 timing did not impact the effect of the exogenous cue on T2. We ruled out this possibility by fitting a generalized linear model with a Gaussian to T2 accuracy. The model included cue validity, SOA and their interaction as predictors, and subject as a random factor. This analysis revealed neither main effects nor an interaction between these predictors (SOA: $Pr[>|z|] = 0.142$, cue validity: $Pr[>|z|] = 0.837$; SOA × Cue validity: $Pr[>|z|] = 0.869$) (see Table 1 for statistics). Therefore we collapsed across the three different T1–T2 SOAs for the rest of the analyses.

	Estimate	SE	z value	Pr(>|z|)
SOA	18.358	12.496	1.469	0.142
Cue validity	−0.552	2.675	−0.206	0.837
SOA × cue validity	1.458	8.836	0.165	0.869

Table 1. General linear mixed model results. T2 accuracy was analyzed by fitting a linear model with a Gaussian. The model included T1–T2 stimulus onset asynchrony (SOA), cue validity, and their interaction as predictors, and subject as a random factor. *Notes*: SE = standard error.

	Estimate	SE	z value	Pr(>|z|)
Cue validity	0.014	0.005	2.74	0.006
Target	0.016	0.004	3.96	<0.0001
Temporal uncertainty	−0.007	0.004	−1.62	0.105
Cue validity × Target	−0.017	0.007	−2.44	0.015
Cue validity × Temporal uncertainty	0.012	0.007	1.67	0.094

Table 2. General linear mixed model results. Accuracy was analyzed by fitting a linear model with a Gaussian. The model included cue validity, target, temporal uncertainty, interactions of cue validity with target and temporal uncertainty as predictors, and subject as a random factor. *Notes*: SE = standard error.

To test benefits and costs of exogenous temporal attention, we fit a linear model that included cue validity, target, and temporal uncertainty, as well as the interaction between cue validity and target, and cue validity and temporal uncertainty as predictors, and subject as a random factor, because the independent variable of interest is the cue validity. The accuracy results revealed main effects of cue validity ($Pr[>|z|] = 0.006$) and target ($Pr[>|z|] < 0.0001$), and a significant interaction between them ($Pr[>|z|] = 0.015$) (see Table 2 for statistics). Holm-corrected post hoc

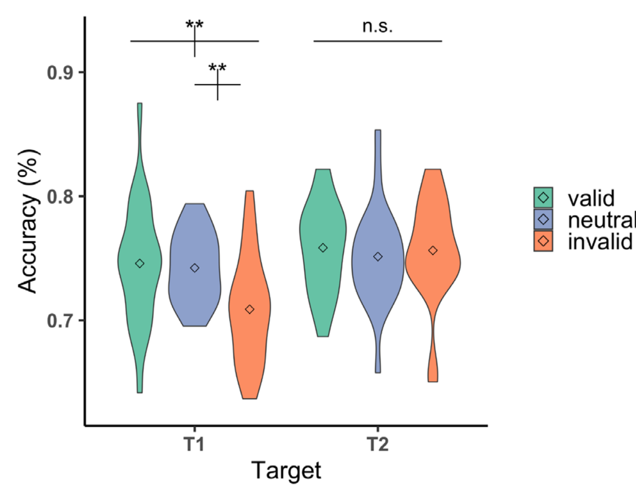

Figure 2. The target (T1 and T2) is defined by the response cue, which indicates the stimulus that the observers were instructed to respond to at the end of the trial. Cue validity (valid, neutral, invalid) is determined by the match between the precue and the response cue (i.e., a valid T1 cue indicates that T1 was both precued and indicated by the response cue; an invalid T1 means that T2 was precued but the response cue indicated T1). Performance differences were found for the first target (T1). Higher accuracy for valid and neutral than invalid conditions. No significant effect was found for the second target (T2). The error bars represent within-subject error. Diamond markers represent the mean values.

comparisons of cue validity for the targets revealed that, for T1, observers performed better in the valid condition ($p_{\text{holm}} = 0.005$) and the neutral condition ($p_{\text{holm}} = 0.0011$) than in the invalid condition, whereas for T2 there was no significant effect of cue validity (all p values > 0.1) (Figure 2).

One of our main research questions was whether and how exogenous temporal attention varies with temporal uncertainty. There was a marginal interaction of cue validity and temporal uncertainty (Pr[>|z|] = 0.094) (see Table 2 for statistics). To explain this marginal interaction, we collapsed the data across targets and compared the cue validity effects for low- and high-temporal uncertainty by performing pairwise comparisons. For high-temporal uncertainty, there was no significant difference across cue validity conditions (all $p_{\text{holm}} > 0.1$). In contrast, for low-temporal uncertainty, performance was higher in the valid than the neutral ($p_{\text{holm}} = 0.025$) and invalid ($p_{\text{holm}} = 0.007$) conditions (Figure 3).

Although T2 was presented at a variable interval after T1, it was always presented shortly after T1. Given these different temporal contexts for the two targets, we performed pairwise comparisons for the attention effects on each target separately for the different levels of temporal uncertainty. For high-temporal uncertainty, T1 performance was higher in the neutral than invalid condition ($p_{\text{holm}} = 0.05$), whereas T2 performance did not differ ($p_{\text{holm}} > 0.1$). For low temporal uncertainty, T1 performance was better in the valid than invalid condition ($p_{\text{holm}} = 0.008$), and there was a trend for neutral being better than the invalid condition ($p_{\text{holm}} = 0.073$), whereas T2 performance was marginally better in the valid than in the neutral condition ($p_{\text{holm}} = 0.06$).

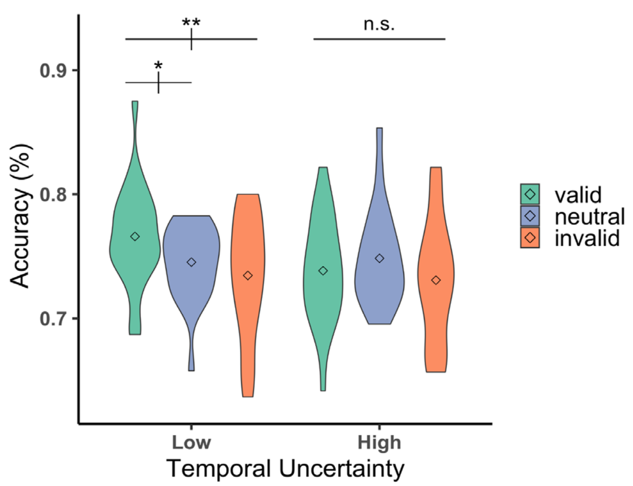

Figure 3. Attentional effects on performance varied with temporal uncertainty. Accuracy was significantly higher in valid as compared to neutral and invalid conditions under low temporal uncertainty. The error bars represent within-subject error. Diamond markers represent the mean values. *$p < 0.05$; **p < 0.01.

	Estimate	SE	z value	Pr(>|z|)
Cue validity	−0.037	0.028	−1.311	0.189
Target	−0.135	0.023	−5.764	<0.0001
Temporal uncertainty	0.016	0.023	0.679	0.497
Cue validity × Target	0.021	0.039	0.523	0.601
Cue validity × Temporal uncertainty	0.004	0.039	0.104	0.917

Table 3. General linear mixed model results. Reaction times were analyzed by fitting a generalized linear model with beta function and logit link transformation function. The model included cue validity, target, temporal uncertainty, interactions of cue validity with target and temporal uncertainty as predictors, and subject as a random factor. *Notes*: SE = standard error.

In sum, with high temporal uncertainty, performance costs were present for T1 when not attended, although no significant change in performance was found for T2 with attention. With low temporal uncertainty, when T1 was attended performance improved and when it was not attended performance decreased; when T2 was cued, performance only improved marginally.

To rule out possible speed–accuracy trade-offs, we analyzed the RTs using a generalized linear model with beta function and logit link transformation function. The model included the target, cue validity, temporal uncertainty, and their interaction as predictors, and subject as the random effects factor. The results revealed neither significant main effects or interactions (all ps > 0.1), except for a significant main effect of target (Pr[>|z|] < 0.001) (see Table 3 for statistics). Post hoc comparisons revealed that RT were faster for T2 than T1 ($p_{\text{holm}} < 0.001$).

We compared the results of generalized linear models of the accuracy and RT to 3-way analyses of variances (Cue validity × Target × Temporal uncertainty), and the overall pattern of results was the same.

Exogenous temporal attention effects on accuracy yielded an effect size $<\eta^2_G = 0.06>$, approximately one-half as large as those of endogenous temporal attention, with comparable T1-T2 SOA and number of manipulations ($\eta^2_G = 0.12$ at Denison et al., 2017, $\eta^2_G = 0.14$ at Fernández et al., 2019).

Discussion

We used a novel experimental procedure that allowed for differentiating exogenous temporal attention and temporal expectation. We led observers to prioritize accuracy by using a separate go cue that prevented observers from responding too quickly. Hence, we were able to observe the performance effects of exogenous temporal attention. Accuracy improved with exogenous temporal attention, specifically for the first target. The accuracy improvements were more pronounced when there was less uncertainty regarding the stimulus timing. Our results provide evidence that specific moments can be selected and prioritized with exogenous cues, and this selection leads to behavioral benefits and costs, which vary with temporal uncertainty.

In our design, the temporal uncertainty window differed for T1 and T2. For T1 the stimulus could appear 1 or 2 seconds after the ready signal, whereas T2 onset varied between 250 and 350 ms after the T1 onset. This difference may have resulted in differences in the precision of temporal expectations for T1 and T2. Because we aimed to investigate the benefits and costs of attending to specific moments in time, we had a temporal window short enough that T1 and T2 would compete, that is, precluding the system from recovering resources from attending to T1 and deploying them to T2. We chose the short T1–T2 SOA based on the findings from a study in which a range of SOAs were tested and the strongest attention effects emerged with a T1–T2 SOA between 250 and 350 ms (Denison et al., 2021).

The findings of the present study are in line with the dynamic normalization of temporal attention (Denison et al., 2021). The effects of exogenous temporal attention were modeled as a function of the SOA between the two targets, but this component did not play a critical role in the model. In line with the previous results, we did not find any significant effect of the SOA between T1–T2 on the T2. However, we observed an effect of the cue validity on the performance; when the stimulus timing is unpredictable, as in the attentional blink paradigm simulated in the paper. Our findings show that exogenous temporal attention can affect performance in the presence of temporal uncertainty.

Previous studies investigating the effect of involuntary temporal attention reported improvements in RT, and no change in the accuracy (Lawrence & Klein, 2013), because the performance was often at a ceiling level. In our design, to investigate whether visual performance changes, we prioritized accuracy specifically over speed by having observers wait 1,000 ms after the response cue, and allowing them unlimited time to respond. We also titrated the neutral accuracy at 75% to be able to see both the benefits and costs in performance in different conditions, and we used task-irrelevant, although temporally informative, cues. With our experimental design, we observed slight benefits and costs in accuracy, without any speed–accuracy tradeoff.

Spatial attention can be deployed endogenously or exogenously, and their similarities and differences are well characterized (e.g., Barbot et al., 2012; Dugué et al., 2020; Fernández et al., 2021; Jigo et al., 2021). Feature-based attention, selective prioritization of specific features (for reviews, Carrasco, 2011; Serences & Kastner, 2014; Liu, 2019) can be deployed endogenously across space, even when irrelevant for the task at hand (e.g., White & Carrasco, 2011; Störmer & Alvarez, 2014; Liu & Jigo, 2017). Stimulus-driven feature-based attention has been reported (Lin, Hubert-Wallander, Murray, & Boynton, 2011; Qian & Liu, 2015), but these exogenous effects have not been replicated in more recent experiments (Donovan, Zhou & Carrasco, 2019). In any case, feature-based attention is primarily an endogenous process. Here, we characterize the effect of exogenous temporal attention on visual perception, and note that it is not as pronounced as that of endogenous temporal attention.

Can the effects observed here reflect endogenous temporal attention? Two studies have shown that endogenous temporal attention can be deployed quickly (Hilkenmeier & Scharlau, 2010; Yeshurun & Tkacz-Domb, 2021), but we contend that the pattern of results in the present study cannot be explained by such an effect. The first study showed that endogenous temporal attention can be allocated to a target in 100 ms, when its onset is temporally contingent on the first target (Hilkenmeier & Scharlau, 2010). In our experimental design, the cue–target SOA was 100 ms, but the onset of the second target was not temporally contingent on the presentation of the first target as the T1–T2 SOA was randomized across trials. We did not find any cueing effect on performance for T2, suggesting that the cues did not drive endogenous temporal attention. The second study compared performance for stimuli preceded by temporally informative or uninformative cues presented shortly before the target (150 ms) and found a higher performance when the cue was temporally informative (Yeshurun & Tkacz-Domb, 2021). Thus, the authors concluded that endogenous temporal attention can be deployed in a fast manner. In that experimental design, there was only one target presented after the cue that was behaviorally relevant, so endogenous attention needed to be allocated to the relevant time points preceded by the cues. In contrast, we present two targets, the cues are not informative about behavioral relevance because the response cue is equally likely for both targets, and it is presented at the end of the trial. Thus, endogenous temporal attention should be allocated equally to both targets. Furthermore, endogenous temporal attention can selectively improve performance for the first or the second target across different SOAs while impairing performance at the unattended interval (Denison et al., 2017, 2021). Accordingly, when the first target was cued, we would have expected a benefit for the first target and a cost for the second target, and, vice versa, when the second target was cued we would have expected a benefit at the second target and a cost at the first. However, we did not observe any attention effect in T2. Overall, the pattern of results suggests that with our experimental protocol 100 ms was too short to deploy voluntary attention in time.

Both accuracy and RTs were better for T2 than T1, regardless of the cueing condition. Could the T1 onset have induced endogenous temporal attention to T2? We think this was not the case. In our experiment, endogenous temporal attention should be distributed across both intervals because both stimuli were equally likely to be the target in all conditions, as is the case in the neutral condition in endogenous temporal attention studies (Denison et al., 2017, 2021; Fernandez et al., 2019), for which accuracy and RT was also better for T2 than T1. In this study, the performance difference between T1 and T2 may be due to the higher uncertainty for T1 than T2.

Could the exogenous temporal attention be merely due to a decrease in uncertainty, because the cue presentation always indicates the subsequent appearance of the target? We think that this is not the case, because this decrease would play a greater role for trials with high rather than low temporal uncertainty. The precues decreased the possible stimulus presentation window from a longer time (2 seconds) to 100 ms in the high uncertainty condition, and from a shorter time (1 second) to 100 ms in the low uncertainty condition. Accordingly, we would expect either a larger, or at least the same, effect of uncertainty reduction in the high than the low uncertainty conditions, because the precues predict the target onset equivalently. However, the cueing effect was present for the low, but not for the high, uncertainty condition. Likewise, in the previous temporal attention studies with endogenous attention, the cue gives the same timing information in all cueing conditions. Thus, any contribution of reduced uncertainty would have been constant across cueing conditions and the observed effects can be attributed to attention (Denison et al., 2017, 2021; Fernández et al., 2019).

Can the effects observed here result from arousal, which is another mechanism that affects performance in time (Sara & Bouret, 2012; Petersen, Petersen, Bundesen, Vangkilde, & Habekost, 2017; Wang et al., 2018; Burlingham, Mirbagheri, & Heeger, 2022)? Arousal is described as nonspecific, global enhancements of biological processes (Hebb, 1955; Eysenck, 1976; Robbins, 1997). It has strong physiological components (Taylor & Epstein, 1967), and is related to overall readiness or wakefulness (Posner & Petersen, 1990; Robbins, 1997). Arousal levels, indexed by pupil responses, increase with temporal uncertainty, such that higher arousal levels are observed when a visual target onset is not predictable (Shalev & Nobre, 2022), as well as when auditory targets are uncertain (Friedman, Hakerem, Sutton, & Fleiss, 1973), and visual perception improves with high arousal (Kim, Lokey, & Ling, 2017). Thus, had the arousal level mediated the temporal attention effects in our study, we would have expected a larger effect for high rather than low temporal uncertainty. However, in the present study, exogenous attention improved performance more under low than high temporal uncertainty. Hence, although manipulating temporal expectations may have modulated arousal levels, the exogenous attention effects cannot be explained by arousal.

Both attention and expectation extend in different dimensions: space (Zuanazzi & Noppeney, 2018, 2020), feature (Summerfield & Egner, 2016), and time (Doherty et al., 2005; Todorovic, Schoffelen, van Ede, Maris, & de Lange, 2015; Moon et al., 2019). Attention and expectation differ in terms of the behavioral outcomes and the underlying neural mechanisms (Summerfield & Egner, 2009; Carrasco, 2011; Lange, 2013; Vangkilde, Petersen, & Bundesen, 2013; Cheadle, Egner, Wyart, Wu, & Summerfield, 2015; Summerfield & Egner, 2016; Denison, Yuval-Greenberg, & Carrasco, 2019; Zuanazzi & Noppeney, 2019; Rungratsameetaweemana & Serences, 2019; Wilsch, Mercier, Obleser, Schroeder, & Haegens,2020). These two mechanisms were often treated as a single cognitive function in the previous temporal attention and expectation literature, and the experimental designs and the conclusions often did not differentiate between them. However, it is important to define attention and expectation clearly and manipulate them either independently or separately to be able to characterize and differentiate their effects.

Attention is a limited resource, and the performance improvements for the selected information trade-off with impairments for the unselected information. Hence, attending to every expected or probable stimuli would neither be efficient, nor possible. In complex daily life situations, it is likely that attention and expectation work together. Given that the critical factors that drive attention are goal-driven by task relevance (endogenous attention) and stimulus-driven by a salient change (exogenous attention), whether the expected stimuli will be attended or not depends on context.

An example for the interplay between exogenous temporal attention and predictability of events is the red hands game. The first player puts their hands facing up, and the second player puts their hands on top, facing down. The first player tries to slap the second player's hands before they pull them away. From the second player's perspective, it is important to attend the moment when the opponent will hit them. However, there is no temporal information to endogenously attend to a certain moment, although the uncertainty of the event decreases in time: As the first player does not make a move, the probability of making a move in the next moment increases. And the salient exogenous cue in this scenario is the first player moving their hands, which cues the time point when to attend where the hand will be shortly to try to avoid being hit by the first player. The exogenous cue captures attention to a future time point, such that the performance at that specific moment increases, while lowering performance at the unattended moments. Temporal uncertainty affects the benefits and costs of exogenous temporal attention.

Here, we investigated the effects of exogenous temporal attention under different levels of temporal uncertainty. We showed that attentional selection in time affects performance based on the temporal predictability of the events. Overall, the results pointed out an interplay between temporal attention and temporal expectation.

Keywords: temporal attention, temporal uncertainty, visual performance

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