Voluntary temporal attention improves perception even in the absence of temporal competition

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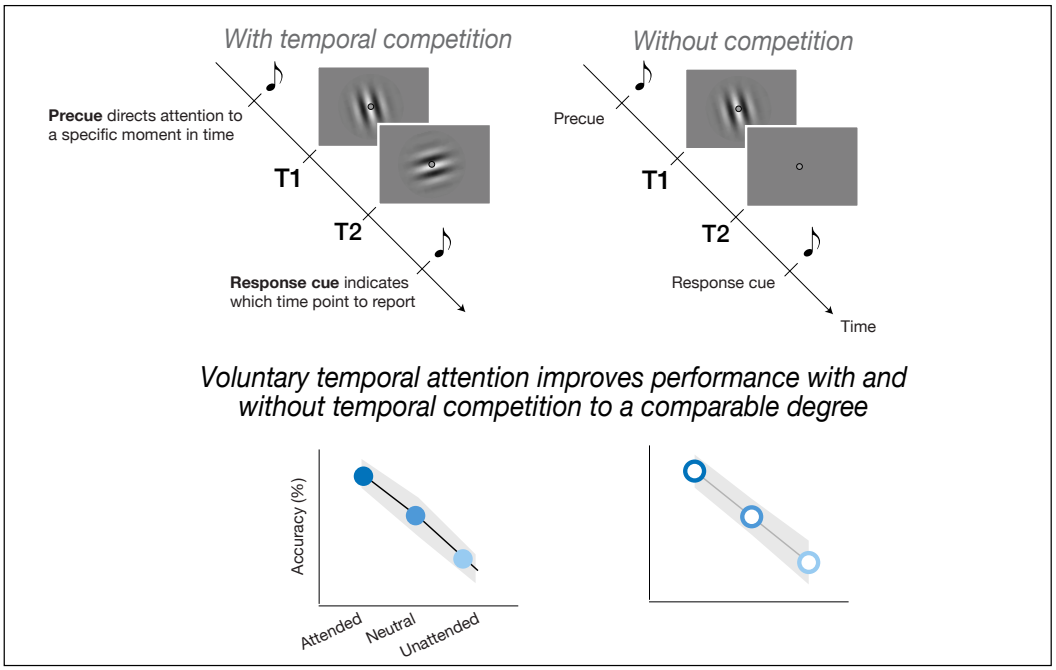
Abstract

When successive stimuli occur close enough together in time, their perception can be impaired. Such impairments indicate temporal competition between successive stimuli for representational resources. Voluntary temporal attention can bias processing resources in favor of a behaviorally relevant moment, improving perception at the attended time at the expense of impairments at unattended times. However it is unclear whether these perceptual tradeoffs across time arise because voluntary temporal attention selects among actively competing stimulus representations, such as within visual working memory, or if instead, temporal attention facilitates stimulus processing prior to a competitive stage. Here we used a temporal cueing task with up to two targets in succession to test whether and how the effects of temporal attention depend on temporal competition. We found that voluntary temporal attention improved performance even in the absence of temporal competition, when only one stimulus appeared during the trial. Moreover, the magnitude of attentional enhancement was comparable with and without competition. These results suggest that voluntary temporal attention enhances perception by facilitating processing prior to a competitive stage, rather than by resolving conflicts between actively competing stimulus representations.

Graphical abstract



Introduction

Visual input is continuous, yet visual processing is limited. Perception can be impaired when successive stimuli appear close together in time (Epstein et al., 2025; Hochmitz et al., 2024; Sahar and Yeshurun, 2023; Shapiro and Raymond, 2025; Breitmeyer and Öğmen, 2006), demonstrating temporal competition for processing resources. Such processing constraints can be managed by attention. Voluntary temporal attention can selectively prioritize sensory input at a specific moment in time (Denison et al., 2017, 2024; Nobre and van Ede, 2018, 2023), improving visual perception at the attended time point at the expense of impaired perception at unattended time points. One interpretation of these perceptual tradeoffs is that temporal attention, similar to spatial attention, biases representational resources in favor of behaviorally relevant stimuli (Desimone, 1998; Desimone and Duncan, 1995), mediating biased competition across time. However, it remains unclear whether temporal attention improves perception for a stimulus at an attended moment even when it is presented alone, without temporal competition.

Many studies cueing a single target in time have shown faster reaction times (Capizzi et al., 2023; Correa et al., 2006; Coull, 2004; Coull et al., 2000; Coull and Nobre, 1998; Griffin et al., 2001; Miniussi et al., 1999; Nobre, 2001) and performance improvements (Chauvin et al., 2016; Rohenkohl et al., 2011) for a target presented at a more versus less expected time. Such findings seem to imply that perceptual benefits with temporal attention can arise without temporal competition. However in these single-target designs, the cue simultaneously manipulated temporal attention (the task-relevance of a particular moment) and temporal expectation (the predictability of a stimulus appearing at that moment), leaving it unclear whether the observed benefits reflect prioritization by temporal attention, temporal expectation, or both. Although attention and expectation can both facilitate perception, they are distinct cognitive processes that have been shown to have dissociable neural (Denison et al., 2024; Zhu et al., 2024) and oculomotor (Denison et al., 2019; Duyar and Carrasco, 2025; Palmieri et al., 2023) effects in the temporal domain, as well separable effects in the visual spatial (Kok et al., 2012) and featural (Summerfield and Egner, 2009, 2016) domains, underscoring the importance of empirically isolating their contributions.

When temporal attention was isolated from temporal expectation by manipulating the relevance of one of two successive stimuli that were fully predictable in time, temporal attention produced perceptual tradeoffs that were most pronounced when the stimuli were separated by 200–450 ms (Denison et al., 2021). Several other studies have demonstrated attentional tradeoffs on performance for stimuli separated by a temporal interval in this range (Denison et al., 2017, 2019, 2024; Duyar et al., 2024; Fernández et al., 2019; Huang et al., 2025; Jing et al., 2023; Palmieri et al., 2023; Zhu et al., 2024). Interestingly, the temporal attentional tradeoffs on performance dissipated as the stimuli were separated by longer intervals, and disappeared entirely when they were 800 ms apart (Denison et al., 2021), suggesting that attentionally-driven benefits and costs in behavior may be contingent on temporal competition. Such findings have led to the proposal that voluntary temporal attention is a limited resource (Denison et al., 2021), which could be depleted in processing successive stimuli close together in time but replenished when they are sufficiently far

apart. Alternatively, some other limited resource may underlie the tradeoffs generated by temporal attention (Denison et al., 2024).

Because effects of voluntary temporal attention on performance (isolated from temporal expectation) have only been observed in temporally competitive contexts, it remains unclear whether temporal attention could affect performance when only a single stimulus is presented. If attentional tradeoffs across successive stimuli emerge from managing constraints imposed by temporal competition—for example, by selecting among actively competing stimulus representations in the ventral stream or in visual working memory—then temporal attention should enhance performance only when stimuli compete for limited representational resources. Under this "prioritization during competition" hypothesis **(Figure 1a)**, when a single target is presented alone, without needing to vie with temporally proximal stimuli for representational resources, attending to the target time point should not enhance its performance.

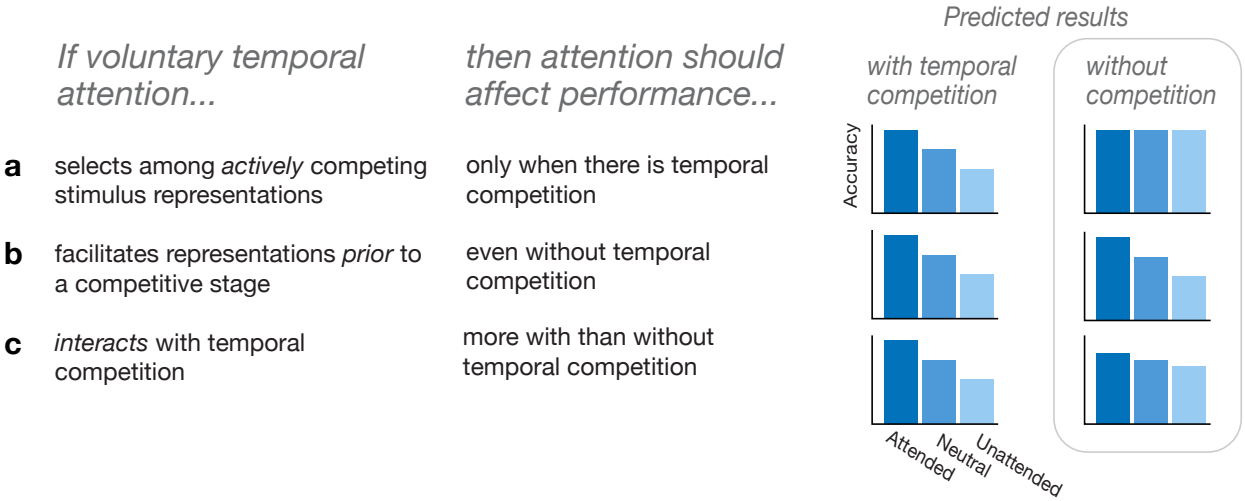


Figure 1. Hypothesized mechanisms of temporal attention and predicted behavioral outcomes. Voluntary temporal attention could **a)** select among actively competing stimulus representations, **b)** facilitate relevant stimulus representations before a competitive stage, or **c)** bias relevant stimulus representations both before and during active competition, resulting in an interaction with temporal competition. These three mechanistic accounts predict behavioral effects of temporal attention that are indistinguishable when temporal competition is present (left column of bars). However, when temporal competition is absent (right column of bars), these accounts predict different outcomes. Depending on the underlying mechanism, the effects of voluntary temporal attention for a single stimulus are predicted to either disappear (a), persist at full magnitude (b), or persist but to a reduced degree compared to when competition is present (c).

Alternatively, if voluntary temporal attention facilitates relevant stimulus representations before a competitive stage—for example, via neural gain in early visual areas at the attended moment (Denison et al., 2024)—then temporal attention should enhance performance even when a single target is presented. Under this "prioritization before competition" hypothesis **(Figure 1b)**, the magnitude of attentional enhancement should be similar whether a target is presented alone or in a temporally competitive context, as long as the selection mechanism is temporally precise.

Finally, if both mechanisms are at play—and temporal attention affects stimulus representations both prior to and during an active competitive stage—we would predict attention to modulate performance even when a target is presented alone, but to a lesser extent than when it is presented with temporal competition **(Figure 1c)**. Thus identifying the behavioral signatures of voluntary temporal attention in different temporal contexts may allow us to adjudicate among these mechanistic possibilities that are indistinguishable when temporal competition is always present (**Figure 1**, predicted results with temporal competition).

Here to investigate whether and how the effects of voluntary temporal attention on visual perception depend on temporal competition, we designed a task in which the attended time point and temporal competition were independently manipulated trial-to-trial, and temporal expectation was controlled. We found that voluntary temporal attention improved perception even in the absence of temporal competition, with effects comparable in magnitude to when competition was present. These findings suggest that temporal attention enhances perception by facilitating relevant stimulus representations prior to a competitive stage.

Results

To investigate whether and how voluntary temporal attention depends on temporal competition, we designed a task in which attention and competition were independently manipulated. We manipulated the attended moment using a precue and temporal competition by presenting a target with or without a temporally proximal non-target. Each trial contained two successive time points (T1 and T2) at which visual stimuli could appear **(Figure 2a)**. Visual stimuli were full-contrast gratings briefly presented for 50 ms each. Gratings could be tilted clockwise or counterclockwise from the vertical or horizontal axis at individual tilt thresholds. The participants' task was to report what was shown at one of the time points, which was indicated by a response cue at the end of the trial. Participants made a three-way perceptual judgment, reporting whether the indicated time point contained a clockwise grating, a counterclockwise grating, or no grating (stimulus absent) **(Figure 2c)**. T1 and T2 onsets were fully predictable in time following a precue, thus controlling temporal expectation, and separated by 250 ms, an interval that has been shown to produce perceptual tradeoffs with temporal attention (Denison et al., 2021). To reduce temporal uncertainty, T1 and T2 were marked with auditory clicks and fixation dims.

To manipulate temporal attention, a precue tone before the visual sequence instructed participants to attend to either T1 or T2 (80% of trials). On these informative trials, the precue matched the response cue with 75% validity. On the remaining 20% of trials, the precue instructed participants to distribute attention across both time points ("neutral" condition) and was not informative about the response cue, such that each time point was equally likely to be probed for report. To manipulate temporal competition, a grating could be present or absent with equal probability at each of the possible target time points, resulting in trials with zero, one, or two gratings **(Figure 2b)**. Two-grating trials generated temporal competition whereas the other possible stimulus sequences did

not, thus enabling us to assess the impact of temporal competition on target perception and any interaction with voluntary temporal attention.

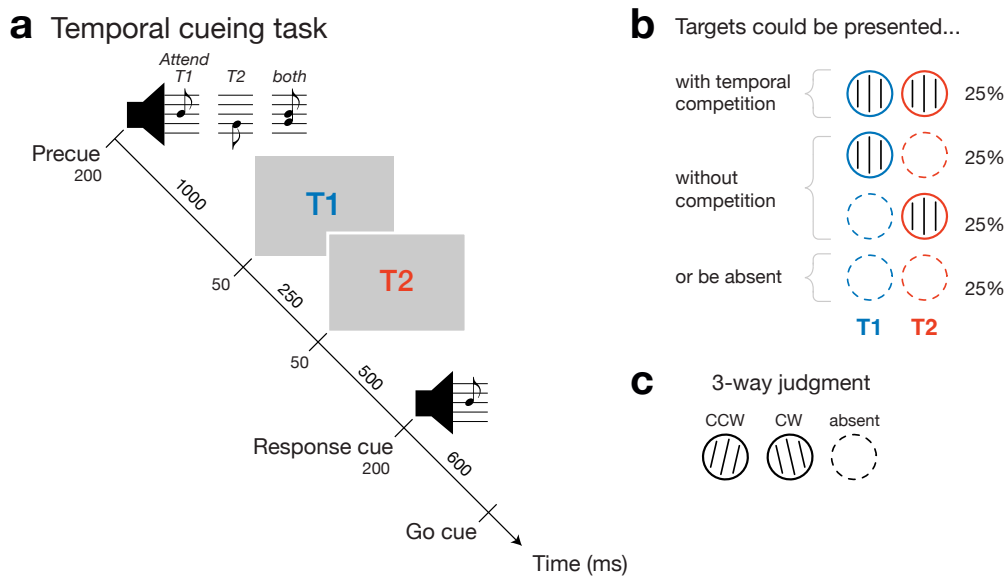


Figure 2. Temporal cueing task. a) Trial timeline. On each trial participants viewed a sequence containing two possible time points (T1, T2) at which gratings could appear. An auditory precue instructed participants to attend to T1 or T2 (as indicated by a single precue tone) or to distribute attention across both time points (tones together, neutral attention condition). T1 and T2 onsets were marked by auditory and visual cues to reduce temporal uncertainty. A response cue tone indicated which single time point to report and was 75% valid for informative precues. **b)** Possible stimulus sequences. On a given trial, gratings could appear at both time points (generating temporal competition), at only one time point (thus without competition), or at neither time point. Trial percentages are shown for each sequence type. Gratings were full-contrast and tilted at individual thresholds from either the vertical or horizontal axis, with independent presence, axis, and tilt for T1 and T2. Grating schematics are shown vertically oriented for illustration only. **c)** Participants made a three-way perceptual judgment, reporting whether or not they saw a grating at the response-cued time point, and if so, its tilt (CCW = counterclockwise, CW = clockwise).

Voluntary temporal attention improved perceptual accuracy

To confirm the efficacy of our voluntary temporal attention manipulation, we assessed accuracy on the three-way perceptual judgment ("CW, CCW, or absent?") as a function of the precue condition, regardless of whether a non-target was presented. We focused first on trials in which the target was present **(Figure 3a)**. Across both targets, accuracy was highest for valid, intermediate for neutral, and lowest for invalid conditions (main effect of validity: $F(2,34) = 28.74$, $p < 0.001$, $\eta^2_G = 0.15$; valid $>$ neutral: $F(1,17) = 8.89$, $p = 0.008$, $\eta^2_G = 0.05$; neutral $>$ invalid: $F(1,17) = 27.76$, $p < 0.001$, $\eta^2_G = 0.07$), demonstrating temporal attentional tradeoffs on perception (Denison et al., 2017, 2021, 2024; Fernández et al., 2019; Jing et al., 2023; Zhu et al., 2024; Fu et al., 2026). Because of the directional nature of time, we also examined each target separately. Temporal attention significantly improved performance for T1 ($F(2,34) = 23.64$, $p < 0.001$, $\eta^2_G = 0.22$) and T2 ($F(2,34) = 6.02$, $p = 0.006$, $\eta^2_G = 0.08$). The attentional effect was stronger for T1 (interaction

of validity and target: $F(2,34) = 4.31$, $p = 0.022$, $\eta_G^2 = 0.03$), which may reflect the overall higher accuracy for T2 (main effect of target: $F(1,17) = 69.12$, $p < 0.001$, $\eta_G^2 = 0.23$).

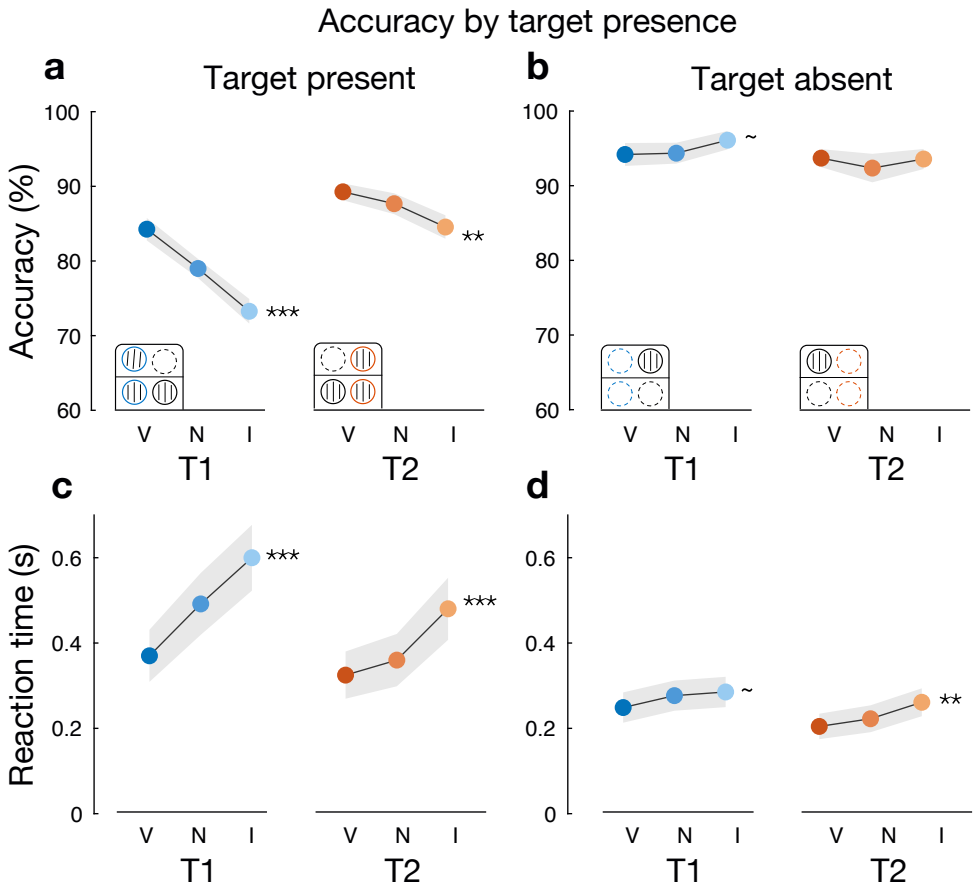


Figure 3. Temporal attentional improvements to accuracy and reaction times. a,b) Accuracy and **c,d)** reaction time on the three-way perceptual judgment as a function of target and non-target presence. Grating icons show possible trial sequences for each condition; e.g., the target present T1 condition at left includes both T1 present / T2 absent trials and T1 present / T2 present trials. Data (n = 18) are shown as group means ±1 SEM. Stars indicate significance levels for effects of validity (V = valid, N = neutral, I = invalid), $\sim p < 0.1$, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Reaction times were fastest for valid, intermediate for neutral, and slowest for invalid trials across targets **(Figure 3c)** (main effect of validity: $F(2,34) = 18.20$, $p < 0.001$, $\eta_G^2 = 0.07$, $\varepsilon = 0.67$). The speeding of reaction times with attention was observed for each target individually (T1: $F(2,34) = 16.48$, $p < 0.001$, $\eta_G^2 = 0.09$; T2: $F(2,34) = 15.04$, $p < 0.001$, $\eta_G^2 = 0.06$, $\varepsilon = 0.59$), with overall faster responses for T2 (main effect of target: $F(1,17) = 24.53$, $p < 0.001$, $\eta_G^2 = 0.03$). Thus, the improvement in accuracy with temporal attention cannot be attributed to a speed-accuracy trade-off (Heitz, 2014).

We next turned to trials in which the target was absent **(Figure 3b)**. Accuracy was overall high (mean = 94.04%, SD = 6.13%), as expected given the ease of detecting full-contrast gratings, and was not modulated by temporal attention (no main effect of validity: $F(2,34) = 2.33$, $p = 0.113$,

$\eta_G^2 < 0.01$). Thus, although temporal attention improved the challenging tilt discrimination of a present target, attention did not enhance the near-ceiling accuracy in labeling an absent target (interaction of validity and target presence: $F(2, 34) = 35.23$, $p < 0.001$, $\eta_G^2 = 0.05$). Unexpectedly, T1 was correctly judged absent marginally more often when unattended ($F(2, 34) = 2.61$, $p = 0.088$, $\eta_G^2 = 0.01$), with pairwise comparisons showing significantly higher accuracy on invalid versus valid trials ($t(35) = -1.91$, $p = 0.045$, $d = -0.35$). This result could reflect a strategy of using the presence of T2 to infer the absence of T1. Temporal attention speeded reaction times on target-absent trials overall **(Figure 3d)** (main effect of validity: $F(2, 34) = 5.42$, $p = 0.009$, $\eta_G^2 = 0.02$), which was significant for T2 individually ($F(2, 34) = 5.53$, $p = 0.008$, $\eta_G^2 = 0.03$) and trended for T1 ($F(2, 34) = 2.82$, $p = 0.074$, $\eta_G^2 < 0.01$), likely reflecting the time it takes for participants to update their response plan following an invalid precue.

Taken together, these results show that voluntary temporal attention improved perceptual accuracy and speeded reaction times when the target was present, validating the attentional manipulation and allowing us to address our main question: Is temporal competition required to generate perceptual tradeoffs with attention?

Temporal attention improved perception to a similar degree with and without temporal competition

To assess whether perceptual tradeoffs with temporal attention depend on temporal competition, we next analyzed accuracy on the three-way perceptual judgment ("CW, CCW, or absent?") according to the presence of the non-target. Trials in which both the target and non-target were present generated temporal competition, whereas other possible stimulus sequences (in which only one grating or no gratings appeared) did not **(Figure 2b)**.

When the target was present **(Figure 4a)**, voluntary temporal attention improved accuracy both with temporal competition (main effect of validity: $F(2, 34) = 10.40$, $p < 0.001$, $\eta_G^2 = 0.17$) and without competition ($F(2, 34) = 14.98$, $p < 0.001$, $\eta_G^2 = 0.13$). Critically, the magnitude of the attentional modulation did not differ with temporal competition (no interaction of validity and non-target presence: $F(2, 34) = 0.06$, $p = 0.941$, $\eta_G^2 < 0.01$). Because one of our hypotheses predicted no interaction of temporal attention and temporal competition **(Figure 1b)**, we conducted planned Bayesian statistics (see Methods, Statistical analysis) to determine whether the nonsignificant interaction reflected insufficient statistical power or instead provided evidence in support of the null hypothesis. This analysis yielded a BF_{10} of 0.084, which indicates strong evidence in favor of the null (Lee and Wagenmakers, 2014). Thus, temporal attention generated perceptual tradeoffs even in the absence of temporal competition, with effects comparable in magnitude to when competition was present. This pattern supports a mechanism in which temporal attention facilitates stimulus representations prior to a competitive stage **(Figure 1b)**.

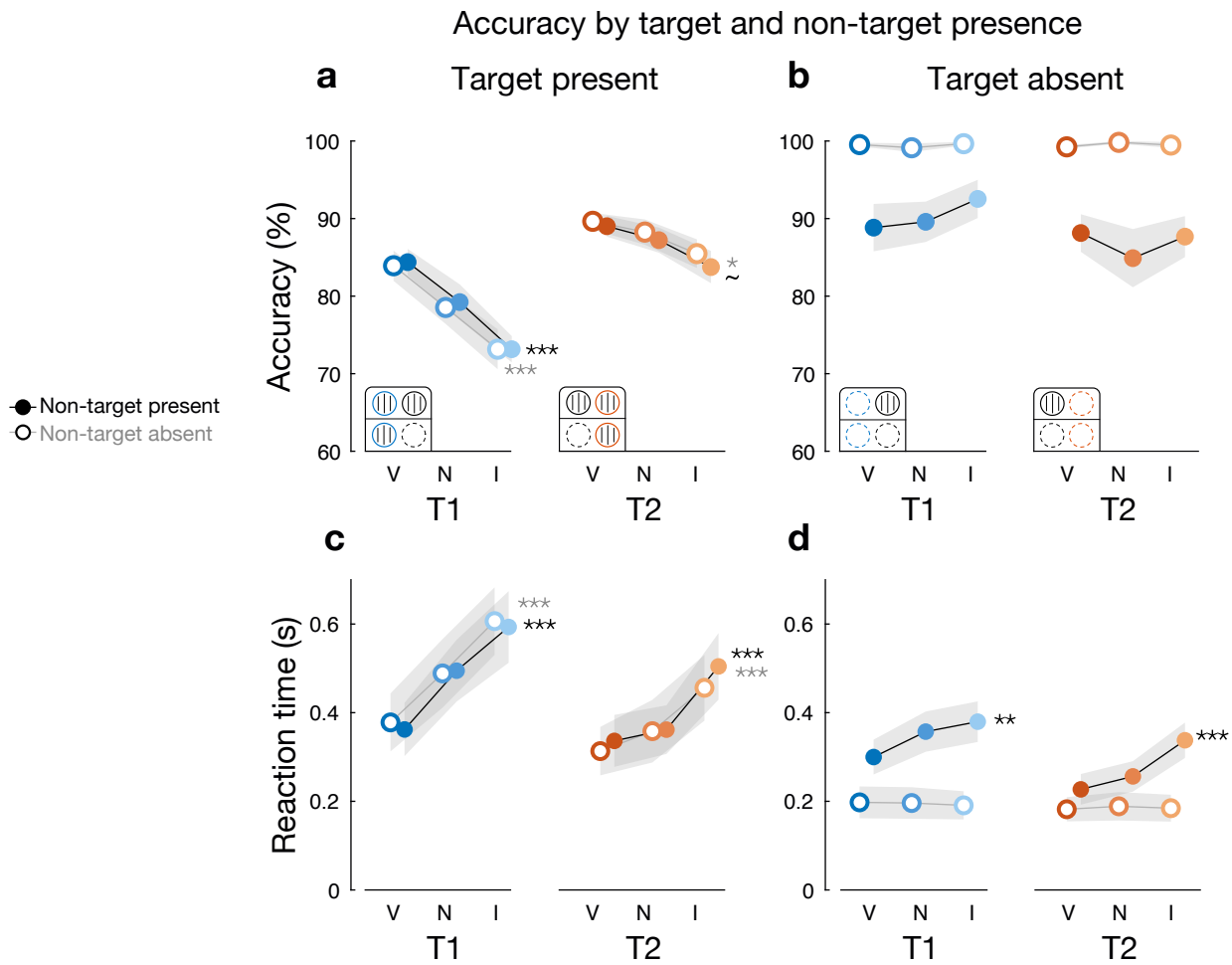


Figure 4. Attentional tradeoffs on perception with and without a non-target. a,b) Accuracy and **c,d)** reaction time on the three-way perceptual judgment as a function of target and non-target presence. Plotting conventions and grating icons as in Figure 3. Black significance symbols correspond to non-target present condition; gray correspond to non-target absent condition. Data (n = 18) are shown as group means ±1 SEM. Stars indicate significance levels for effects of validity (V = valid, N = neutral, I = invalid), $\sim p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Assessing each target separately, temporal attention significantly improved T1 accuracy both with temporal competition ($F(2,34) = 9.11$, $p < 0.001$, $\eta^2_G = 0.25$) and without competition ($F(2,34) = 11.42$, $p < 0.001$, $\eta^2_G = 0.19$), and to a comparable degree (no interaction of validity and non-target presence: $F(2,34) = 0.02$, $p = 0.982$, $\eta^2_G < 0.01$; $BF_{10} = 0.171$, indicating moderate evidence in favor of the null). For T2, the effect of temporal attention was significant without temporal competition ($F(2,34) = 5.04$, $p = 0.012$, $\eta^2_G = 0.07$) and trended with competition ($F(2,34) = 3.07$, $p = 0.059$, $\eta^2_G = 0.09$), with pairwise comparisons for the latter showing significantly higher accuracy on valid compared to invalid trials ($t(17) = 2.28$, $p = 0.036$, $d = 0.54$). Again, no interaction of temporal attention and temporal competition was found ($F(2,34) = 0.12$, $p = 0.889$, $\eta^2_G < 0.01$; $BF_{10} = 0.150$, indicating moderate evidence in favor of the null). These results indicate

that the perceptual tradeoffs of temporal attention generalize across time points and operate independently of temporal competition.

Temporal attention speeded reaction times to a present target **(Figure 4c)**, both with temporal competition ($F(2,34) = 15.38$, $p < 0.001$, $\eta^2_G = 0.08$, $\varepsilon = 0.57$) and without competition ($F(2,34) = 14.91$, $p < 0.001$, $\eta^2_G = 0.06$). This effect was found for each target individually, whether the non-target was present (T1: $F(2,34) = 16.83$, $p < 0.001$, $\eta^2_G = 0.10$; T2: $F(2,34) = 9.91$, $p < 0.001$, $\eta^2_G = 0.07$) or absent (T1: $F(2,34) = 11.57$, $p < 0.001$, $\eta^2_G = 0.09$; T2: $F(2,34) = 12.98$, $p < 0.001$, $\eta^2_G = 0.04$).

When the target was absent **(Figure 4b)**, accuracy was impaired by the presence of a non-target (main effect of non-target presence: $F(1,17) = 21.31$, $p < 0.001$, $\eta^2_G = 0.30$), but unaffected by temporal attention, regardless of the non-target (all $F(2,34) < 0.17$, $p > 0.110$). Reaction times were slower when the non-target was present **(Figure 4d)** (main effect of non-target presence: $F(1,17) = 35.70$, $p < 0.001$, $\eta^2_G = 0.14$). Despite the lack of an attentional effect on accuracy when the target was absent, attention still speeded reaction times, only when the non-target was present (interaction of validity and non-target presence: $F(2,34) = 10.62$, $p < 0.001$, $\eta^2_G = 0.02$; main effect of validity: T1: $F(2,34) = 5.87$, $p = 0.006$, $\eta^2_G = 0.03$; T2: $F(2,34) = 15.14$, $p < 0.001$, $\eta^2_G = 0.09$). When both the target and non-target were absent, temporal attention did not further reduce the already fast reaction times ($F(2,34) = 0.07$, $p = 0.930$, $\eta^2_G < 0.01$), likely reflecting an easy decision when no stimulus is presented.

In sum, voluntary temporal attention did not require temporal competition to produce perceptual tradeoffs. Next, we used signal detection theory (SDT) to assess whether temporal attention and temporal competition exert separable effects on target detection and tilt discrimination, which are combined in accuracy of the three-way judgment.

Temporal attention improved discrimination sensitivity with and without competition

We first used SDT (Green and Swets, 1966) to assess the effects of voluntary temporal attention and temporal competition on tilt discrimination, which was necessarily restricted to trials in which the target was present and a tilt response (CW or CCW) was supplied. Because trial counts differed across attention conditions, we applied a subsampling procedure for all SDT analyses to control trial counts (see Methods, Signal detection theory analysis), which could otherwise affect SDT estimates differentially across conditions.

Voluntary temporal attention enhanced tilt discrimination overall **(Figure 5)**, with highest sensitivity for valid, intermediate for neutral, and lowest for invalid trials (main effect of validity: $F(2,34) = 19.44$, $p < 0.001$, $\eta^2_G = 0.10$; valid $>$ neutral: $F(1,17) = 8.01$, $p = 0.012$, $\eta^2_G = 0.04$; neutral $>$ invalid: $F(1,17) = 12.77$, $p = 0.002$, $\eta^2_G = 0.04$). Temporal competition decreased discrimination sensitivity (main effect of non-target presence: $F(1,17) = 22.61$, $p < 0.001$, $\eta^2_G = 0.13$). Critically, temporal attention enhanced discrimination sensitivity both with temporal competition (main effect of validity: $F(2,34) = 11.53$, $p < 0.001$, $\eta^2_G = 0.18$) and without competition (main effect of validity: $F(2,34) = 4.36$, $p = 0.021$, $\eta^2_G = 0.04$), and to a comparable degree (no interaction of validity

and non-target presence: $F(2,34) = 2.45$, $p = 0.101$, $\eta_G^2 = 0.02$, $BF_{10} = 0.908$ indicating anecdotal evidence in favor of the null).

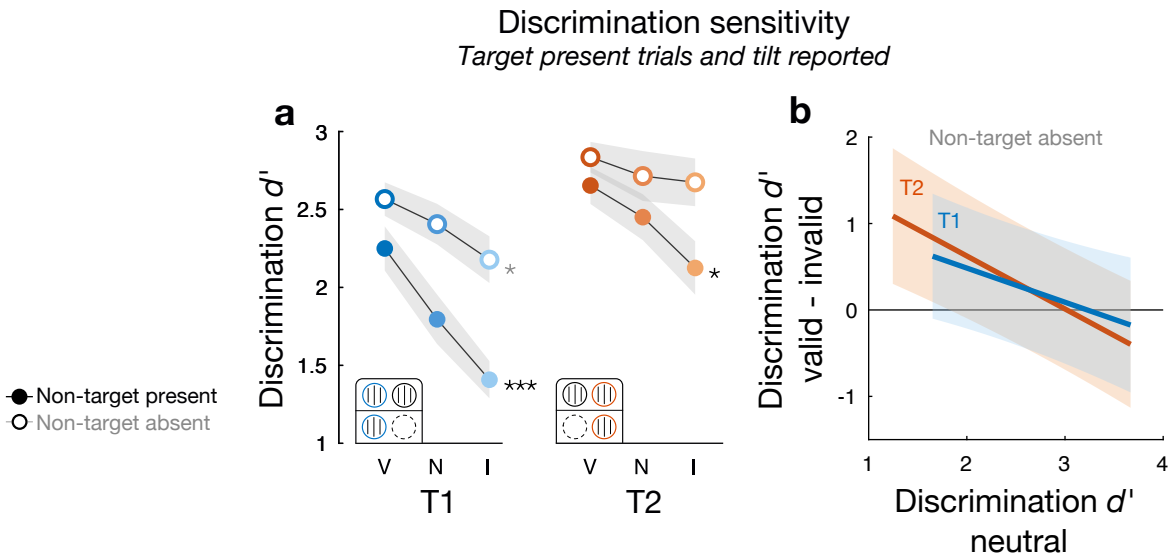


Figure 5. Temporal attentional effects on orientation discrimination sensitivity. Discrimination sensitivity (d') was computed from trials in which the target was present and a tilt response was supplied. **a)** Temporal attention enhanced discrimination sensitivity and temporal competition reduced it, with no significant interaction. **b)** Across participants, discrimination sensitivity on neutral non-target absent trials was negatively correlated with the magnitude of attentional modulation, suggesting that higher overall performance left less opportunity for improvement with attention. Data (n = 18) are shown as group means ±1 SEM (a) or the 95% confidence interval of the regression line (b). Stars indicate significance levels for effects of validity (V = valid, N = neutral, I = invalid). $^*p < 0.05$, $^{**}p < 0.01$.

We next investigated discrimination sensitivity for each target separately. With temporal competition, temporal attention enhanced discrimination sensitivity for each target (T1: $F(2,34) = 10.35$, $p < 0.001$, $\eta_G^2 = 0.26$; T2: $F(2,34) = 4.07$, $p = 0.026$, $\eta_G^2 = 0.11$). However, without temporal competition, the attentional effect remained significant for T1 only (T1: $F(2,34) = 4.09$, $p = 0.026$, $\eta_G^2 = 0.08$; T2: $F(2,34) = 1.00$, $p = 0.379$, $\eta_G^2 = 0.01$, $BF_{10} = 0.294$, indicating strong evidence in favor of the null). We wondered whether the lack of a significant attentional benefit on T2 discriminability without competition was driven by its higher performance overall (main effect of target: $F(1,17) = 14.35$, $p < 0.001$, $\eta_G^2 = 0.09$), leaving less opportunity for improvement with attention. Consistent with this idea, across targets, discriminability for neutral trials when the non-target was absent was negatively correlated with the magnitude of attentional modulation (quantified as the difference in sensitivity between valid and invalid trials) across participants **(Figure 5b)** ($r(16) = -0.458$, $p = 0.005$). Assessing each target separately, the relationship between neutral performance and the magnitude of attentional modulation remained significant for T2 ($r(16) = -0.539$, $p = 0.021$) but not T1 ($r(16) = -0.325$, $p = 0.188$). Future work using target-specific tilt titration procedures could compensate for such baseline performance differences across time.

Temporal attention improved detection sensitivity when the non-target was absent

The influence of voluntary temporal attention and temporal competition on fine orientation discriminability suggests that these processes can independently alter the fidelity of perceptual representations. To assess whether these processes also influence stimulus detection, we calculated detection sensitivity—the ability to distinguish whether a grating target was present from absent—as a function of temporal attention and temporal competition conditions. For this analysis, we treated "CW" and "CCW" tilt responses in the three-way judgment as reporting the target as present. Because all gratings were high contrast when present, detection errors here were likely due to temporal order errors, such as reporting T1 as present when in fact only T2 was present.

Detection sensitivity was overall high **(Figure 6a)** (mean d' =3.63, SD = 0.54), as expected in a suprathreshold task with full contrast gratings, and higher for T2 than T1 (main effect of target: $F(1,17) = 5.78$, $p = 0.028$, $\eta_G^2 = 0.02$). Nonetheless, detection sensitivity was impaired by the presence of a non-target (main effect of non-target presence: $F(1,17) = 6.12$, $p = 0.024$, $\eta_G^2 = 0.05$). An interaction of target and non-target presence ($F(1,17) = 16.50$, $p < 0.001$, $\eta_G^2 = 0.09$) showed that the impairment induced by the non-target was specific to T2 (main effect of non-target presence: $F(1,17) = 17.29$, $p < 0.001$, $\eta_G^2 = 0.24$) and not present for T1 (no main effect of non-target presence: $F(1,17) = 0.38$, $p = 0.544$, $\eta_G^2 < 0.01$).

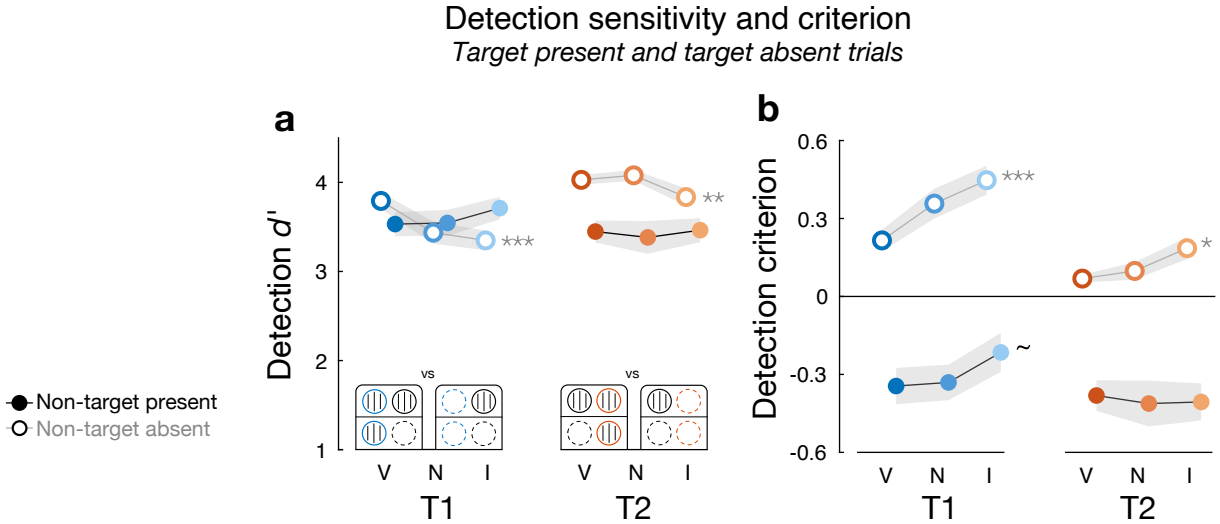


Figure 6. Temporal attentional effects on detection sensitivity. Detection sensitivity (d') and criterion for distinguishing whether the target was present or absent. **a)** Detection sensitivity, even for a suprathreshold target, was impaired by the presence of a non-target. Temporal attention enhanced detection sensitivity only when the non-target was absent. **b)** Detection criterion was strongly influenced by the non-target, with more liberal (i.e., lower) values when the non-target was present. Temporal attention decreased the criterion for non-target absent trials, increasing the propensity to report seeing the target. Data (n = 18) are shown as group means ±1 SEM. Stars indicate significance levels for effects of validity (V = valid, N = neutral, I = invalid). $\sim p < 0.1$, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

The effect of temporal attention on detection sensitivity depended on the non-target (interaction of validity and non-target presence: $F(2,34) = 11.10$, $p < 0.001$, $\eta_G^2 = 0.03$, $\varepsilon = 0.70$). When the

non-target was absent, temporal attention enhanced detection sensitivity overall (main effect of validity: $F(2,34) = 10.48$, $p < 0.001$, $\eta_G^2 = 0.10$). The attentional effect was significant for each target individually (T1: $F(2,34) = 9.06$, $p < 0.001$, $\eta_G^2 = 0.15$, $\varepsilon = 0.72$; T2: $F(2,34) = 5.86$, $p = 0.006$, $\eta_G^2 = 0.11$) and stronger for T1 (interaction of validity and target: $F(2,34) = 5.16$, $p = 0.011$, $\eta_G^2 = 0.10$). However, when the non-target was present, attention did not affect detection sensitivity ($F(2,34) = 1.35$, $p = 0.273$, $\eta_G^2 < 0.01$). Thus attentional enhancements of detection sensitivity only occurred without a non-target. This finding could indicate that, when only one stimulus is presented, temporal attention improves the perception of stimulus timing.

Detection criterion—the propensity to report seeing a target—was strongly modulated by the non-target (main effect of non-target presence: $F(1,17) = 66.39$, $p < 0.001$, $\eta_G^2 = 0.58$), such that criterion was liberal (i.e., negative values) when a non-target was present but conservative (i.e., positive values) when the non-target was absent **(Figure 6b)**. The non-target had a stronger influence on detection criterion for T1 (interaction of non-target presence and target: $F(1,17) = 4.54$, $p < 0.048$, $\eta_G^2 = 0.02$). Thus participants' detection reports were biased to be consistent with the presence or absence of the non-target, despite its independence from the target. This bias may reflect temporal order errors or temporal integration, at perceptual or decisional levels.

Temporal attention induced a more liberal detection criterion overall (i.e., lower values) (main effect of validity: $F(2,34) = 12.52$, $p < 0.001$, $\eta_G^2 = 0.04$), such that participants had a greater propensity to report a target as present when it was attended. Assessing detection criterion by the non-target condition, attention induced a liberal criterion shift when the non-target was absent ($F(2,34) = 13.66$, $p < 0.001$, $\eta_G^2 = 0.14$), which was evident for each target individually (T1: $F(2,34) = 8.42$, $p = 0.001$, $\eta_G^2 = 0.17$; T2: $F(2,34) = 4.08$, $p = 0.026$, $\eta_G^2 = 0.12$). However, when the non-target was present, attention had only a marginal effect on detection criterion for T1 ($F(2,34) = 2.54$, $p = 0.093$, $\eta_G^2 = 0.04$) and no significant effect for T2 ($F(2,34) = 0.13$, $p = 0.876$, $\eta_G^2 < 0.01$). Thus, when the non-target was absent, detection criterion was overall conservative, but made more liberal with temporal attention.

Temporal attention modulated swap errors

Accuracy and sensitivity measures reveal the fidelity of target processing, but error patterns can reveal what information intrudes when perceptual decisions go awry. We therefore next investigated the influence of voluntary temporal attention and temporal competition on the types of errors participants made. We focused in particular on swap errors **(Figure 7a)**: trials in which participants' reports incorrectly described the target and instead matched the non-target (Williams et al., 2023). For each participant and condition, we calculated swap rates as the number of swap errors divided by the number of incorrect trials eligible for swapping, which required that the target and non-target identities differ (see Methods, Swap errors).

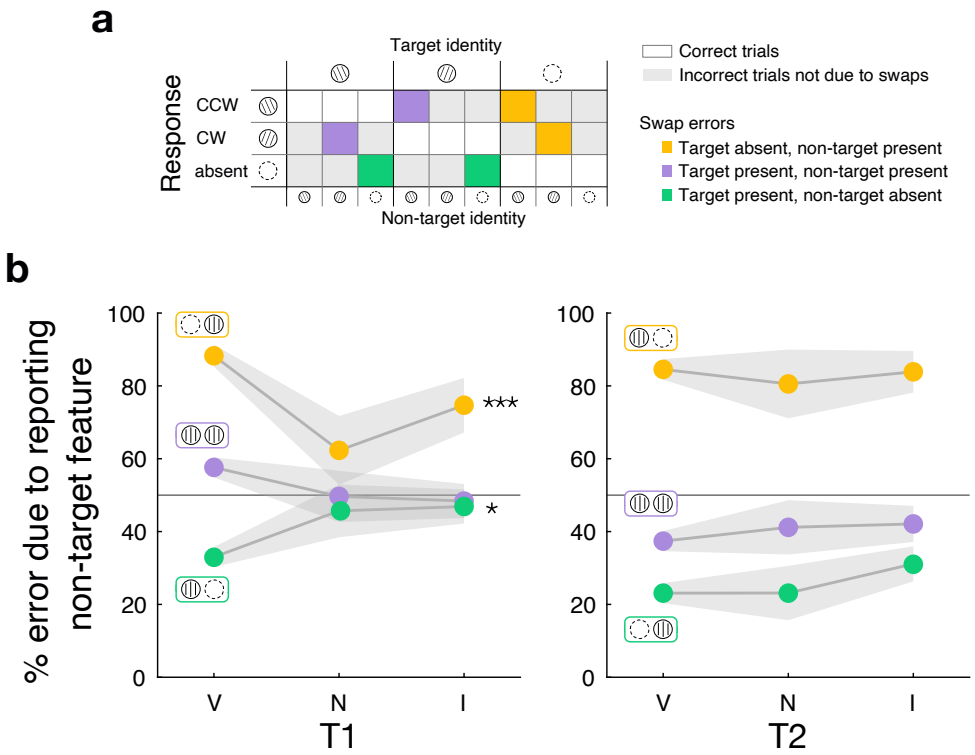


Figure 7. Temporal context affects swap errors. a) Schematic of stimulus and response categories. Swap errors occur when a participant's response incorrectly describes the target and instead matches the non-target. Cell colors indicate swap errors for different stimulus sequences. Incorrect responses not due to swaps are shaded gray and correct responses are unshaded. **b)** The plot shows percent error due to swapping conditioned on an incorrect response. The horizontal line marks the swap rate expected from random guesses (50%, given two possible incorrect response options). Swap rates were lowest on trials in which the target was present and non-target was absent (green), and highest when the target was absent and non-target was present (yellow). Data (n = 18) are shown as group means ±1 SEM. Stars indicate significance levels for effects of validity (V = valid, N = neutral, I = invalid). *$p < 0.05$, ***$p < 0.001$.

Swap rates **(Figure 7b)** depended strongly on the stimulus sequence ($\chi^2(2) = 234.25$, $p < 0.001$) and target ($\chi^2(1) = 14.72$, $p < 0.001$), and these factors interacted ($\chi^2(2) = 13.52$, $p < 0.001$). The swap rate expected from random guessing is 50%, given two possible incorrect choices on each trial. Swap rates were lowest on trials in which the target was present and non-target was absent (**Figure 7b**, green). For these trials, swap rates were significantly below chance ($t(103) = -6.51$, $p < 0.001$, $d = -0.64$), which was the case for each target individually (T1: $t(52) = -2.68$, $p = 0.010$, $d = -0.37$; T2: $t(50) = -6.74$, $p < 0.001$, $d = -0.94$). That is, errors on trials in which only the target was present were more likely to be the incorrect tilt than to be a report of absence (the non-target identity).

Swap rates were highest on trials in which the target was absent and non-target was present (**Figure 7b**, yellow). For these trials, swap rates were significantly above chance across targets ($t(70) = 12.91$, $p < 0.001$, $d = 1.53$) and for each target individually (T1: $t(31) = 6.69$, $p < 0.001$, $d = 1.18$; T2: $t(38) = 12.35$, $p < 0.001$, $d = 1.98$), with marginally higher rates of swapping for T2

than T1 ($\chi^2(1) = 1.808$, $p = 0.076$). Thus when participants made an error on trials in which only the non-target appeared, participants tended to report its tilt. This proclivity is consistent with the liberal shift in detection criterion observed for these trials using SDT analyses **(Figure 6b)**.

Temporal crowding has been reported to increase swap errors (Tkacz-Domb and Yeshurun, 2021), possibly reflecting greater temporal order confusion or temporal integration when successive stimuli are close together in time. Here the condition with temporal competition (when both the target and non-target were present) had the highest swap rate (**Figure 7b**, purple). Swap rates for this condition were higher for T1 than T2 ($\chi^2(1) = 10.82$, $p = 0.001$). Whereas T1 swap rates were near chance, T2 swap rates were below chance ($t(49) = -3.16$, $p = 0.003$, $d = -0.45$), indicating that errors on these trials primarily reflected missed targets rather than incorrect tilt judgments.

We next assessed the effect of voluntary temporal attention on swap rates. Temporal attention modulated swap rates for T1 but not T2. For T1, there was a significant interaction of temporal attention and stimulus sequence ($\chi^2(4) = 20.39$, $p < 0.001$), such that attending to T1 increased swap rates when the sequence only had a stimulus at T2 ($\chi^2(2) = 15.09$, $p < 0.001$) but decreased swap rates when the sequence only had a stimulus at T1 ($\chi^2(2) = 7.61$, $p = 0.002$). This means that attending to T1 exacerbated the tendency to report presence on trials in which only a single stimulus appeared, regardless of whether T1 or T2 was actually present. For T2, there was no significant effect of attention on swap rates for any stimulus sequence ($\chi^2(2) < 0.36$, $p > 0.835$).

Discussion

Here we investigated whether the perceptual tradeoffs generated by voluntary temporal attention require temporal competition. Participants viewed a sequence of up to two stimuli while directing voluntary attention to particular moments in time. Voluntary temporal attention modulated orientation discriminability, with higher performance at attended than unattended time points. Attentionally-driven tradeoffs in performance occurred even when a single target was presented, in the absence of a temporally competing stimulus, with effects similar in magnitude to when competition was present. These findings are inconsistent with models in which attention acts solely to resolve active competition, and instead support a mechanism in which attention facilitates processing at a task-relevant moment prior to a competitive stage.

Similar timescales of temporal competition and temporal attentional tradeoffs

Visual input can be registered rapidly. For example, an optic nerve fiber can signal its preferred feature with millisecond precision (Berry et al., 1997; Zheng and Meister, 2024), and temporal order can be distinguished for visual events just 3 ms apart (Akyürek, 2025). Yet the perception of a stimulus can be influenced by its temporal context extending even hundreds of milliseconds into the past and future (Chapman and Denison, 2025; Epstein et al., 2025; Fleming and Michel, 2025; Herzog et al., 2020; Sergent et al., 2013), demonstrating competitive interactions that are comparatively slow. In temporal crowding, the identification of a target is impaired when it is presented with other stimuli within a temporal window of 150–450 ms (Hochmitz et al.,

2026; Sahar and Yeshurun, 2023; Tkacz-Domb and Yeshurun, 2017, 2021). In the attentional blink, the ability to identify a stimulus is impaired when it follows an initial target by 200–500 ms (Broadbent and Broadbent, 1987; Raymond et al., 1992; Shapiro and Raymond, 2025). In studies of voluntary temporal attention, attention generates perceptual tradeoffs across time that are most pronounced when successive stimuli are 200–450 ms apart (Denison et al., 2021). These phenomena, identified using a variety of experimental tasks, operate on a remarkably similar timescale, suggesting that they may be different expressions of a common processing bottleneck.

Attention as a mediator of biased competition in space

The biased competition framework, developed for spatial and feature-based attention, proposes that attention enhances perception by resolving competition between stimuli for limited processing resources (Desimone, 1998; Desimone and Duncan, 1995). Motivating this view, when multiple stimuli fall within a receptive field, attention biases the neuron's response towards what it would be if only the attended stimulus were present (Chelazzi et al., 1993, 2001; Luck et al., 1997; Moran and Desimone, 1985; Reynolds et al., 1999, 2000; Reynolds and Chelazzi, 2004). The modulatory effects of attention can be less pronounced or absent altogether when only a single stimulus is presented within the receptive field (Chelazzi et al., 2001; Ito and Gilbert, 1999; Luck et al., 1997; Moran and Desimone, 1985; Motter, 1993; Posner and Gilbert, 1999; Reynolds et al., 1999, 2000). At the behavioral level, spatial attention still enhances perception for a single stimulus (Cameron et al., 2002; Carrasco et al., 2000, 2002; Jigo and Carrasco, 2020; Ling and Carrasco, 2006), but the effects can increase with the number of competing stimuli (Carrasco and McElree, 2001; Foley and Schwarz, 1998; Giordano et al., 2009; Palmer, 1994). Such patterns are consistent with the normalization model of attention (Reynolds and Heeger, 2009), which predicts that attention provides a competitive advantage by shifting the balance of excitation and suppression between simultaneous stimuli, thus exerting greater modulatory influence in more competitive contexts.

Does voluntary temporal attention bias competitive interactions in time?

For the processing of dynamic sequences, we can consider at least two possible sites of temporal competition: 1) in ventral stream regions with long temporal integration windows (Chaudhuri et al., 2015; Hasson et al., 2008; Honey et al., 2012; Murray et al., 2014), and 2) in visual working memory, where sequential items are concurrently maintained (Shalev and van Ede, 2021). Temporal attention may mediate competitive interactions by biasing relevant stimulus representations at one or both of these sites. Given that perceptual tradeoffs driven by voluntary temporal attention had only been observed in temporally competitive contexts, it was unclear whether temporal attention would still improve behavior in the absence of active competition.

To assess whether the effects of voluntary temporal attention depend on temporal competition, we compared attentional effects for a target presented alone versus together with a non-target, while controlling temporal expectation. In our task, the target and non-target stimuli appeared in the same spatial location, were identical in physical properties (apart from tilt and phase), and occurred in close temporal proximity—conditions expected to induce substantial competition.

Indeed, tilt discriminability was impaired by the presence of a temporal competitor, and temporal attention produced a strong performance advantage for these trials, consistent with previous studies (Denison et al., 2017, 2019, 2021, 2024; Duyar et al., 2024; Fernández et al., 2019; Huang et al., 2025; Jing et al., 2023; Palmieri et al., 2023; Zhu et al., 2024). If temporal attention improves performance by mediating active temporal competition, as in the "prioritization during competition" hypothesis, temporal attention should have no effect on behavior when competition is eliminated. However, this outcome did not occur; voluntary temporal attention still generated perceptual tradeoffs on trials in which no competing stimulus appeared. Moreover, temporal attentional effects on discriminability were comparable with and without temporal competition, unlike observations in the spatial domain where attentional effects can scale with competition (Carrasco and McElree, 2001; Foley and Schwarz, 1998; Giordano et al., 2009; Palmer, 1994). The present results support a "prioritization before competition" hypothesis, in which temporal attention facilitates processing at a task-relevant moment before active competition arises.

Mechanisms of voluntary temporal attention

In what ways might voluntary temporal attention facilitate stimulus processing before an active competitive stage? Any mechanism that completes before the arrival of a temporal competitor could, in principle, operate independently of competition. There is evidence that voluntary temporal attention affects neural processing both in anticipation of the first stimulus (Denison et al., 2019, 2024; Duyar and Carrasco, 2025; Palmieri et al., 2023) and in response to it, before the second stimulus appears (Denison et al., 2024; Zhu et al., 2024). Leading up to a visual sequence, visual cortex exhibited low-frequency ($\sim$2 Hz) periodic modulations that shifted approximately half a cycle in phase depending on the attended time point (Denison et al., 2024). Such a mechanism could coordinate visual cortex to be in a maximally responsive state at the attended moment while reducing the interference of temporal competitors through rhythmic gating of excitability (Jensen and Mazaheri, 2010).

In response to the first stimulus in a sequence, voluntary temporal attention enhanced visual activity approximately 150 ms after stimulus onset (Denison et al., 2024), consistent with transient gain modulations proposed by dynamic normalization models of attention (Denison et al., 2021). The attended stimulus information was selectively routed from sensory to fronto-cingulate cortex (Zhu et al., 2024). The routing occurred approximately 250 ms after the onset of the first stimulus, just before the next stimulus arrived. Such a mechanism could act to protect the attended stimulus information from being overwritten in sensory cortex by a temporal competitor.

The above-mentioned anticipatory and evoked mechanisms of voluntary temporal attention unfold in advance of a competing stimulus, and thus should operate whether or not competition ultimately appears. However, it was not a foregone conclusion from these neural findings that temporal attention would impact the perception of a single stimulus. For example, if stimulus information is routed to anterior regions to protect it from sensory interference, but no competing stimulus ever appears, then the mechanism would be functionally irrelevant. Even if a competing stimulus were to appear, early attentional mechanisms are not guaranteed to affect perception if it depends

on unresolved downstream competition. For example, the effects of temporal attention on early sensory processing could have been small compared to attentional effects on stimulus selection within working memory.

Whether these mechanisms of voluntary temporal attention depend on anticipating temporal competition remains an open question. In our task, each time point was equally likely to contain a stimulus or not, and this probability was independent across time points. Thus participants started each trial expecting that two stimuli could appear, even if only one stimulus ultimately appeared. This raises the possibility that temporal attention requires the expectation of a competing event to facilitate processing at a task-relevant moment, whether or not competition ultimately materializes. Future work that systematically varies participants' expectation of a competing stimulus may clarify whether the mere expectation of competition is sufficient to generate perceptual tradeoffs with voluntary temporal attention.

The mechanisms of attentional prioritization in time must in some ways be distinct from those of prioritization in space, given fundamental differences between these dimensions. Time is fleeting and directional, whereas space is stable and symmetric (Denison, 2024). Effects of spatial attention are typically symmetric about the midline (Carrasco et al., 2001; Lee and Carrasco, 2026), but we observed asymmetries in perception and attentional effects across time: performance was higher for T2 than for T1, whereas attentional effects were stronger for T1 than for T2. The weaker attentional effects for T2 may reflect its higher baseline performance, leaving less room for improvement with attention. Or the weaker effects could reflect an inherent difference in attending to the first versus later moments of a sequence. For example, if T1 were attended but no stimulus appeared, it is possible processing resources could be allocated to T2 because they were not utilized for T1. Such a mechanism could not operate in the reverse because of the directional nature of time.

Conclusion

Using a novel task that independently manipulated the attended time point and temporal context, we demonstrated that voluntary temporal attention generates perceptual tradeoffs in a challenging discrimination task even when only a single stimulus is presented, in the absence of temporal competition. These tradeoffs cannot be attributed to timing predictability, which was controlled. The magnitude of the attentional modulation was comparable whether the stimulus appeared alone or accompanied by a temporal competitor. Such results suggest that voluntary temporal attention acts by facilitating the processing of task-relevant information prior to a competitive stage, rather than by selecting among actively competing stimulus representations—drawing a distinction from accounts that have stressed the importance of competition in eliciting attentional effects in the spatial domain. In summary, voluntary temporal attention does not require temporal competition to enhance perception, shedding light on the mechanisms by which attention prioritizes information in dynamic visual environments.

Methods

Participants

Eighteen participants (11 females, 7 males; mean age = 26.4 years old, SD = 5.3 years, based on self-report) completed the experiment. All participants, except authors J.A.M. and R.N.D., were naive to the study. The sample size was larger than those used in previous studies demonstrating effects of temporal attention (Denison et al., 2017, 2021, 2024; Fernández et al., 2019). Based on a previous effect size (η_G^2 = 0.25; (Denison et al., 2024), a power analysis using G*Power 3.1 (Faul et al., 2007) indicated that a sample size of 18 would achieve 96% power to detect an effect of attention on performance at a 0.05 significance level. No sex or gender-based analyses were performed, and we did not consider sex or gender in the study design, as neither sex nor gender played a role in our research questions. All participants had normal or corrected-to-normal vision and were monetarily compensated for their time. All participants provided informed consent and Boston University's Institutional Review Board approved the experimental methods.

Stimuli

Stimuli were generated using MATLAB R2023a and Psychophysics Toolbox 3.0.19 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) on Linux. The stimuli were displayed on a VPixx VIEWPixx LCD display (VPixx Technologies Inc., QC, Canada) with a resolution of 1920 x 1080 and a refresh rate of 120 Hz and placed at a viewing distance of 75 cm. A chin-and-head rest stabilized the participants' heads. Throughout the trial, a central white fixation circle with a diameter of 0.25° appeared on a gray background with mean luminance of 45.56 cd m^{-2}. Stimulus timing and audiovisual synchrony were confirmed with photodiode and digital oscilloscope (PicoScope 2000 Series 2204A, Pico Technology, Cambridgeshire, UK) measurements to millisecond precision.

Visual stimuli were full contrast sinusoidal gratings with a Gaussian envelope (0.7° standard deviation), presented foveally for 50 ms each. Gratings had a spatial frequency of 4 cycles per degree, and one of four possible phases (0°, 90°, 180°, 270°). Gratings could be tilted clockwise or counterclockwise at participants' individual tilt thresholds from either the vertical or horizontal axis. We varied the gratings in phase and axes to make it difficult to perform the orientation discrimination task by learning an image template and to discourage comparison between the sequential targets.

Auditory cues were pure sine wave tones, which could be high-pitched (1046.5 Hz, C6), low-pitched (440 Hz, A4), or the combination of the low and high tones. The pitch instructed participants to attend to a single time point (T1: high tone, T2: low tone) or to distribute attention across both time points (both tones). Auditory cues were 200 ms long, enveloped by cosine-squared ramps 10 ms in duration. Brief, auditory clicks (0.5 ms) generated as broadband noise ranging from 2–20 kHz were presented simultaneously with T1 and T2 onsets. Auditory stimuli were presented via Sennheiser HD 569 noise-isolating headphones (Sennheiser, Lower Saxony, Wedemark, DE) and a Focusrite Scarlett 2i2 audio interface (Focusrite, High Wycombe, Buckinghamshire, UK) at a comfortable volume.

Task

Participants directed attention to different time points in a minimal stimulus sequence, while performing a challenging visual perceptual task **(Figure 2a)**. Each trial had two temporally predictable time points (T1 and T2) at which gratings could be presented. On each trial, gratings could be presented at both time points (creating temporal competition), at only one time point, or at neither time point. The probability of a grating's occurrence at each time point was 50% and independent for each time point.

To manipulate voluntary temporal attention, a precue tone presented 1000 ms before T1 directed the participant's attention to either T1 (high tone), T2 (low tone), or both time points (both tones played simultaneously). A response cue tone, presented 500 ms after T2, indicated a single time point to report. The precue matched the response cue on 60% of trials (valid trials), mismatched on 20% of trials (invalid trials), and was uninformative on 20% of trials (neutral trials), yielding 75% validity when a single time point was precued. Thus participants were incentivized to attend to the precued time point. T1 and T2 occurred at fixed, predictable times following the precue and were separated by a 250 ms stimulus onset asynchrony. To reduce temporal uncertainty about the possible target times, brief auditory clicks and fixation dims (from white to a light gray of 69.61 cd m^{-2}, 0.5 ms) were presented simultaneously with T1 and T2.

Participants reported whether or not they saw a grating at the response-cued time point and, if they saw the grating, its tilt, resulting in three response options (clockwise, counterclockwise, absent) **(Figure 2c)**. Participants were allowed to make their response after a go cue, indicated by a fixation dim from white to a dark gray of 22.97 cd m^{-2}, presented 600 ms after the response cue until the response was submitted. Participants had unlimited time to respond. When a response was registered, a fixation color change provided feedback (green = correct, red = incorrect) for 500 ms. After feedback, the screen was a blank gray except for the white fixation circle for 750 ms before the next trial. After each block of 40 trials, participants received block feedback in the form of percent accuracy.

Each participant completed 1280 trials across 32 blocks, over the course of two to three 1.5 hour sessions on separate days. Cue validity (valid, neutral, invalid), target presence (present, absent), non-target presence (present, absent), the response-cued time point (T1, T2), grating tilt (counterclockwise, clockwise), and grating axis (vertical, horizontal) were counterbalanced and independent. Grating phase was pseudorandomized, so that the probability of each phase's occurrence was controlled but not its probability conditioned on other variables.

Training

Before the main experiment, participants completed training sessions to familiarize them with the task and to determine their individual tilt thresholds. To learn the task, participants completed practice trials identical to the main task, except that two gratings were always presented, each grating was clearly tilted (5°), and all precues were neutral. Participants repeated the practice condition until 75% accuracy was achieved within a single block of 32 trials. Then, to determine

individual tilt thresholds (mean threshold = 1.05°; SD = 0.34°), participants completed 128 trials in which all precues were neutral, grating targets could be present or absent with equal probability, and tilt was adaptively adjusted trial-to-trial. Two staircases were alternated: the first staircase starting from an easily discriminable coarse tilt (5°) and the other from a difficult-to-discriminate fine tilt (0.2°). Each staircase followed a 3-up-1-down procedure (converging to an accuracy of $\sim$79%), except for three participants for whom a 2-up-1-down procedure was used (converging to an accuracy of $\sim$71%) (Levitt, 1971). The staircases were updated only if the target was present, as the tilt judgment was irrelevant when the target was absent. Individual thresholds were calculated as the average of the two staircase estimates, each based on the average tilt values of the last six trials for that staircase. After the thresholding procedure, participants performed 64 trials of practice using their individual tilt threshold in trials in which two gratings always appeared and all precues were valid. The final step of the training session was to complete 64 trials identical to the main experiment.

Online fixation monitoring

Fixation was monitored using an EyeLink 1000 Plus eye tracker (SR Research, Ottawa, Ontario, CA) with a sampling frequency of 1000 Hz. Trial initiation was contingent upon central fixation within a 2.5° radius for 300 ms. Fixation maintenance was required from the onset of the precue until the response cue. If fixation was broken during this time, the trial was stopped and repeated at the end of the block. On average, 3.43% (SD = 2.97%) of trials were repeated per participant due to broken fixation.

Signal detection theory analysis

We used signal detection theory (SDT) analysis (Green and Swets, 1966) to calculate sensitivity and criterion separately for detecting a target and discriminating its orientation when present. To calculate the SDT measures for detection, we considered a response of either counterclockwise or clockwise as reporting the target as “seen” because the alternative was to report the target as “absent”. Hits were defined as “seen” responses to a present target, and false alarms were defined as “seen” responses to an absent target. To calculate the SDT measures for orientation discriminability, we only used trials in which the target was present and a tilt response was supplied because orientation information is not available otherwise. We arbitrarily defined “hits” as correctly identifying a clockwise tilted grating as clockwise, and false alarms as incorrectly reporting a counterclockwise tilted grating as clockwise. To handle extreme hit or false alarm rates, for which the signal detection measures are indeterminate, we applied a $1/2N$ correction (Hautus et al., 2022), which adjusts rates of 0 to $\frac{1}{2N}$ and rates of 1 to $1 - \frac{1}{2N}$.

Because the valid condition had three times more trials than the invalid and neutral conditions, differences in trial counts could affect SDT estimates, especially when accuracy is very high, as was the case in detecting full contrast gratings. To control trial counts across attention conditions, we performed a subsampling procedure as follows. To calculate the SDT detection measures, we randomly sampled trials without replacement from the valid condition per participant to match

the trial counts for the invalid and neutral conditions. For the SDT discrimination measures, we necessarily excluded trials in which an "absent" response was supplied, which could unequalize trial counts across SDT categories (i.e., the number of trials constituting "signal" versus "noise"). Therefore, for each participant, we identified the minimum number of trials within an SDT category across attention conditions, and subsampled all other categories to match this count. The subsampling procedure was repeated 1000 times for each measure and participant. The final trial-count-matched SDT measures were taken as the average of the estimates across subsamples.

Swap error analysis

We quantified swap errors to assess how the non-target influenced the type of errors made. We considered a report to be a "swap error" if the target feature was misreported, and instead the report matched the non-target feature (counterclockwise, clockwise, or absent). Thus, trials in which the target and non-target features were the same were not considered eligible for swaps. For each participant and condition, the swap error rate was calculated as the number of swap errors divided by the number of incorrect trials eligible for swapping. Conditions per participant with fewer than two incorrect trials were excluded, because such low trial counts yield unstable proportions.

Statistical analysis

Repeated measures ANOVAs were used to assess the impact of experiment conditions on behavior using the ez package (Lawrence, 2016) in R. For measures of accuracy, reaction time, and discrimination d' and criterion, the within-subject factors were validity (valid, neutral, or invalid with respect to the match between the precue and response cue), target time point (T1 or T2), target presence (present or absent), and non-target presence (present or absent). For measures of detection d' and criterion, the within-subject factors were validity, target time point, and non-target presence. When Mauchly's test indicated a violation of sphericity assumptions (Mauchly, 1940), we reported Greenhouse-Geisser epsilon ϵ and corrected *p*-values. To assess attentional benefits and costs, we performed planned pairwise comparisons using ANOVAs or two-tailed paired *t*-tests between all combinations of attention conditions (valid vs. invalid, valid vs. neutral, neutral vs. invalid). Effect sizes are provided as generalized eta squared η_G^2 for ANOVAs and as Cohen's *d* for *t*-tests.

When null results were of theoretical interest (i.e., in assessing the absence of an interaction between temporal attention and temporal competition), we quantified the amount of evidence in favor of the null versus alternative hypothesis using Bayes factor (BF_{10}) (Lee and Wagenmakers, 2014). We calculated BF_{10} using the BayesFactor package (Morey and Rouder, 2023) in R by comparing a full model (H_1), in which an interaction term of validity and non-target presence was included, against a reduced model (H_0) that was identical except the interaction term was excluded. A BF_{10} greater than 1 indicates evidence in favor of the alternative whereas a BF_{10} less than 1 indicates evidence in favor of the null. To grade the decisiveness of evidence for the null hypothesis, we interpreted Bayes factors less than 1 following the recommendations of Lee and Wagenmakers (2014, Section 7.2).

For swap error analyses, we conducted two-tailed one-sample t-tests to assess whether observed swap rates deviated from chance. We modeled swap rates using linear mixed-effects models implemented with the lme4 package in R (Bates et al., 2015), with target (T1, T2), stimulus sequence (e.g., target present and non-target absent), and validity (valid, neutral, invalid) as fixed effects, and participant as a random intercept. We assessed the significance of fixed effects and their interactions using Type II Wald χ^2 tests.

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Data availability

The data is available on Open Science Framework at `https://doi.org/10.17605/OSF.IO/KWFCX`.

Code availability

The experimental and analysis code is available on GitHub at `https://github.com/denisonlab/ZOOT`.

Author contributions

All authors conceptualized and designed the experiment. J.A.M. programmed the experiment and collected the data with supervision from K.J.T and R.N.D. K.J.T. and J.A.M. analyzed the data with supervision from R.N.D. All authors interpreted the data. K.J.T. and J.A.M. drafted the manuscript. All authors edited the manuscript and approved the final version.

Competing interests

The authors declare no competing interests.

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