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The Role of Temporal Certainty in Feature-Specific Suppression During Visual Search

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Abstract

Visual attention has been proposed to be influenced not only by spatial and feature-based information but also by temporal expectations. The present study explores whether temporal certainty improves attentional selection and proactive suppression in visual search. Participants completed a spatial cueing task in a positive (target-colour cue) or a negative (distractor-colour cue) condition. Temporal certainty was manipulated with fixed or mixed cue–target intervals (100 ms, 200 ms). Reaction times (RTs) and accuracy were analysed separately for fast and slow responses. Temporal certainty had only a limited effect. Longer cue–target intervals (200 ms) often improved accuracy, but reaction time effects were inconsistent. Inverse validity effects occurred in both conditions. In the negative condition this was expected, but in the positive condition it was unexpected. Cue–matching effects were weak, possibly due to small colour differences or a greater reliance on spatial over feature-based guidance. Overall, temporal certainty alone did not enhance attentional selection or proactive suppression. Longer intervals or larger temporal differences may be needed.

*Keywords***:** Visual search; temporal certainty; distractor suppression

Zusammenfassung

Visuelle Aufmerksamkeit wird nicht nur durch räumliche und merkmalbasierte Informationen, sondern auch durch zeitliche Erwartungen beeinflusst. Die vorliegende Studie untersucht, ob zeitliche Gewissheit die Aufmerksamkeitsauswahl und die proaktive Unterdrückung bei der visuellen Suche verbessert. Hierzu bearbeiteten Teilnehmer*innen ein Spatial-Cueing-Paradigma unter einer positiven (Zielfarbhinweis) oder einer negativen (Ablenkungsfarbhinweis) Bedingung. Die zeitliche Gewissheit wurde mit festen oder gemischten Fixations-Target-Intervalle (100 ms, 200 ms) manipuliert. Reaktionszeiten und Genauigkeit wurden getrennt für schnelle und langsame Reaktionen analysiert. Zeitliche Gewissheit hatte nur einen begrenzten Effekt. Längere Intervalle (200 ms) verbesserten häufig die Genauigkeit, die Auswirkungen auf die Reaktionszeit waren jedoch inkonsistent. Inverse Validitätseffekte traten unter beiden Bedingungen auf. In der negativen Bedingung war dies zu erwarten, in der positiven hingegen überraschend. Die Effekte der Farbübereinstimmung zwischen Hinweisreiz und Ziel- bzw. Distraktorfarbe waren schwach, möglicherweise aufgrund kleiner Farbunterschiede oder einer stärkeren Abhängigkeit von räumlicher statt merkmalsbasierter Anleitung. Insgesamt verbesserte zeitliche Gewissheit allein weder die Aufmerksamkeitsauswahl noch die proaktive Unterdrückung. Wahrscheinlich wären längere Intervalle oder größere zeitliche Unterschiede erforderlich.

Schlagwörter: Visuelle Suche; Distraktorunterdrückung; Zeitliche Gewissheit

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Introduction

Visual Search and the Role of Distractor Suppression

In everyday life, people are often engaged in visual search, such as looking for an exit sign on the motorway or a navigation button in an online interface. In such instances, knowing what and when to ignore is often as important as knowing what to look for in improving search efficiency. Even though ignoring irrelevant information can improve search efficiency, a strong focus on seemingly unimportant aspects can slow down the search for a desired item. In such cases, attention might first be drawn to the item one wants to ignore before being redirected to the relevant aspects. This phenomenon, coined the *white bear effect* (Wegner et al., 1987), was originally outlined in the context of thought suppression. It highlights the difficulty of suppressing attention to a known salient distractor, that is, a visually striking but irrelevant object (Cunningham & Egeth, 2016).

Nevertheless, even though a salient distractor can at first hinder search performance, people can, with practice or knowledge about what should be ignored, improve their ability to filter it out (Moher et al., 2014). Previous studies have shown that both the ability to inhibit irrelevant stimuli and the predictability of temporal events play an essential role in visual search (Arita et al., 2012; Boettcher et al., 2022). Temporal certainty allows better allocation of attention by using resources at precise moments when targets are expected (Rohenkohl et al., 2014). This improvement could be supported by research on neuronal oscillations (Lakatos et al., 2008; Schroeder & Lakatos, 2009). These oscillations, especially in the alpha and theta frequency bands, are thought to play an important role in controlling attention and the filtering of irrelevant information. Although we do not focus extensively on neuronal oscillations here, their influence on cognitive processes and attention is well established in the literature.

Attentional Mechanisms: Selection Versus Suppression

The focus of attention is often explained by the *Biased Competition Theory* (Desimone & Duncan, 1995). This theory proposes that visual stimuli compete for processing capacities and that this competition favours task-relevant items. This means that suppression of irrelevant stimuli is not a passive process but rather an active, top-down mechanism (Gaspelin & Luck, 2018; Geng, 2014).

Temporal expectations are theorized to enhance performance through two distinct processes: first, increasing sensitivity to anticipated targets (selection) (Correa et al., 2005) and second, pre-emptively reducing interference from distractors (suppression) (Nobre & van Ede, 2018). Critically, suppression relies on proactive control mechanisms that require time to deploy (Arita et al., 2012), even though reactive types of distractor suppression have also been found (Gaspelin & Luck, 2018; Sawaki & Luck, 2013). This indicates that temporal certainty may disproportionately benefit suppression, as predictable timing allows participants to proactively suppress distractors during time windows, whereas target selection may rely more on reactive processes. Even though previous research has shown that temporal certainty can improve performance in visual search (Nobre & van Ede, 2018), it is still unclear whether it promotes attentional selection and suppression equally. Temporal certainty may improve both processes. However, it might support one more than the other. In our design, a cue appeared briefly before the search display. In the positive condition, the cue shared the target's colour, and in the negative condition, it shared the distractor's colour. Importantly, the cue did not reliably predict the target location: it was either valid (same location) in 25% of the cases or invalid (different location) in 75% of the cases. When it enhances proactive suppression of irrelevant information, then in the negative condition a stronger validity inversion should emerge, as indicated by slower responses at cued locations. This pattern probably comes from attentional suppression at the location previously associated with the distractor. When the target appears at that suppressed location, attention first needs to be reoriented there, which takes time and delays responding. This effect is distinct from the cueing effects on target selection observed in the positive condition and should be interpreted separately to avoid mixing up the two mechanisms. If temporal certainty has no effect on cue validity, these effects should remain stable across certain and uncertain timing conditions. We therefore hypothesise that temporal certainty helps to guide attention strategically, enhancing attentional selection in the positive condition and proactive suppression in the negative condition.

Temporal Certainty as a Factor in Attentional Control

On the other hand, some research has shown different results, indicating that temporal certainty helped performance in general but did not selectively improve either target selection or distractor suppression. For example, Seibold and Rolke (2014) found that temporal certainty led, in general, to faster RTs. However, it did not influence the difference between valid and invalid trials, indicating that temporal certainty did not enhance attention. Furthermore, Vatterott and Vecera (2012) showed that distractor suppression primarily depends on repeated distractor features. In their study, attention capture by a salient colour singleton only decreased when the distractor's colour was consistent across trials. This means that suppression is shaped more by consistent regularities in distractor features than by information available on a trial-by-trial basis. This raises the question if temporal certainty on its own is enough to support proactive control.

The Present Study

In each trial, a visual target was presented unpredictably at one of four locations. Prior to the target, a spatial cue was shown at one of the four positions, either at target position (valid condition) or elsewhere (invalid condition). Across trials, cue and target locations appeared at the same location in only 25% of the trials. Further, in 50% of trials the cue colour matched the target colour in the positive condition, and the distractor colour in the negative condition, while in the other trials the cue colour did not match the respective target-defining or distractor-defining colour. Critically, we conducted the experiment in two different groups with separate participants for the search task. In the positive condition, participants knew the colour of the upcoming target and the cue having the same colour as the target in 50% of the trials. In the negative condition, the participants only knew the colour of an upcoming and otherwise target-similar distractor, but not the colour of the target. Here the cue matched the distractor colour in 50% of the trials. Nevertheless, they knew that the target, like the distractor, had to be vertical in orientation. Each condition included two different cue–target intervals (100 ms and 200 ms). In the temporally certain condition, only one of the cue–target intervals was used, while in the uncertain condition both intervals were randomly mixed, so that the participants could not anticipate when the search display appeared.

Hypotheses

Our focus was on the interaction of cue validity with temporal certainty. In general, during positive search a cue with the same colour as the target attracts attention and therefore the target search is faster in valid than in invalid conditions. This validity effect stands in contrast to the absence of such effects when the cue does not share the target's colour. The validity effect is typically interpreted as evidence for the top-down contingent capture of attention by any stimulus matching a target search template (Ansorge et al., 2005). In contrast, during negative search a cue with the same colour as the distractor shows evidence of suppression that extends to the target-search display. This leads to slower search for targets at the cue positions under valid conditions, compared to targets presented away from the cue under invalid conditions. In theory, this inverse validity effect is found with cues with a negative feature but not with cues carrying an irrelevant feature (Forstinger et al., 2022; Forstinger & Ansorge, 2023).

While previous research shows that temporal certainty improves search performance, we still do not fully understand the effects of temporal uncertainty on validity effects of cues. This is especially true for inverse validity effects, that is, suppression. If temporal certainty has no effect, straight and inverse validity effects should remain similar across temporally certain and uncertain blocked conditions. However, it is assumed that temporal certainty enhances the impact of cues by improving strategic attention allocation. In particular, in the negative condition, temporal certainty should enhance attentional suppression. This should consequently increase the inverse validity effect. In the positive condition, temporal certainty should enhance attentional selection of the target. This, in turn, should increase the straight validity effect. At least under uncertain conditions with both cue–target intervals unforeseeably intermixed we also predict faster RTs and higher accuracy for the longer cue–

target interval (200 ms vs. 100 ms) because additional time allows for greater certainty of target occurrence.

Methods

Participants

Forty psychology students from the University of Vienna were recruited. One participant was excluded due to the overall accuracy deviating more than 2.5 SD from the group mean, leaving a final sample of 39 (24 female, M_{age} = 23.7 years, age range = 19–33) all with normal or corrected-to-normal vision, were recruited. 19 participants were assigned to the positive condition and 20 participants to the negative condition. All participants signed a declaration of consent before starting and were debriefed in written form afterwards. In exchange for their participation, they received coursework credits.

Apparatus

The experiment was held in a dimly lit loom. The LCD monitor for the experiment had a resolution of 1,920 x 1080 pixels (54.4 cm x 30.3 cm) with a refresh rate of 99.930 Hz. To maintain the approximate viewing distance of 57 cm to the monitor, a chin rest was used. The PyCharm (JetBrains, 2023) and the Psychopy package (Peirce et al., 2019) were used to generate and control the stimuli and to record the participants' input of the arrow keys of a standard keyboard.

Stimuli

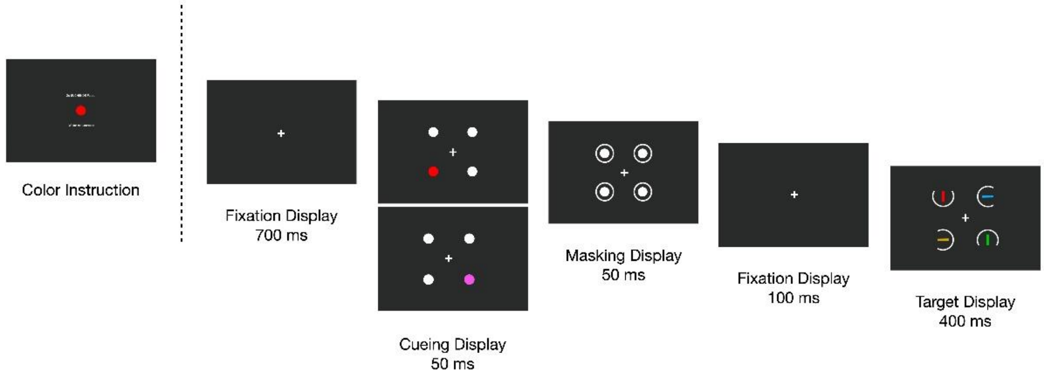
The stimuli were displayed against a dark grey background (L* = 17.58, a* =−2, b* = 0.04). Four stimuli locations were arranged in the corners of an imaginary rectangle with a visual angle of 4° for both the vertical and the horizontal offset from the screen's centre. The stimuli differed depending on the condition. For the positive condition the target colour was red (L* = 53.26, a* = 80.13, b* = 65.72), while the distractors' colours were orange (L* = 69.97, a* = −0.17, b* = 72.87) and blue (L* = 66.78, a* = 6.79, b* = 51.61). In the negative condition the to-be-ignored distractor was always red, while the colours of the target and the remaining distractors varied across the trials and were either green (L^* = 69.88, a^* = −69.9, b^* = 66.9), orange, or blue.

Procedure and Design

A schematic illustration of the trial procedure is shown in Figure 1. The experiment setup was identical across both conditions. We used two different cue–target intervals: 100 ms and 200 ms. Each trial started with a fixation display, presented for 700 ms. This was followed by a 50 ms cueing display showing four discs with a 2° diameter at the four possible target positions. Three of the discs were white (L^* = 100, a^* = 0, b^* = 0), and the fourth disc, serving as the cue, was red in 50% of the trials and purple (L^* = 61.49, a^* = 66.42, b^* = −42.55) in the other 50%. The red cue was at a valid position (i.e., the same position as the target) in 25% of the trials. The position was chosen pseudo-randomly, ensuring that all possible positions appeared equally often. Following the cueing display, a 50 ms masking display appeared, displaying four white discs with a 2° diameter, surrounded by circles with a 3.5° diameter at the four possible target positions. Only for the 200 ms cue−target interval there was an additional 100 ms fixation display after the masking display.

Figure 1

Procedure of the Negative Condition 100 ms cue–target interval



Note. Each trial began with a 700 ms fixation display, followed by a 50 ms cue display showing four discs at possible target positions, three white and one coloured (red or purple, 50 % each) serving as the cue. It appeared at the target position (valid) in 25 % of the trials. A 50 ms masking display followed, and after a 100 ms interval, the target display appeared. It had four coloured bars (two horizontal, two vertical), each with a gap (up, down, left, or right) A red vertical distractor was always present, while the target (vertical bar) was either orange, green or blue.

The target display consisted of four different coloured and oriented bars (two vertical, two horizontal). Each was surrounded by white rings with a 3.5° diameter and contained a gap at one of four possible positions (up, down, left or right). Each gap direction appeared only once per display. The occurrence was pseudorandomised across locations and appeared equally often at each stimulus position, including the target position. The target display was presented until there was a response but not for more than 1.5 s. The conditions differed only in the target display configuration. In the first, in the positive condition, one vertical (the target) and one horizontal bar were red with the remaining bars coloured blue or orange. In the second, in the negative condition one vertical bar was always red (to-be-suppressed distractor), while the target vertical bar was randomly orange, green, or blue. The horizontal bars took on the remaining two colours not used for the target, to guarantee that all four bars were uniquely coloured in each trial.

Before the experiment was started, the participants received instructions with the help of a schematic presentation similar to Figure 1, how the experiment worked. Further, they were informed that in the positive condition the colour red corresponded to the target colour and in the negative condition it corresponded to the distractor colour. Participants were only shown the condition, in which they would participate. The target display and its elements were explained in more detail by the instructors.

Each participant started the experiment with at least 80 training trials. They had to reach an accuracy of >= 80% to continue with the main experiment.

For each condition, there were 192 trials with a 100 ms cue–target interval (certain condition) and 192 trials with a 200 ms cue–target interval (certain condition). Furthermore, there were 384 trials with a mixed cue–target interval (uncertain condition). The order of certain/uncertain blocks was counterbalanced across participants.

Statistical Analysis

All analyses were conducted in R (Version 4.4.2; R Core Team, 2024) using the packages car (Version 3.1-3; Fox & Weisberg, 2019), dplyr (Version 1.1.4; Wickham & François, 2023), easystats (Version 0.7.3; Lüdecke et al., 2021), ez (Version 4.4-0; Lawrence, 2016), ggplot2 (Version 3.5.1; Wickham, 2016), ggpubr (Version 0.6.0; Kassambara, 2023), kableExtra (Version 1.4.0; Zhu, 2024), Matrix (Version 1.7-1; Bates et al., 2024), readxl (Version 1.4.3; Wickham & Bryan, 2023), rstatix (Version 0.7.2; Kassambara, 2023), and stringr (Version 1.5.1; Wickham, 2023).

To prepare the data for analysis, the RTs below 150 ms or above 1400 ms were removed (fast or late guesses and timeouts). For each participant and condition (positive and negative conditions) the mean and the standard deviation (*SD*) were calculated, and only trials within ± 2.5 SD of the individual mean were retained. Participants whose mean performance was more than 2.5 SD from the mean of all other participants were excluded. RT analyses, including outlier removal, were based only on correct responses.

Next, for each condition, the response speed was calculated for each participant. Trials with RTs between the mean RT and the mean RT + 2 *SD* were classified as “slow,” and RTs between the mean RT – 2 *SD* and the mean RT were classified as “fast.” RTs outside those parameters were excluded from further analysis.

For the accuracy analyses, accuracy values were arcsine-transformed to improve normality and homogeneity of variance. The same ±2.5 *SD*s outlier criterion was applied.

Repeat-measures analyses of variance (ANOVAs) were conducted separately for the positive and negative conditions, with temporal certainty (fixed vs. mixed cue–target intervals), cue validity (valid vs. invalid), cue–target interval (100 ms vs. 200 ms), cue matching (matching vs. non-matching and response speed (fast vs. slow) as within-subject factors. Descriptive statistics are reported for the main effects for the significant ones. Follow-up paired-sample *t*-tests were conducted for significant interactions.

Results

Reaction Time

Positive Condition

For the positive condition the repeated-measures ANOVA revealed significant main effects of response speed (F(1, 18) = 750.56, p < .001. Fast responses (M = 0.573 s) were on average 0.172 s faster than slow responses (M = 0.745 s). There was also a significant main effect of cue–target interval (F(1, 18) = 12.29, p = .003). Responses at the 100-ms interval (M = 0.662 s) were slower than at the 200-ms interval (M = 0.656 s), a difference of .006 s. Temporal certainty (F(1, 18) = 1.48, p = .240), cue validity (F(1, 18) = 4.38, p = .051), and cue condition (F(1, 18) = 0.22, p = .646) did not reach significance.

A significant two-way interaction was observed between cue validity and response speed (F(1, 18) = 15.81, p < .001). Follow-up *t*-tests revealed no significant difference in cue validity (valid vs. invalid) for the fast responses (t(18) = 1.88, p = .077). In the slow responses, RTs were significantly faster for invalid cues compared to valid cues (t(18) =

−4.95, $p < .001$). No other interactions reached significance. The complete results of the ANOVA are shown in Table A1.

Negative Condition

For the negative condition, the repeated-measures ANOVA revealed a significant main effect of response speed ($F(1, 19) = 1489.18$, $p < .001$). Fast responses (M = 0.626 s) were on average 0.236 s faster than slow responses (M = 0.862 s). Cue validity ($F(1, 19) = 1.95$, $p = .179$), temporal certainty ($F(1, 19) = 1.09$, $p = .310$), cue condition ($F(1, 19) < 0.01$, $p = .978$), and cue–target interval ($F(1, 19) < 0.01$, $p = .993$) were not significant.

A significant two-way interaction was found between cue validity and response speed ($F(1, 19) = 10.86$, $p = .004$). Follow-up *t*-tests showed that in the fast responses, RTs were significantly faster for invalid cues compared to valid cues ($t(19) = −3.94$, $p < .001$). In the slow responses, the difference between valid and invalid cues was not significant ($t(19) = 0.93$, $p = .365$).

Another significant two-way interaction was found between response speed and cue–target interval ($F(1, 19) = 6.71$, $p = .018$). However, follow-up *t*-tests for cue–target interval revealed no differences in either the fast ($t(19) = −1.95$, $p = .066$) or slow ($t(19) = 1.48$, $p = .156$) responses. No other effects reached significance. The complete results of the ANOVA are shown in Table A2.

Accuracy

Positive Condition

Accuracy data in the positive condition indicated a significant main effect of cue validity ($F(1, 18) = 11.14$, $p = .004$). On average, accuracy for invalid cues (M = 96.4%) was 1.1% higher than for valid cues (M = 95.3%). Temporal certainty ($F(1, 18) < 0.01$, $p = .996$), response speed ($F(1,18) = 0.93$, $p = .348$), cue condition ($F(1, 18) = 2.12$, $p = .163$), and cue–target interval ($F(1, 18) = 1.63$, $p = .217$) were not significant.

A significant two-way interaction was observed between temporal certainty and cue–target interval ($F(1, 18) = 4.75$, $p = .043$). Follow-up *t*-test revealed, in the certain condition, accuracy for the 200 ms intervals was 1.14% higher than for the 100 ms intervals ($t(18) =$

2.41, *p* = .027). In the uncertain condition, there was no significant effect. No other interactions reached significance. The complete results of the ANOVA are shown in Table A2.

Negative Condition

The results showed a significant main effect of response speed (*F*(1, 19) = 6.05, *p* = .023). Accuracy for fast responses (*M* = 92.4%) was on average 2.75% higher than for slow responses (*M* = 89.7%) Temporal certainty (*F*(1, 19) = 0.41, *p* = .529), cue validity (*F*(1, 19) = 1.81, *p* = .196), cue condition (*F*(1, 19) = 0.22, *p* = .646), and cue–target interval (*F*(1, 19) = 0.81, *p* = .378) were not significant.

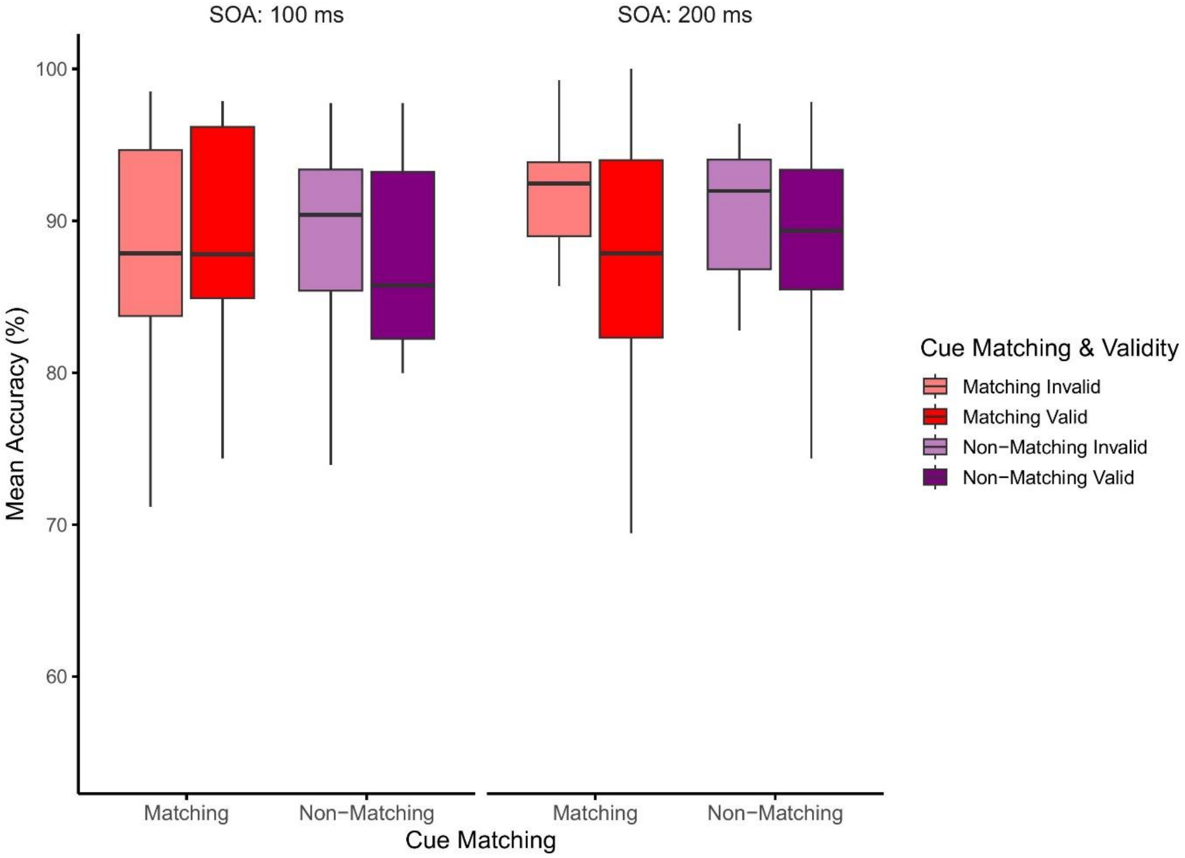
A significant two-way interaction was shown between temporal certainty and cue–target interval (*F*(1, 19) = 7.50, *p* = .013). Follow-up *t*-tests showed that in the certain condition, accuracy was 2.51% higher for the 200 ms interval than for the 100 ms interval (*t*(19) = 2.52, *p* = .021), The *t*-test for the uncertain condition revealed no significant difference.

Additionally, a significant two-way interaction was observed between speed category and cue–target interval (*F*(1, 19) = 7.39, *p* = .014). In the slow responses, accuracy for the 200 ms cue–target interval was 3.0% higher than for the 100 ms interval (*t*(19) = 2.93, *p* = .009). All other comparisons were not significant.

A further significant three-way interaction was found between cue validity and cue condition with cue–target interval (*F*(1, 19) = 6.48, *p* = .020). In the matching-cue condition at the 200 ms cue–target interval, accuracy for the invalid cues was 3.99% higher than for valid cues (*t*(19) = 2.78, *p* = .012), illustrated in Figure 2. No other comparisons were significant.

Figure 2

Mean Accuracy (%) for Valid and Invalid Trials by Cue Matching and Cue–Target Interval in the Negative Condition



Note. Error bars represent 95% confidence intervals. SOA = stimulus onset asynchrony.

Finally, a significant four-way interaction between temporal certainty, response speed, cue condition, and cue–target interval was also observed ($F(1, 19) = 5.33$, $p = .032$). Follow-up *t*-tests comparing matching and non-matching cues within each combination of temporal certainty, response speed, and cue–target interval revealed no significant differences. The complete ANOVA results are shown in Table A4.

Discussion

The current study examined whether temporal certainty changes cue validity effects in positive and negative visual search. Overall, we found that temporal certainty had only limited influence on attentional selection and suppression. Some benefits emerged for longer cue–target intervals, particularly in accuracy, but these effects were not consistent across conditions.

In the positive condition, RTs were slightly faster for the 200 ms than for the 100 ms cue–target intervals. For the slow responses invalid cues enhanced target detection in comparison with valid cues.

A similar trend was observed in the negative condition, where an interaction between cue validity and response speed emerged. For fast responses, invalid cues enhanced target detection compared to valid cues.

Turning to the accuracy results, in the positive condition, we surprisingly found an inverse validity effect, where invalid trials achieved better accuracy than the valid ones. Moreover, under temporal certainty, the 200 ms cue–target intervals produced more accurate responses than the 100 ms intervals.

The analysis of the negative condition showed that the participants were more accurate in their fast responses compared to the slow ones: Under temporal certainty condition, the 200 ms cue–target intervals trials led to higher accuracy than the 100 ms intervals. This was similar to the positive condition. Further in slow responses, the 200 ms cue–target intervals produced more accurate responses. Finally, again the invalid cues made more accurate responses in the interaction of matching cue colour to distractors colour in the 200 ms cue–target intervals trials.

Contrary to our hypothesis, temporal certainty did not consistently enhance attentional selection in the positive condition or improve proactive suppression in the negative condition. The few significant effects were limited only to interactions in the accuracy data and did not appear in the RTs. In the positive condition, we even found an inverse validity effect in the slow response RTs and overall, in accuracy. In the negative condition, an inverse validity effect appeared only in the fast response RTs. Longer cue–target intervals (200 ms) were generally associated with higher accuracy in both conditions, but this effect was not specific to temporal certainty.

The Limited Effect of Temporal Certainty for Attentional Selection and Proactive Suppression

These findings show that temporal certainty alone does not reliably improve attentional selection or proactive suppression. For example, Balke et al. (2021) used a visual search paradigm with spatial cues and found only a modest improvement of temporal certainty. This suggests that its effectiveness depends on additional factors such as cue salience and task demands. Pomper et al (2023) reported that temporal certainty produced only limited success when presented in isolation. With stronger effects only emerging when it was combined with other predictive information. Their findings from a visual search task imply that timing alone is insufficient to guide attention effectively.

By contrast, some studies have found clear effects of temporal certainty. They often used longer cue–target intervals, for example 300 ms and 1500 ms (Coull & Nobre, 1998), or fixed (400 ms) versus jittered (200, 300, 400, 500, or 600 ms) intervals (Rohenkohl et al., 2012). They also had fewer possible intervals or tasks with lower visual complexity. These factors may have made it easier for participants to prepare. Such methodological differences could explain why the expected effects did not appear as strongly in our study. In line with the findings of Balke et al. (2021) and Pomper et al. (2023), we observed accuracy benefits for the longer cue–target interval. This indicates that temporal certainty by itself is not effective to improve accuracy in guiding attention toward the target or suppressing the distractor. One possible reason for this limited effect in our study could be the cue–target intervals. Perhaps, the cue–target intervals of 100 ms and 200 ms were overall too short. It is possible that longer intervals might allow for more complete attentional preparation. This, in turn, would lead to faster RTs and higher accuracy under temporally certain conditions. Moreover, the 100 ms difference between the two intervals may have been too small for participants to perceive them as meaningfully different. A larger gap between intervals might have produced a stronger effect. Another explanation could be that participants might have prepared mentally for the two cue–target intervals, if they had known of the existence before, thereby improving their performance. Correa et al, (2005) found that distributional temporal expectations can enhance preparation across multiple intervals which may have reduced any additional benefit of temporal certainty.

The Inverse Validity Effect in the Positive and Negative Condition

The most surprising result was the inverse validity effect in the positive condition. For the slow responses, invalid cues produced faster RTs than valid cues, and overall, they also led to higher accuracy. These results do not fully align with previous research, where valid cues lead to faster responses and higher accuracy (Folk et al., 1992; Posner, 1980). A possible explanation for this could be that the trials in which invalid cues led to faster RTs in slow responses and higher accuracy in general in the positive condition were more cognitively demanding and possibly involved other mechanisms were involved for the target search, such as *inhibition of return,* which refers to a bias against reorienting attention to previously attended location (Klein, 2000). Another explanation could be that participants unintentionally developed a tendency to allocate more attention to locations indicated by invalid cues, even though they did not know whether a cue would be helpful in the search in advance. Such a pattern could have been adopted as part of their search strategy over time and could have led to longer search times but higher accuracy.

However, in the negative trials, the pattern is in line with published research suggesting that invalid cues may reflect successful proactive suppression. Forstinger et al. (2022) found that when cues consistently indicated a distractor location, participants shifted attention away from the cued position, resulting in improved target detection and higher accuracy. Interesting enough, our results showed only in two cases a reverse validity effect and not as an overarching effect. Namely, the invalid cues led to shorter response times in the fast response speed category and in the interaction between the cue validity and cue matching colours and interval duration. For the fast responses, it is possible that the participants were better able to ignore the invalid cues, which led to generally faster responses and may explain why the effect was only observed in the fast response speed condition. In the other scenario, the strategy of ignoring the invalid cue was feasible only when the cue matched the distractor's colour and the cue–targe interval was long. A possible explanation could be that the participants had more time to process the cue and therefore were able to ignore it better which led to better accuracy in this case.

Possible Influence of Colour Similarity on Cue–Matching Effects

An effect not discussed in our hypothesis was the impact of cue–matching colour with the target in the positive condition and the cue–matching with the distractor in the negative condition. In the positive condition, a colour-matching cue should enhance attentional selection by directing attention more effectively to the target location. In the negative condition it should improve distractor suppression and potentially guide attention away from its location. We found only one interaction, namely that matching cues produced higher accuracy than non-matching cues in the negative condition. In contrast to Kugler et al., (2015), who emphasized slower and less efficient guidance by negative cues, our findings show enhanced accuracy for matching cues in the negative condition. However, this would not explain why there was hardly any effect. One possible explanation is that participants did not perceive the colour-matching red cue and the non-matching purple cue as two clearly distinct different colours, given the short presentation time of the cue. The two colours may simply not have been sufficiently different. Previous research has shown that cueing efficiency in visual search is sensitive to even small variations in colour similarity between the cue and the target (Goller et al., 2016). Another explanation could be that the participants ignored the colour of the cue altogether because they assumed it would always be red. Therefore, there was no need to focus on the cue colour, only on the location of it, which also explains why there was no overall effect (Leber & Egeth, 2006). Additionally, the participants have possibly adopted a broader, less colour-specific search strategy relying more in the spatial aspect of the cue than the colour guidance. Previous work has shown that feature guidance is most effective when the target is strongly represented in working memory. If the representation is weak, search is less reliant on feature cues (Beck & Kastner, 2009; Goldstein & Beck, 2018).

The Possible Effects of Longer Cue–Target Intervals

Another effect not mentioned in our hypothesis was the influence of different cue–target interval duration. In both the positive and negative conditions, the longer cue–target interval (200 ms) often led to faster RTs and higher accuracy than the shorter one (100 ms). Given the short cue presentation and the demand of a visual search task, a slightly longer interval may allow participants to process the cue information more effectively before target onset. A longer interval could also improve the precision of attentional selection and proactive suppression toward the cued location, as a result enhancing both the speed and accuracy of the target response. This aligns with previous research (Lee & Han, 2020; van Ede et al., 2012). While van Ede et al. (2012) experimented primarily with 250 ms or longer intervals, results support the conclusion that longer time intervals allow more time for processing the cues. This can improve both RT and accuracy by allowing more complete attentional preparation. Similarly, the study from Lee & Han (Lee & Han, 2020) researched stimulus-onset asynchronies in a visual search task that proceeded concurrently with central processing stages. This, in turn led to faster RTs and in some cases to higher accuracy. This additional time could also support positive cues by enhancing the consistent use of feature information. For negative cues, it could improve the suppression of the distractor location before target onset. Moher & Egeth (2012) found that observers often attend to to-be-ignored items before suppressing them. They argue that such suppression may require additional time to fully develop.

Conclusion

The present study found that temporal certainty in isolation does not reliably improve attentional selection or enhance proactive suppression in visual search. However, longer cue–target intervals (200 ms) were often associated with higher accuracy, although those effects were not so consistently found in RTs. The improvement in accuracy depends on factors such as response speed and whether the cue was colour matched with the target or distractor. A reverse validity effect was observed in both conditions, expected in the negative condition, but surprisingly also in the positive condition. This suggests that participants may have adopted alternative search strategies or that mechanisms such as *inhibition of return* promoted performance patterns. Additionally, the limited cue–matching effects could be due to the small colour differences between cues or a tendency of participants to rely more on spatial than feature guidance.

Overall, these findings indicate that the relationship between temporal certainty, cue validity and different cue–target intervals is more complex than previously assumed. The limited effects may partly reflect the short cue–target intervals used in the experiment. Potentially, longer intervals could allow more complete attentional preparation, enhancing both selection and suppression. Future research should explore whether longer cue–target intervals or alternative timing manipulations can produce stronger and more consistent effects.

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Appendix

Table A1

ANOVA Results for Reaction Times in the Positive Condition

Effect	*df*	*F*	*p*	η^2
(Intercept)	1, 18	3686.47	< .001	0.994
temporal certainty	1, 18	1.48	.240	0.001
cue validity	1, 18	4.38	.051	0.001
response speed	1, 18	750.56	< .001	0.739
cue colour condition	1, 18	0.22	.646	0.000
Cue–target interval (ms)	1, 18	12.29	.003	0.003
tc:cv	1, 18	0.02	.898	0.000
tc:rs	1, 18	0.07	.796	0.000
cv:rs	1, 18	15.81	< .001	0.004
tc:ccc	1, 18	0.04	.850	0.000
cv:ccc	1, 18	0.06	.812	0.000
rs:ccc	1, 18	1.16	.296	0.000
tc:cti	1, 18	0.00	.952	0.000
cv:cti	1, 18	0.07	.801	0.000
rs:cti	1, 18	4.11	.058	0.001
ccc:cti	1, 18	0.31	.584	0.000
tc:cv:rs	1, 18	0.01	.909	0.000
tc:cv:ccc	1, 18	0.87	.364	0.000
tc:rs:ccc	1, 18	2.04	.171	0.000
cv:rs:ccc	1, 18	1.33	.265	0.000
tc:cv:cti	1, 18	2.63	.122	0.000
tc:rs:cti	1, 18	0.27	.609	0.000
cv:rs:cti	1, 18	0.43	.520	0.000
tc:ccc:cti	1, 18	0.04	.840	0.000
cv:ccc:cti	1, 18	0.72	.408	0.000
rs:ccc:cti	1, 18	0.08	.775	0.000
tc:cv:rs:ccc	1, 18	0.00	.991	0.000
tc:cv:rs:cti	1, 18	0.04	.848	0.000
tc:cv:ccc:cti	1, 18	0.54	.473	0.000
tc:rs:ccc:cti	1, 18	0.69	.417	0.000
cv:rs:ccc:cti	1, 18	0.00	.960	0.000
tc:cv:rs:ccc:cti	1, 18	2.50	.132	0.000

Note. tc = temporal certainty; cv = cue validity; rs = response speed; ccc = cue colour condition; cti = cue–target interval (ms).

Interactions are denoted by colons (e.g., tc:cv = interaction between temporal certainty and cue validity).

Table A2

ANOVA Results for Reaction Times in the Negative Condition

Effect	*df*	*F*	*p*	*η²*
(Intercept)	1, 19	4148.80	< .001	0.994
temporal certainty	1, 19	1.09	.310	0.001
cue validity	1, 19	1.95	.179	0.001
response speed	1, 19	1489.18	< .001	0.812
cue colour condition	1, 19	0.00	.978	0.000
Cue–target interval (ms)	1, 19	0.00	.993	0.000
tc:cv	1, 19	0.27	.611	0.000
tc:rs	1, 19	0.01	.943	0.000
cv:rs	1, 19	10.86	.004	0.002
tc:ccc	1, 19	3.54	.075	0.001
cv:ccc	1, 19	0.94	.344	0.000
rs:ccc	1, 19	0.13	.727	0.000
tc:cti	1, 19	0.60	.448	0.000
cv:cti	1, 19	0.25	.621	0.000
rs:cti	1, 19	6.71	.018	0.002
ccc:cti	1, 19	0.77	.391	0.000
tc:cv:rs	1, 19	0.06	.803	0.000
tc:cv:ccc	1, 19	0.20	.659	0.000
tc:rs:ccc	1, 19	0.14	.710	0.000
cv:rs:ccc	1, 19	1.47	.241	0.000
tc:cv:cti	1, 19	0.00	.979	0.000
tc:rs:cti	1, 19	0.11	.749	0.000
cv:rs:cti	1, 19	0.00	.975	0.000
tc:ccc:cti	1, 19	3.07	.096	0.001
cv:ccc:cti	1, 19	0.89	.358	0.000
rs:ccc:cti	1, 19	0.17	.688	0.000
tc:cv:rs:ccc	1, 19	0.68	.420	0.000
tc:cv:rs:cti	1, 19	0.13	.719	0.000
tc:cv:ccc:cti	1, 19	2.62	.122	0.001
tc:rs:ccc:cti	1, 19	0.01	.917	0.000
cv:rs:ccc:cti	1, 19	1.66	.213	0.000
tc:cv:rs:ccc:cti	1, 19	0.00	.982	0.000

Note. tc = temporal certainty; cv = cue validity; rs = response speed; ccc = cue colour condition; cti = cue–target interval (ms).

Interactions are denoted by colons (e.g., tc:cv = interaction between temporal certainty and cue validity).

Table A3

ANOVA Results for Accuracy in the Positive Condition

Effect	*df*	*F*	*p*	*η²*
(Intercept)	1, 18	34,300.72	< .001	0.997
temporal certainty	1, 18	0.00	0.997	0.000
cue validity	1, 18	11.14	0.004	0.012
response speed	1, 18	0.93	0.348	0.001
cue colour condition	1, 18	2.12	0.163	0.005
Cue–target interval (ms)	1, 18	1.63	0.217	0.002
tc:cv	1, 18	0.78	0.388	0.001
tc:rs	1, 18	0.05	0.831	0.000
cv:rs	1, 18	0.23	0.639	0.000
tc:ccc	1, 18	0.00	0.987	0.000
cv:ccc	1, 18	0.21	0.649	0.000
rs:ccc	1, 18	0.08	0.777	0.000
tc:cti	1, 18	4.75	0.043	0.009
cv:cti	1, 18	0.03	0.873	0.000
rs:cti	1, 18	0.18	0.677	0.000
ccc:cti	1, 18	0.37	0.549	0.000
tc:cv:rs	1, 18	0.20	0.658	0.000
tc:cv:ccc	1, 18	0.84	0.370	0.001
tc:rs:ccc	1, 18	2.49	0.132	0.004
cv:rs:ccc	1, 18	1.15	0.297	0.001
tc:cv:cti	1, 18	1.17	0.294	0.002
tc:rs:cti	1, 18	0.42	0.527	0.001
cv:rs:cti	1, 18	0.35	0.562	0.000
tc:ccc:cti	1, 18	0.03	0.868	0.000
cv:ccc:cti	1, 18	0.67	0.425	0.001
rs:ccc:cti	1, 18	0.23	0.639	0.000
tc:cv:rs:ccc	1, 18	1.23	0.283	0.002
tc:cv:rs:cti	1, 18	0.37	0.551	0.000
tc:cv:ccc:cti	1, 18	0.00	0.969	0.000
tc:rs:ccc:cti	1, 18	0.53	0.477	0.001
cv:rs:ccc:cti	1, 18	1.00	0.330	0.002
tc:cv:rs:ccc:cti	1, 18	0.12	0.735	0.000

Note. tc = temporal certainty; cv = cue validity; rs = response speed; ccc = cue colour condition; cti = cue–target interval (ms).

Interactions are denoted by colons (e.g., tc:cv = interaction between temporal certainty and cue validity)

Table A4

ANOVA Results for Accuracy in the Negative Condition

Effect	*df*	*F*	*p*	*η²*
(Intercept)	1, 19	5590.92	< .001	0.988
temporal certainty	1, 19	0.41	0.529	0.002
cue validity	1, 19	1.81	0.195	0.002
response speed	1, 19	6.05	0.024	0.017
cue colour condition	1, 19	0.22	0.646	0.000
Cue–target interval (ms)	1, 19	0.81	0.378	0.001
tc:cv	1, 19	1.04	0.320	0.002
tc:rs	1, 19	0.98	0.335	0.002
cv:rs	1, 19	0.12	0.733	0.000
tc:ccc	1, 19	0.06	0.807	0.000
cv:ccc	1, 19	0.11	0.738	0.000
rs:ccc	1, 19	0.01	0.931	0.000
tc:cti	1, 19	7.50	0.013	0.007
cv:cti	1, 19	2.51	0.130	0.003
rs:cti	1, 19	7.39	0.014	0.003
ccc:cti	1, 19	0.37	0.548	0.001
tc:cv:rs	1, 19	0.01	0.939	0.000
tc:cv:ccc	1, 19	0.60	0.450	0.000
tc:rs:ccc	1, 19	0.01	0.910	0.000
cv:rs:ccc	1, 19	0.81	0.380	0.001
tc:cv:cti	1, 19	4.28	0.052	0.003
tc:rs:cti	1, 19	0.42	0.522	0.000
cv:rs:cti	1, 19	1.91	0.182	0.002
tc:ccc:cti	1, 19	0.71	0.409	0.001
cv:ccc:cti	1, 19	6.48	0.020	0.006
rs:ccc:cti	1, 19	0.08	0.775	0.000
tc:cv:rs:ccc	1, 19	0.03	0.856	0.000
tc:cv:rs:cti	1, 19	0.24	0.632	0.000
tc:cv:ccc:cti	1, 19	0.00	0.969	0.000
tc:rs:ccc:cti	1, 19	5.33	0.032	0.002
cv:rs:ccc:cti	1, 19	0.00	0.979	0.000
tc:cv:rs:ccc:cti	1, 19	0.76	0.396	0.001

Note. tc = temporal certainty; cv = cue validity; rs = response speed; ccc = cue colour condition; cti = cue–target interval (ms).

Interactions are denoted by colons (e.g., tc:cv = interaction between temporal certainty and cue validity).