How Temporal Preparation Influences Spatial Selection

Dissertation
der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen
zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

vorgelegt von
Janina-Hannah Balke
aus Würzburg

Tübingen
2024

How Temporal Preparation Influences Spatial Selection

Dissertation
der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen
zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

vorgelegt von
Janina-Hannah Balke
aus Würzburg

Tübingen
2024

Gedruckt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Eberhard Karls Universität Tübingen.

Tag der mündlichen Qualifikation:	31.07.2024
Dekan:	Prof. Dr. Thilo Stehle
1. Berichterstatter/-in:	Prof. Dr. Bettina Rolke
2. Berichterstatter/-in:	Prof. Dr. Hartmut Leuthold

Table of Contents

List of figures

List of tables

List of abbreviations

CNV	contingent negative variation
EEG	electroencephalography
ERP	event-related potential
FP	foreperiod
hEOG	horizontal electro-oculogram
N2pc	N2posterior-contralateral
N_D	N2pc evoked by the singleton distractor
N_T	N2pc evoked by the target
P_D	distractor positivity
PTM	perceptual template model
rmANOVA	repeated-measures analysis of variance
RT	reaction time
vEOG	vertical electro-oculogram

Statement

Parts of the published studies (Chapter 3: Study 2, Chapter 4: Study 3) overlap in content with the introduction (Chapter 1) and the discussion (Chapter 5) of this dissertation. The author's own contributions to the published studies are listed before each chapter.

Abstract

Studies provide evidence that temporal preparation facilitates spatial selection in visual search. According to visual search models, spatial selection of stimuli can be influenced by several factors such as bottom-up salience, top-down goals, and prior selection history. The question is *how* temporal preparation facilitates spatial selection. To this end, this dissertation investigated whether temporal preparation affects spatial selection by influencing bottom-up and/or top-down processing. To manipulate temporal preparation, a constant foreperiod (FP) paradigm was applied in which the interval between an auditory warning signal and a subsequent search display was varied (i.e., short or long FP). Study 1, a series of behavioral experiments, aimed to investigate whether temporal preparation interacts with target salience, examining bottom-up processing, or with prior knowledge of the target constancy, corresponding to the formation of a top-down representation. Participants' (experiment 1: N = 24, experiment 2: N = 32) task was to find a pop-out target among homogeneous distractors. Replicating previous findings, Study 1 showed an FP effect in reaction time (RT), i.e., an indicator of temporal preparation. Most importantly, this FP effect did not interact with target salience or target constancy. These RT results do not support a direct influence of temporal preparation on bottom-up or top-down processing in visual search. In Study 2, event-related potentials (ERPs) were measured to investigate whether temporal preparation facilitates spatial selection as a function of target salience, and thus bottom-up processing. Participants (N = 24) searched for a salient target among homogeneous distractors, with the N2pc being measured as an index of spatial selection. Temporal preparation accelerated the spatial selection of the target, as indexed by a reduction of the onset latency of the target N2pc. Furthermore, temporal preparation reduced the onset latency of the N2pc to a greater extent for low salient targets than for high salient targets. This result provides evidence that temporal preparation facilitates spatial selection as a function of stimulus salience. In addition, Study 3 aimed to further investigate the influence of temporal preparation on bottom-up and top-down processes in spatial selection. Therefore, participants (N = 24) performed a visual search task for a shape target while ignoring a color singleton distractor. Interestingly, temporal preparation also modulated the amplitude of the N2pc elicited by the salient but task-irrelevant distractor. This finding supports the notion that temporal preparation influences the processing of all salient stimuli in spatial

selection, regardless of their task-relevance. Taken together, the results of the two ERP studies (Studies 2 and 3) provide evidence that temporal preparation facilitates spatial selection by influencing bottom-up processing.

Zusammenfassung

Studien belegen, dass zeitliche Vorbereitung die räumliche Selektion in der visuellen Suche erleichtert. Nach Modellen der visuellen Suche kann die räumliche Selektion von Stimuli durch verschiedene Faktoren beeinflusst werden, z. B. durch Bottom-up-Salienz, Top-down-Gewichtung und vorangegangene Selektionsvorgänge. Die Frage ist, wie zeitliche Vorbereitung die räumliche Selektion erleichtert. Zu diesem Zweck wurde in dieser Dissertation untersucht, ob zeitliche Vorbereitung die räumliche Selektion durch Beeinflussung der Bottom-up- und/oder Top-down-Verarbeitung beeinflusst. Zur Manipulation der zeitlichen Vorbereitung wurde ein geblocktes Vorperiodenparadigma verwendet, bei dem das Intervall zwischen einem akustischen Warnsignal und einem anschließenden Suchdisplay variiert wurde (d. h. kurze oder lange Vorperiode, FP). Studie 1, eine Reihe von Verhaltensexperimenten, hatte zum Ziel zu untersuchen, ob zeitliche Vorbereitung mit der Salienz des Zielreizes interagiert, also die Bottom-up-Verarbeitung beeinflusst, oder mit dem Vorwissen über die Konstanz des Zielreizes, also die Bildung eines Top-down-Sets beeinflusst. Die Teilnehmer (Experiment 1: N = 24, Experiment 2: N = 32) hatten die Aufgabe, einen Pop-Out-Zielreiz unter homogenen Distraktoren zu finden. In Übereinstimmung mit früheren Ergebnissen zeigte sich in Studie 1 ein FP-Effekt in der Reaktionszeit (RT), d. h. ein Indikator für zeitliche Vorbereitung. Besonders wichtig ist, dass dieser FP-Effekt nicht mit der Salienz des Zielreizes oder der Zielreizkonstanz interagierte. Diese RT-Ergebnisse sprechen nicht für einen direkten Einfluss der zeitlichen Vorbereitung auf die Bottom-up- oder Top-down-Verarbeitung in der visuellen Suche. In Studie 2 wurden ereigniskorrelierte Potentiale (ERPs) gemessen, um zu untersuchen, ob zeitliche Vorbereitung die räumliche Selektion in Abhängigkeit von der Salienz des Zielreizes und damit die Bottom-up-Verarbeitung erleichtert. Die Teilnehmer (N = 24) suchten nach einem salienten Zielreiz unter homogenen Distraktoren, und die N2pc wurde als Index für räumlichen Selektion gemessen. Zeitliche Vorbereitung beschleunigte die räumliche Selektion des Zielreizes, was sich in einer Verringerung der Onset-Latenz der N2pc für den Zielreiz zeigte. Darüber hinaus verringerte zeitliche Vorbereitung die Onset-Latenz der N2pc in einem größeren Ausmaß für niedrig saliente Zielreize als für hoch saliente Zielreize. Dieses Ergebnis belegt, dass zeitliche Vorbereitung die räumliche Selektion in Abhängigkeit von der Salienz des Zielreize erleichtert. Darüber hinaus sollte in Studie 3 der Einfluss der zeitlichen Vorbereitung

auf Bottom-up- und Top-down-Prozesse in der räumlichen Selektion weiter untersucht werden. Zu diesem Zweck führten die Teilnehmer (N = 24) eine visuelle Suchaufgabe für ein Formzielreiz durch, während sie einen andersfarbigen Distraktor ignorieren sollten. Interessanterweise modulierte die zeitliche Vorbereitung auch die Amplitude der N2pc, die durch den salienten, aber für die Aufgabe irrelevanten Distraktor ausgelöst wurde. Dieses Ergebnis unterstützt die Annahme, dass zeitliche Vorbereitung die Verarbeitung aller salienten Reize in der räumlichen Selektion beeinflusst, unabhängig von ihrer Aufgabenrelevanz. Zusammengenommen liefern die Ergebnisse der beiden ERP-Studien (Studien 2 und 3) Evidenz dafür, dass zeitliche Vorbereitung die räumliche Selektion durch Beeinflussung der Bottom-up-Verarbeitung erleichtert.

1. Introduction

“Ready – Set – Go!”

In our minds, we have an image of runners standing at the starting line. With the signal "Ready!" they crouch down and take their starting positions. The "Set!" signal increases concentration and anticipation for the start signal. Finally, at the "Go!" signal, the runners launch, dedicating all their resources to the sprint, perfectly prepared for this moment.

This illustration shows that shifting our resources to a specific moment in time is a fundamental cognitive function to prepare for an anticipated event. This process is known as temporal preparation, which describes the process of preparing for a time when an upcoming event or stimulus is most likely to occur and is therefore expected (Minuissi et al., 1999; Müller-Gethmann et al., 2003; Rolke & Ulrich, 2010). In the case of the race, it seems obvious that preparation increases motor processes at the expected time point of the start signal. However, research has also shown that temporal preparation affects perceptual processing (e.g., Correa et al., 2006; Jepma et al., 2012; Rolke, 2008). Consequently, the question arises as to whether this optimized perceptual processing through temporal preparation is limited to specific stimuli in our environment or whether this advantage improves the entire perceptual process globally.

One of the aims of this dissertation will be to investigate how temporal preparation can affect perceptual processing. Before addressing this question through experimental studies, the first chapter (Chapter 1) will provide an overview of temporal preparation and its influence on perceptual processing, highlighting aspects that are crucial for understanding the specific research question of this dissertation. Following the Introduction, the next chapters (Chapters 2 to 4) describe three experimental studies that were conducted to address this question. The results of these studies are discussed in the final chapter (Chapter 5).

1.1 Experimental paradigms for manipulating temporal preparation

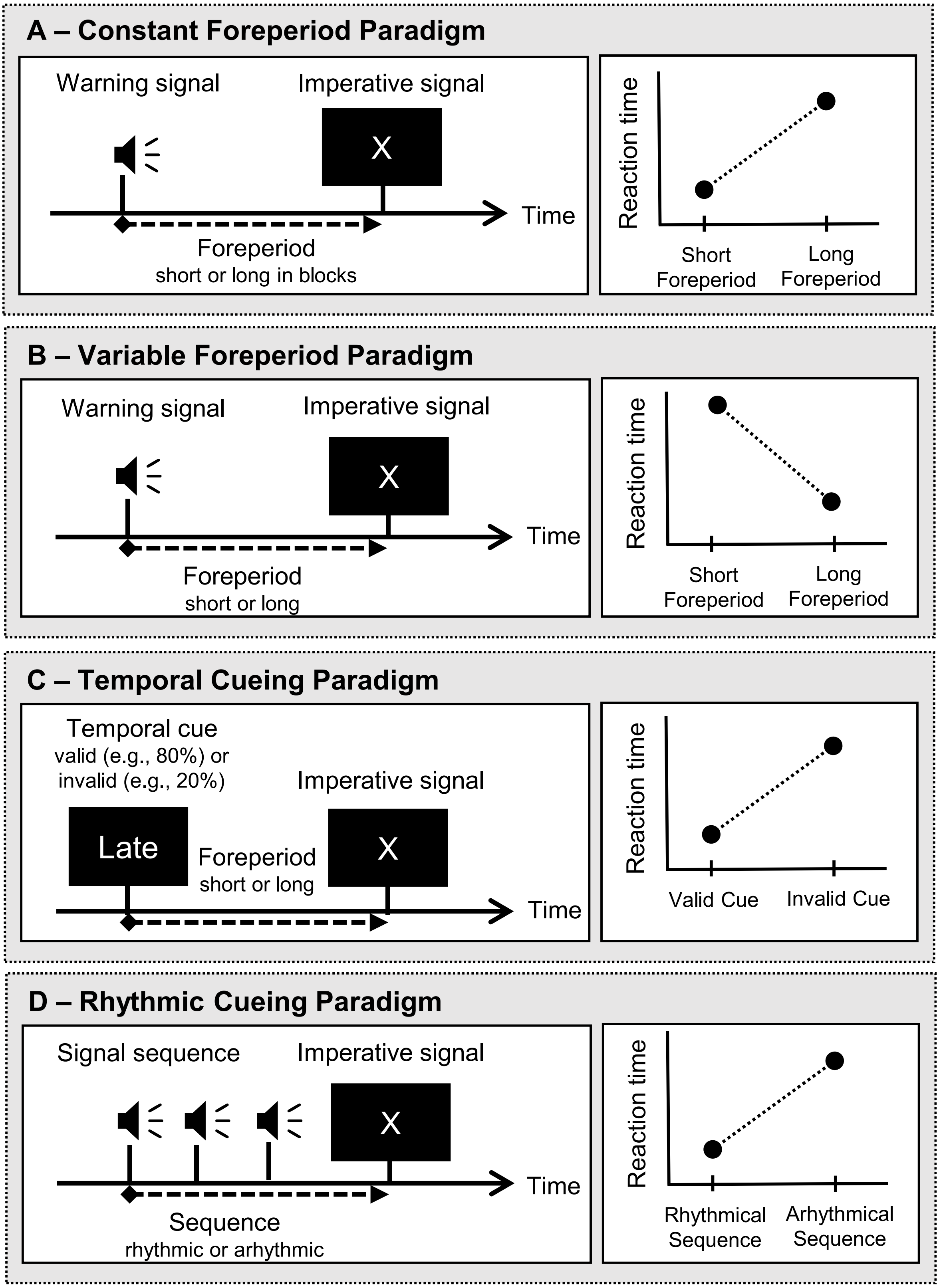
In the early 20th century, Woodrow (1914) began to study the influence of temporal preparation on attention. In his pioneering work, he systematically investigated the effects of preparatory intervals on imperative signals and the participants’ subsequent responses. From this origin, the following section provides an overview of current paradigms in the study of temporal preparation, highlighting both similarities and differences among them.

One of the experimental approaches used to study temporal preparation is the *constant* (or blocked) *foreperiod paradigm*. In this paradigm, a warning signal predicts the subsequent appearance of an imperative target signal. The interval between the warning signal and the imperative signal, known as the foreperiod (FP), can vary in length, being either relatively short or long. Within one part or block of the experiment, the length of the FP remains constant but varies across the entire experiment. In particular, in the constant FP paradigm, it has been consistently observed that participants' responses are faster in blocks with relatively short FPs (e.g., 800 ms) compared to blocks with relatively long FPs (e.g., 2,400 ms; see Figure 1-1A; Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Woodrow, 1914). This finding can be explained by the inability of our system to accurately estimate longer intervals: As the FP length increases, the temporal uncertainty increases, resulting in an imprecise estimation of the exact time of occurrence of the imperative signals (Klemmer, 1956; Müller-Gethmann et al., 2003). Furthermore, maintaining a high level of response preparation is only possible and beneficial for a short interval in the range of 100 to 300 ms (Alegria, 1974, Gottsdanker, 1975; Müller-Gethmann et al., 2003). Therefore, temporal preparation is more effective when the estimation of the occurrence of the imperative signal is more accurate, as it is the case for a short FP when response preparation is optimally tuned to the expected point in time (Müller-Gethmann et al., 2003; Näätänen et al., 1974; Rolke & Ulrich, 2010).

Another approach to manipulating temporal preparation is the *variable FP paradigm*, which varies the FP interval between warning signal and the imperative signal (see Figure 1-1B). In contrast to the constant FP paradigm, the FP length in the variable FP paradigm is not fixed within a block but varies from trial to trial. Interestingly, the pattern of reaction time (RT) observed in the variable FP paradigm is reversed compared to the constant FP paradigm: participants' RT decreases with increasing FP length (see Figure 1-1B; Los, 2010; Niemi & Näätänen, 1981; Steinborn et al., 2008). One possible explanation for this pattern is that as FP length increases, the probability – or hazard rate – of the target occurring at the next possible time point increases simply because it has not yet occurred (Müller-

Figure 1-1

Illustration of experimental paradigms and their typically observed result patterns



Note. Shown are typical trial sequences (left) and the observed reaction time results (right) of the (A) constant foreperiod paradigm, (B) variable foreperiod paradigm, (C) temporal cueing paradigm, and (D) rhythmic cueing paradigm.

Gethmann et al., 2003; Niemi & Näätänen, 1981; see Los, 2010 for a review). For example, if there are only two possible FPs in a block, the probability of the target occurring after a long FP, given that it has not yet occurred, is 100%. As time progresses within a trial, temporal uncertainty decreases, allowing for maximal optimization of temporal preparation at the most likely time (see e.g., Los, 2010; Los et al., 2014). Furthermore, another interesting effect in the variable FP paradigm is that the RT in the current trial is influenced by the FP length of the previous trial. This so-called sequence effect is observed in current trials with a short FP, where RTs are shorter when the previous trial was also presented with a short FP compared to a long FP (Los & Agter, 2005). This observation has led to another possible explanation, which assumes that the conditional strength is not fixed, but changes dynamically within a trial, including short-term memory effects such as the previous trial (Los et al., 2014; Los & van den Heuvel, 2001). In summary, manipulating temporal preparation using one of the introduced FP paradigms, i.e. constant or variable FP paradigm, leads to different levels of temporal certainty for specific time points and thus to different RT patterns based on the expected probability of FPs.

However, in both variable and constant FP paradigms, temporal information about the expected time of the imperative stimulus is provided relatively implicitly and is gradually acquired over time. In contrast, temporal expectations can also be formed by cues that provide explicit information about when the imperative stimulus is likely to occur. This process, known as temporal orienting, involves directing attention to a specific time using explicit cues (Correa et al., 2010; Coull & Nobre, 1998; Kingstone, 1992). Analogous to spatial cueing (Posner, 1980), the temporal cueing paradigm uses a symbolic (Correa et al., 2004; Coull & Nobre, 1998; Minuissi et al., 1999) or verbal (Correa et al., 2004; Correa et al., 2010) cue to provide information about the expected timing of the imperative stimulus. In the classical version of this paradigm, the cue is valid or correct in a certain proportion of trials (e.g., 80% of trials), while the cue provides invalid information in a minority of trials (e.g., 20% of trials; see Figure 1-1C). For example, a symbolic cue indicating "early" would indicate a relatively short interval (i.e., 400 ms) in 75% of the trials, whereas "late" would indicate a relatively long interval (i.e., 1,400 ms) in 75% of the trials (Correa et al., 2006).[1] Typically, RTs are faster after

---

[1] There are variants of the temporal orientation paradigms described above in which participants are instructed to attend to only one FP length (see e.g., Hillyard, 1973; Lange et al., 2003; Seibold et al., 2019). In this way, the task-relevance of a specific time point can be manipulated and thus the temporal orienting to this time point.

long intervals compared to short intervals (e.g., Correa et al., 2010). Interestingly, when the cue provides invalid information (i.e., the cue suggests that the imperative stimulus is most likely to appear after a long interval, but it actually appears earlier), the effects differ between short and long intervals: after short intervals, invalid cues significantly slow RTs, referred to as the temporal orienting effect. Thus, when the target appears earlier than expected, temporal orienting to the cued but invalid time point reduces its optimizing effect. In contrast, after long intervals, there is no difference between valid and invalid cues. This latter finding can be explained by a reorientation process resulting from increased probabilistic certainty about potentially attended time points, similar to the variable FP paradigm (Correa, 2010).

A common feature off all the paradigms described above is that attention is endogenously directed to a specific point in time by pre-cues or warning signals. Participants are explicitly instructed to use these signals in a goal-directed manner in order to optimize their attentional resources for the predicted time. However, attention can also be exogenously directed to specific points in time by presenting rhythmic signals or patterns. Such rhythmic temporal expectations play a role in various natural contexts, such as beats, music, and speech (see Nobre & van Ede, 2018, for a review). In experimental settings, *rhythmic cueing* can be modulated by presenting a sequence of signals in a rhythmic or arhythmic manner before the onset of the imperative signal (e.g., Breska & Deouell, 2014; Morillon et al., 2016; Rohenkohl et al., 2011; see Figure 1-1D). For example, Doherty and colleagues (2005) presented stimuli either in a regular, rhythmic pattern (i.e., every 550 ms) or in an irregular pattern (i.e., between 200 and 900 ms), which prevented the formation of temporal expectations. Consistent with current research, participants showed faster responses to rhythmically presented stimuli compared to irregularly presented stimuli (see also e.g., Morillon et al., 2016; Rohenkohl et al., 2011; Sanabria et al., 2011). Regular rhythmic presentation increases temporal predictability because attention can be directed to specific points in time (Jones, 2010). This also affects perception, leading to improved behavioral performance (Breska & Deouell, 2014; Jones et al., 2002; Mathewson et al., 2010), and is also evident in electrophysiological studies (Doherty et al., 2005; Praamstra et al., 2006). These latter observations have led to the concept of entrainment by temporal expectation (Nobre & van Ede, 2018), which describes the process of synchronization of neural brain oscillations to an external rhythm (Breska & Deouell, 2017). This synchronization leads to a state of increased excitability at times of expected rhythmic stimuli, resulting in more efficient processing of these signals (Breska & Deouell, 2017; Herbst et al., 2022; Lakatos et al., 2008; Mathewson et al., 2010).

In summary, several experimental paradigms have been used to investigate the influence of temporal preparation on stimulus processing (for a review see e.g., Seibold et al., 2023). Although these paradigms differ in their approaches to directing attention, they consistently show optimized behavioral performance when attention is directed to specific time points. One question that arises is which processes benefit from this attentional optimization. The following section reviews studies reporting beneficial effects of temporal preparation on different processing stages. From these studies, conclusions can be drawn about the influence of temporal preparation on specific processes such as early visual processing and, more specifically, spatial selection. With regard to the studies conducted, which will be reviewed later in Chapters 2 to 4, the focus will be primarily on paradigms that direct attention endogenously, i.e., the constant FP paradigm.

1.2 The influence of temporal preparation on perceptual processing

Temporal preparation has been a subject of research for more than a century, and numerous experimental approaches have been used to investigate its various aspects. However, earlier studies focused primarily on the influence of temporal preparation on motor processes, while interest in its influence on perceptual processes has grown in recent decades. The following section provides a brief historical overview of research on temporal preparation and, in particular, the shift in its influence from motor to perceptual processes.

Originally, as described in the first experimental studies by Woodrow (1914), most early studies were interested in measuring the effect of temporal preparation on response speed in simple RT tasks. Since RTs reflect the entire processing of a stimulus, from its input to the system to the system's response, research on the influence of temporal preparation was initially mainly interested in motor processes. Evidence for such an influence comes from studies measuring behavioral responses such as RT (Frowein & Sanders, 1978) and response force (Mattes & Ulrich, 1997; Ulrich & Mattes, 1996), as well as event-related potentials (ERPs) associated with motor or action preparation such as, for instance, the contingent negative variation (CNV; Leuthold et al., 2004; Loveless, 1973; van der Lubbe et al., 2004). These results led to the assumption that temporal preparation primarily affects late motor functions by modulating the readiness of the motor system (Sanders, 1998, as cited in Burle et al., 2010).

Recently, however, an increasing number of studies have begun to investigate whether earlier processes also benefit from temporal preparation. To address this question, behavioral studies have first investigated the influence of temporal preparation on pre-motor processes (see e.g., Bausenhart et al., 2007; Müller-Gethmann et al., 2003; Rolke, 2008; Rolke & Hoffmann 2007). Using a constant FP paradigm, Rolke and Hofmann (2007) presented participants with a visual discrimination task and measured - in addition to RT - d' as an indicator of discrimination accuracy. Participants had to identify a target stimulus masked by a noise mask. The duration of the target presentation was varied to manipulate the difficulty of stimulus processing. They observed that d' was higher for short FPs compared to long FPs. This finding provides compelling evidence that premotor processes, and in particular perceptual processing, also benefit from temporal preparation. Further support for this notion comes from behavioral studies using different paradigms, such as the temporal cuing paradigm (Jepma et al., 2012), different modalities, such as auditory discrimination processes (Bausenhart et al., 2006; Niemi & Lehtonen, 1982, Experiment 1), and different tasks, such as temporal order judgments (Correa et al., 2006).

In addition, studies measuring ERPs provide further evidence for the idea that temporal preparation enhances early perceptual processes. ERPs are obtained by measuring brain activity using electroencephalography (EEG) in response to a time-locked event or stimulus and then averaging of the collected data (Luck, 2014; Eimer, 2014). This process results in a distinct waveform characterized by positive and negative deflections known as ERP components (Luck, 2014). Remarkably, each ERP component has a specific signature based on its amplitude and latency, and is associated with specific cognitive processes and functions. Given these characteristics, certain ERP components have attracted particular interest in the study of perceptual processing. For example, the N1 component is a negative deflection between 100 and 200 ms after the presentation of a visual stimulus (Luck, 2014), and due to its early temporal occurrence and its association with perceptual discrimination (Hopf et al., 2002; Mangun & Hillyard, 1991; Vogel & Luck, 2000), it is considered as an index of early visual processing.

Following this approach, the influence of temporal preparation on perceptual processes has been investigated with ERP studies using different paradigms (see Section 1.1). Correa et al. (2006) summarized the influence of temporal preparation on early ERP components (such as the N1 and P1) in a review article. Using a temporal cueing paradigm, they observed a modulation of the P1 amplitude for temporally attended (valid) targets in a perceptually demanding task (Correa et al., 2006). This modulation of the P1 by temporal preparation provides evidence that temporal preparation enhances perceptual processing at an early stage. Further support for this hypothesis comes from studies observing an influence of temporal preparation on the N1 (Griffin et al., 2002; Hackly et al., 2007; Lange et al., 2003; Seibold & Rolke, 2014b). For example, in a study by Lange et al. (2003) in the auditory domain, participants attended to either short or long intervals between a warning tone and an imperative tone. The auditory N1 elicited by imperative tones at attended times was enhanced relative to tones at unattended times. Importantly, this modulation of the N1 together with several other studies observing an effect of temporal preparation on the P1 (Correa et al., 2006), on the N1 (Griffin et al., 2002; Hackly et al., 2007; Seibold & Rolke, 2014b), as well as on behavioral measures (Correa et al., 2005; Rolke & Hofmann, 2007) provides compelling evidence that temporal preparation enhances perceptual processing already at early stages. However, it is important to note that even if there is sufficient evidence that temporal preparation influences perceptual processing, this does not mean that other processes, especially motor processes, do not also benefit from temporal preparation.

Furthermore, and this is the main focus of this dissertation, there is evidence that temporal preparation not only improves early visual processing in general, but also specifically influences selective processes within stimulus perception. Selective processes describe processes that are involved in prioritizing some stimuli over others (Serences & Kastner, 2014) in order to select them for further processing, for example based on their spatial location, as in the case of spatial selection. Spatial selection can be observed in a visual search task where a stimulus, i.e. the target, must be selected from other stimuli, i.e. distractors, based on a specific feature. Evidence for a direct influence on spatial selection can be measured by observing modulations on the N2posterior-contralateral (N2pc). The N2pc is an important ERP component in visual search and has been linked to the spatial selection of targets as well as other salient stimuli (Eimer, 2014; Luck, 2012). For example, one of the first observations was described in a pop-out task, where a target surrounded by homogeneous distractors elicited an N2pc due to its uniqueness in a pop-out feature (i.e., color or orientation; Luck & Hillyard, 1994). There, as in other studies, the N2pc is described as a negative deflection observed over posterior electrodes, typically occurring between 200 and 300 ms after the onset of a search display (Luck, 2014). Significantly, this component arises contralateral to the attended stimulus, such as a salient target, and is characterized by a voltage difference between contralateral and ipsilateral electrodes (Luck, 2014). Difference waves, such as the N2pc, are particularly interesting in the context of temporal preparation because they are unaffected by preceding processes and other potential artifacts (Luck, 2014). Therefore, the N2pc appears to be a promising candidate for investigating whether temporal preparation directly influences spatial selection.

With this in mind, a seminal study by Seibold and Rolke (2014b) provided direct evidence for the influence of temporal preparation on spatial selection. In this study, they combined a constant FP paradigm with a pop-out task to investigate the influence of temporal preparation on the selection of a salient target. Specifically, participants perceived an imperative stimulus, which in this particular study was an auditory tone. Subsequently, participants were presented with a search display consisting of a target stimulus that was salient in terms of its color dimension, surrounded by homogeneous distractors of a different color (i.e., a green target surrounded by blue distractors or vice versa). Participants' task was to identify the target and report the orientation of a horizontal or vertical line within the target. The results showed that participants' responses were faster when they were well prepared temporally, i.e., after a short FP interval compared to a long one. This observation is consistent with previous literature (Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Woodrow, 1914) and supports that temporal preparation accelerates responses even in the presence of spatial uncertainty. In addition, Seibold and Rolke (2014b) were interested in the ERPs to investigate the underlying cognitive processes associated with this acceleration due to temporal preparation. In addition to modulation in early ERP components such as the N1, Seibold and Rolke (2014b) observed that the difference wave of the N2pc elicited by the pop-out target arose earlier and was more pronounced after a short FP compared to a long FP. The observation that not only the onset but also the amplitude of the N2pc was modulated by temporal preparation suggests that the underlying process is not only accelerated but also enhanced. As the N2pc is linked to the process of selective attention, this result provides evidence that temporal preparation not only influences perceptual processes in general, but also enhances spatial selection in this specific study. It can be considered whether this assumption extends to selective processes in general. Importantly, this finding suggests that the process of spatial selection benefits from temporal preparation.

Further evidence for this assumption is provided by Hackley et al. (2007), who used a simplified visual search paradigm with only one target and one distractor. They observed that RT was shorter for short FPs and, most interestingly, that N2pc amplitude was enhanced for short FPs. They attributed the beneficial effect of temporal preparation on RT to an earlier onset of the N2pc and the lateralized readiness potential. This implies that not only early perceptual or motor processes are accelerated by temporal preparation, but also intermediate processes including spatial selection. Further evidence for such an acceleration comes from a study by Rolke et al. (2016), which showed an earlier onset of the N2pc in a visual search task in the short FP condition. Through investigations of the N2pc, several interesting observations have provided evidence that temporal preparation not only influences perceptual processes in general, but also benefits spatial selection and, potentially, selective processes more broadly.

In summary, the preceding discussion has provided compelling evidence for the influence of temporal preparation on spatial selection in visual search. Consequently, an obvious and interesting question arises from these findings: how does temporal preparation influence spatial selection? The next section (1.3) will focus on this particular question and explore how theoretical models of spatial selection can be used to explain such influences.

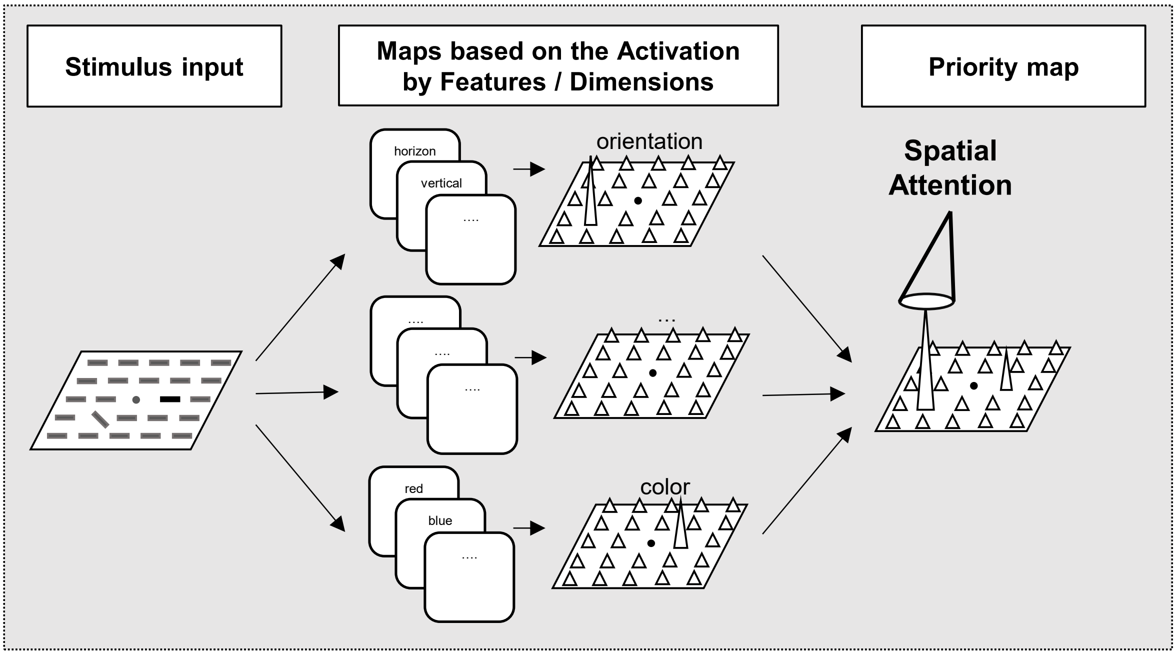
1.3 The influence of temporal preparation on spatial selection

Following the evidence that temporal preparation affects spatial selection (Hackley et al. 2007; Rolke et al., 2016; Seibold & Rolke, 2014b), the aim of this dissertation is to investigate how temporal preparation influences spatial selection. Therefore, the following section will discuss, first, general mechanisms by which attention can be guided in spatial selection, and then these theoretical assumptions will be applied to the influence of temporal preparation on spatial selection.

Several models of visual search (Awh et al., 2012; Itti & Koch, 2001; Liesefeld & Müller, 2021; Theeuwes, 2010; Yantis, 1993) describe how attention can be guided; one of these, which is particularly relevant for spatial attention, is the guided search

Figure 1-2

Schematic representation of the guided search model (Wolfe, 1994; 2021)



Note. In the guided search model, certain stimuli are processed as input in the system to subsequently direct attention to one of them (i.e., here on the far left a visual search display containing an orientation pop-out target and a singleton color distractor surrounded by homogeneous distractors). Location-based maps of activation differences are created based on different properties in features and dimensions. These are then combined into a priority map, which directs attention to the location with the highest activation. Adapted from Müller et al. (2015).

model (Wolfe, 1994; 2021; Wolfe et al., 2003). Importantly, the main assumption of this model is that input from the real word is processed in multiple stages based on different features and, most importantly, depending on its location (see Figure 1-2). In early stages of processing, the visual system extracts the input signal based on basic features or attributes such as color (e.g., red and blue) or orientation (e.g., horizontal or vertical; Wolfe, 2021). The processed information is then represented on spatial maps, where each specific location accumulates activation based on the incoming signal relative to its surroundings. This activation value of a stimulus relative to its surround can be described by the signal-to-noise ratio. Here, signal-to-noise ratio refers to the idea that the input to a system consists of both the actual signal and background noise. All accumulated activation values are then integrated at a higher level to form a priority map[2] (Wolfe, 2021). This priority map serves as a location-based representation where the summed activation values are displayed. In the guided search model, as well as in other models such as the dimensional weighting account (Itti & Koch, 2001; Liesefeld & Müller 2019; Müller et al., 1995), different features can be assigned different weights during this integration process. Based on the local activation values within the priority map, attention is directed to the location with the highest activation, and information from this location is selected for further processing.

The question that arises is how spatial selection, or more specifically the processes associated with the construction of the priority map described above, can be influenced. Several forms of guidance are thought to exist: bottom-up salience, top-down influences, and prior history (Wolfe, 2021). First, processing is driven by low-level properties of the input stimulus, and in this case, guidance depends primarily on bottom-up salience. Salience refers to the local feature contrast of a stimulus relative to its surround (Nothdurft, 2000; 2005). For example, a black bar surrounded by gray bars would evoke high local activation, whereas all gray bars would evoke comparatively lower activation at the level of the color salience map (see Figure 1-2). In addition, guidance can be driven by top-down influences, i.e., the task goals and intentions of the observer. Thus, this goal-driven form of attention depends on the observer's current task or goal and can be voluntarily shifted. For example, if the target is defined as a horizontal singleton, the participant's intention or goal is to detect only changes in the orientation dimension. In terms of visual search models, this can be achieved by weighting-up the 'orientation' dimension or the 'horizontal' feature, thereby prioritizing the processing of these attributes over others (Found & Müller, 1996; Liesefeld & Müller, 2019). Finally, previous experience or prior history, the so-called selection history effect (Awh et al., 2012; Wolfe, 2021), can bias guidance during spatial selection. Examples of this third category include the influence of past rewards on the current selection process (Hickley et al., 2010) or the effects of priming (Maljkovic & Nakayama, 1994). Taken together, spatial selection can be influenced by factors such as bottom-up salience, top-down influences, and prior history. All of these factors can influence the construction of the priority map, for example by weighting certain features (Liesefeld & Müller 2019; Müller et al., 1995) or by changing the activation values itself (Wolfe, 1994; 2021; Wolfe et al., 2003).

---

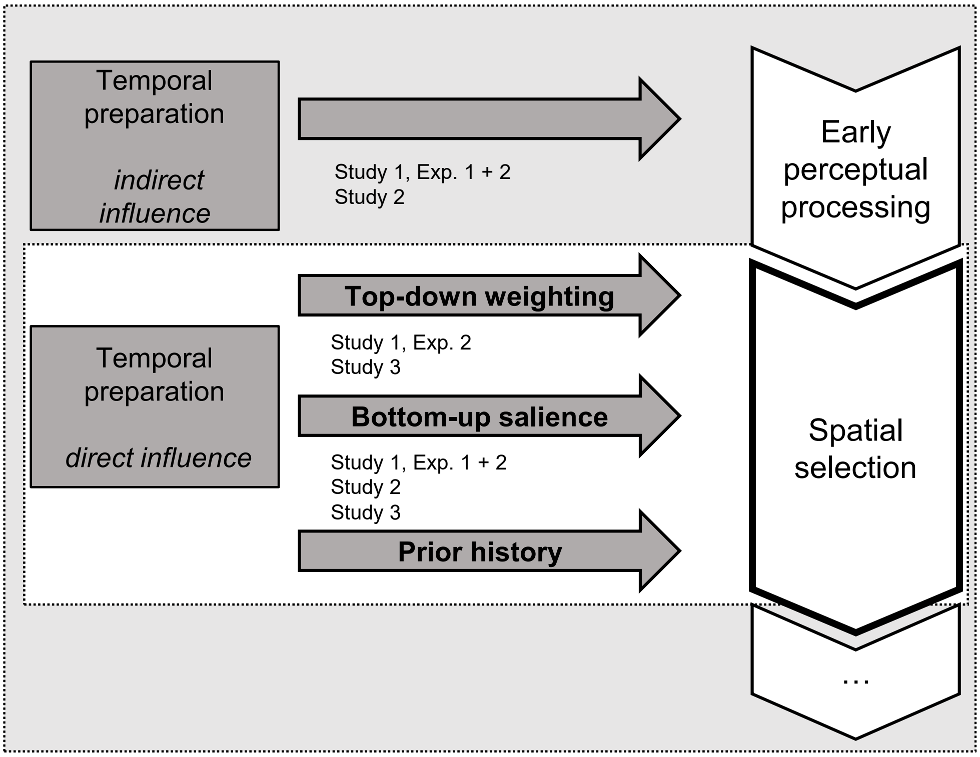
[2] Note that in former versions of the guided search model this integrated priority map is also called activation map (Wolfe, 1994; 2021).

Returning to the focus of this dissertation, there is evidence that temporal preparation influences the process described in the previous paragraph, spatial selection (e.g., Seibold & Rolke, 2014b). With these general models of visual search in mind, the following section aims to explore the theoretical aspects of how temporal preparation may influence spatial selection. In principle, there are two possible ways in which temporal preparation could influence spatial selection (see Figure 1-3). First, temporal preparation could directly influence spatial selection. In other words, temporal preparation could directly affect the processes involved in the construction of the priority map, i.e., those that are necessary to generate the activation values on the priority map. Second, temporal preparation could have a non-specific influence on spatial selection by affecting processes that precede spatial selection but subsequently contribute to it. Thus, temporal preparation may indirectly influence spatial selection by modulating these early stages of information processing. These two possible accounts are discussed in the following sections.

The assumption that temporal preparation directly influences spatial selection is supported by the observation that not only the onset latency of the N2pc but also the mean amplitude is modulated by temporal preparation (Hickey et al., 2007; Seibold & Rolke, 2014b). Theoretically, the amplitude and latency of an ERP component are considered to be independent (Luck, 2014); whereas changes in amplitude can be interpreted as an increase in neural activity during the associated process itself. Changes in the latency of this component can be interpreted as an acceleration or deceleration of the process (Otten & Rugg, 2005). Accordingly, the observed modulation of N2pc amplitude by temporal preparation (Seibold & Rolke, 2014b) may indicate a direct influence of temporal preparation on this specific process. This raises the question of how temporal preparation could directly influence spatial selection in this case. Given that the target in the study by Seibold and Rolke (2014b) was a pop-out due to its salience in color, one might conclude that temporal preparation could influence spatial selection through an influence on bottom-up salience. Based on the results of this study, it seems promising to examine whether temporal preparation facilitates bottom-up processing in spatial selection. Theoretically and consistent with models of visual search, temporal preparation could affect stimulus processing non-

Figure 1-3

Illustration of a possible influence of temporal preparation on spatial selection



Note. The main question is how temporal preparation influences spatial selection. It is conceivable that temporal preparation influences spatial selection directly or indirectly, i.e. latter by influencing previous processes such as early perceptual processing. According to visual search models, spatial selection can be influenced by bottom-up salience, top-down weighting, and prior history.

Study 1 aims to measure in reaction times whether temporal preparation influences spatial selection directly via an influence on bottom-up (Experiment 1) or top-down (Experiment 2) processing or indirectly via an influence on early perceptual processing. Study 2 attempts to investigate whether temporal preparation influences spatial selection directly via an influence on bottom-up salience. Study 3 attempts to distinguish between a direct influence on spatial selection via bottom-up salience and top-down weighting. It is important to note that a direct and an indirect influence of temporal preparation on spatial selection are not mutually exclusive but can simultaneously influence spatial selection.

specifically by increasing the activation value of already salient stimuli. Since this influence is not limited to relevant stimuli such as the target, a bottom-up influence of temporal preparation should be observable for all stimuli depending on the stimulus salience, regardless of their task relevance.

Furthermore, temporal preparation could directly influence spatial selection by specifically facilitating top-down processing. Evidence for this hypothesis is provided by the fact that temporal preparation influences the spatial selection of targets (Hackley et al., 2007; Seibold & Rolke, 2014b), which are per se task-relevant. In particular, in the study by Hackley and colleagues (2007), the search display consisted of two letter-like stimuli, one of which was defined as the target. Since there is no possibility of stimulus-driven target selection in that particular task, the solution of this rudimentary visual search task seems to require a top-down representation of the possible target options. Therefore, one could conclude that the N2pc modulation by FP is due to an influence of temporal preparation on top-down processing in spatial selection. Theoretically, an influence of temporal preparation on top-down processes would be observed specifically for stimuli that are task-relevant, indicating their importance for achieving the observer's current goal. More specifically, temporal preparation could increase activation on the priority map specifically for these stimuli, e.g. by weighting the activation of relevant features or dimensions. Therefore, the effect of temporal preparation should be particularly strong for task-relevant stimuli.

A third theoretical way in which temporal preparation could directly influence spatial selection is through an influence on history or experience-driven processes. Although the precise mechanisms by which history effects affect the construction of the priority map are not yet understood, it is conceivable that temporal preparation could affect stimuli that have a higher activation value on the priority map due to past experiences, such as reward or priming. Although this possibility is theoretically conceivable, there is no strong evidence from the research in the constant FP paradigm to support the assumption that temporal preparation affects spatial selection by influencing experience-driven processing. Results from other temporal preparation paradigms are discussed in Chapter 5. Based on the above observations, this dissertation will focus on whether temporal preparation has an influence on bottom-up or top-down processing, or both, in spatial selection.

An alternative account suggests that temporal preparation does not directly influence spatial selection, but rather influences processes that precede spatial selection, i.e., perceptual processing, and that these processes subsequently influence spatial selection. This idea has been proposed as the early onset hypothesis (Rolke, 2008; Rolke et al., 2016): temporal preparation may influence the onset of early visual processing, thereby accelerating the overall process. This global acceleration is not necessarily limited to low-level stimulus processing at early processing levels, but could also propagate to higher levels as feature information integration (see Rolke, 2008). Accordingly, temporal preparation would have an indirect influence on spatial selection (see Figure 1-3, upper part). Evidence for this account comes from studies that observed modulations of N2pc onset latency (Rolke et al., 2016). Interpreting this latency modulation very cautiously, Rolke and colleagues (2016) propose a "nonspecific boost" of temporal preparation for spatial selection, describing an acceleration of processes prior to target selection. Following this account, one would predict that a nonspecific influence of temporal preparation should not specifically target bottom-up or top-down processing during spatial selection. Rather, because the influence of temporal preparation occurs prior to spatial selection, it should affect bottom-up and top-down processing equally, and thus have an additive effect on spatial selection.

In summary, previous research has provided compelling evidence that temporal preparation influences early visual processing. Furthermore, temporal preparation can influence spatial selection. However, it remains an open question how temporal preparation influences spatial selection - indirect and direct influences are possible. In the case of an indirect influence, temporal preparation could indirectly influence spatial selection through a global acceleration of preceding processes. In the case of a direct influence of temporal preparation on spatial selection, it is conceivable that temporal preparation facilitates bottom-up, top-down, or experience-driven processing. The following section provides an overview of studies conducted in the context of this dissertation that further investigate such a direct influence. It is important to note that a direct and indirect influence of temporal preparation on spatial selection are not exclusive, but it is conceivable that both influence spatial selection simultaneously.

1.4 Overview of the conducted studies

The aim of this dissertation is to clarify how temporal preparation influences spatial selection. As proposed by the early onset hypothesis (Rolke, 2008; Rolke et al., 2016), temporal preparation facilitates perceptual processing and therefore may indirectly influence spatial selection. Moreover, there is evidence that temporal preparation directly facilitates spatial selection. Based on current models of visual search, various factors such as bottom-up salience, top-down weighting, and prior history influence spatial selection. To further explore whether temporal preparation influences one (or more) of these factors, the following chapters (Chapters 2 to 4) present experimental studies conducted to investigate different aspects of this question. First, a series of behavioral experiments were conducted to investigate whether temporal preparation affects bottom-up salience or top-down weighting in a visual search task (Study 1). Study 2 (Chapter 3) addresses the question of whether temporal preparation affects spatial selection by enhancing bottom-up processing. In particular, this ERP study tested if FP modulates the N2pc, as an index of spatial selection, as a function of target salience. Furthermore, Study 3 (Chapter 4) aimed to further investigate the influence of temporal preparation on bottom-up and top-down processes in spatial selection. Therefore, a visual search task consisted of a salient target, a singleton distractor, and homogeneous distractors. Thus, it was possible to investigate whether temporal preparation influences one of several factors in spatial selection: bottom-up processing or top-down suppression of the irrelevant singleton distractor, and top-down processing of the relevant target. Finally, Chapter 5 discusses the results of these studies to address the question of how temporal preparation influences spatial selection.

2. Study 1: No evidence for a direct influence of temporal preparation on spatial selection from a series of behavioural studies

2.1 Introduction

The aim of this series of experiments was to investigate how temporal preparation influences spatial selection in a visual search task. As mentioned in the Introduction (Chapter 1), there is evidence that temporal preparation directly improves selective processing in such tasks (Hackley et al., 2007; Seibold & Rolke, 2014b). To investigate this further, two behavioral experiments were conducted. First, the objective was to investigate whether temporal preparation directly influences bottom-up processes in spatial selection (Experiment 1). Second, an additional aim was to investigate whether temporal preparation affects top-down weighting in addition to bottom-up processes (Experiment 2).

In Experiment 1, following Seibold and Rolke (2014b), a constant FP paradigm was combined with a visual search task in which the target was defined as a pop-out due to its salience in color. To determine whether temporal preparation affects bottom-up processing, the processing of the target stimulus was manipulated by varying its salience. To manipulate the salience of the target stimulus, a manipulation of the setsize was used, i.e., the number of elements in the search display containing the target surrounded by distractors was varied. Studies have observed that for search displays containing a target and homogeneous distractors, RT decreases as the number of distractors increases (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; Mazza et al., 2009). For example, in a task in which participants select a target based solely on its unique color, which changes from trial to trial, RT is slower when there are only few distractors surrounding the target (i.e., 4 elements) than when there are more distractors surrounding the target (i.e., 20 elements; Mazza et al., 2009). The idea is that a salient target stands out in visual search depending on its surrounding. One explanation for this might be that the more homogeneous the stimuli surrounding the target, the more unique the salient target becomes. In terms of the guided search model (Wolfe, 1994, 2021), one could argue that the difference in activation values between the target and the distractors increases as the difference between the target signal and its surround increases. Another explanation would be that the perceptual grouping of the distractors becomes easier with increasing setsize, and thus suppression of the entire distractor group becomes easier (Duncan & Humphreys, 1989; Mazza et al., 2009). However, both explanations require that manipulating the setsize changes target salience and, therefore, influences bottom-up processing. If there would be an influence of temporal preparation on spatial selection as a function of target salience observable, it could be concluded that temporal preparation influences bottom-up processing.

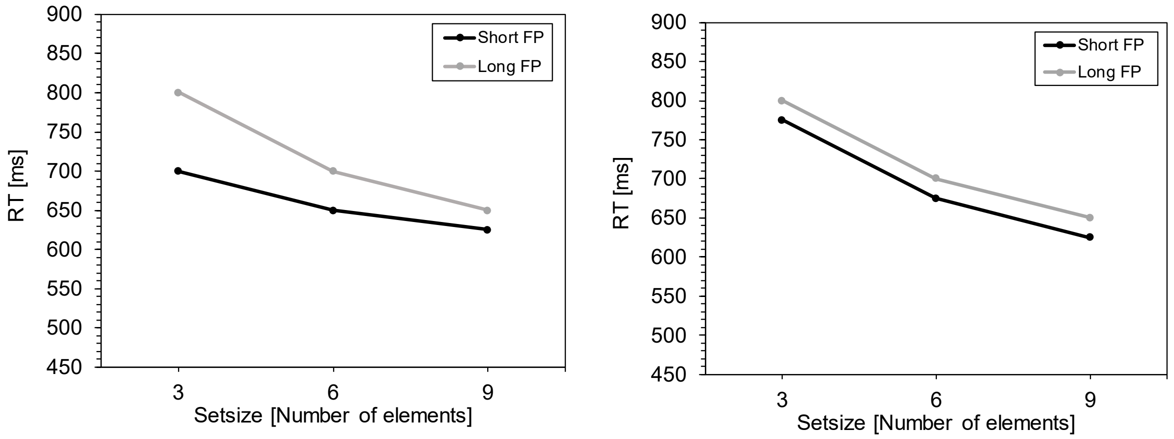
Further, a second experiment was conducted to investigate whether temporal preparation also influences top-down processing in spatial selection. In addition to targeting bottom-up processes by varying target salience using a setsize manipulation, it was of special interest whether temporal preparation is specifically useful in a task in which the relevant pop-out features are constant and explicitly communicated to participants. In one half of the experiment, participants were informed about the relevant dimension (i.e., color or shape pop-out target) and of the specific feature (e.g., red, or green in the case of a color pop-out). In the context of the guided search model (Wolfe, 1994, 2021), it can be hypothesized that temporal preparation directly influences top-down processes in spatial selection by altering the weighting process of the specific feature or dimension and thus its contribution to spatial selection (Itti & Koch, 2001; Liesefeld & Müller 2019; Müller et al., 1995; Wolfe, 2021). Theoretically, this should be most evident in trials where participants can use their explicit top-down knowledge to prepare for a specific stimulus feature.

2.2 Experiment 1 – Influence of temporal preparation on bottom-up processing

The aim of Experiment 1 was to test whether temporal preparation influences bottom-up processing in a visual search task. Therefore, temporal preparation, i.e., using a constant FP paradigm, and target salience, i.e., varying setsize (i.e., 3, 6, or 9 items), were manipulated. If temporal preparation influences bottom-up processing, it was expected that the effects of temporal preparation would be strongest when target salience is low. According to this conclusion, the FP effect should be strongest in the condition with few elements (i.e., 3 elements) and should decrease with increasing setsize. In the case of 9 elements, where target salience is already very high and RT

Figure 2-1

Illustration of the hypotheses for reaction time in the short and long foreperiod conditions in Experiment 1



Note. Expected pattern of reaction time (RT) for a direct (left) or an additive (right) influence of temporal preparation on bottom-up as a function of setsize (i.e., 3, 6, or 9 elements) in the short foreperiod (FP) condition (black lines) and the long FP condition (gray lines). If temporal preparation facilitates bottom-up processing, this should be reflected in a greater FP effect (i.e., difference between short and long FPs) in search displays with fewer elements compared to search displays with more elements (i.e., the 3 elements condition as compared to the 6 and 9 elements condition). In contrast, if temporal preparation influences spatial selection independent of bottom-up processing, this should lead to an additive FP effect (i.e., same FP effect in all setsize conditions).

is therefore already reduced to a near-optimal value, the FP effect should be the smallest. If temporal preparation does not affect bottom-up processing directly, it was expected to observe additive effects for FP and setsize.

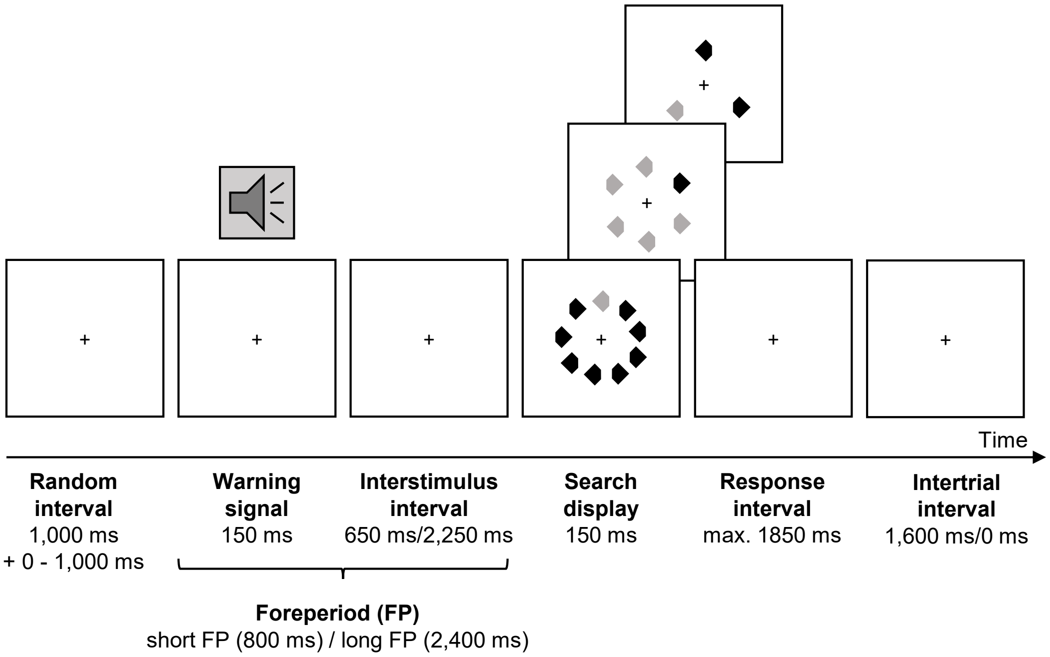
2.2.1 Experimental procedure

Participants

Twenty-five healthy participants, mainly students at the University of Tuebingen, participated either for payment (8 €) or for course credits. In accordance with the 2013 Declaration of Helsinki by the World Medical Association, all participants gave written informed consent before the experiment. The ethics committee of the Faculty of Science (University of Tuebingen, Germany) had approved the overall study protocol. All participants reported normal or corrected-to-normal vision and normal color vision.

Figure 2-2

Schematic illustration of the experimental procedure of Experiment 1



Note. At trial onset, a fixation cross appeared in the center of the screen for a variable interval (from 1,000 to 2,000 ms). An auditory warning signal (presented for 150 ms) marked the beginning of a foreperiod (FP) of either 800 or 2,400 ms (short or long FP condition). At the end of the FP interval, the search display was presented for 150 ms. It consisted of a pop-out color target (i.e., a red or green diamond, shown here as a gray or black diamond) surrounded by either two, five, or eight homogeneously colored distractors (3, 6, or 9 element condition, respectively). Participants' task was to indicate on which side of the target a corner was missing. Valid responses had to be made within an interval of 1,850 ms. This was followed by an intertrial interval of 1,600 ms for the short FP condition and 0 ms for the long FP condition, after which the next trial began.

One participant was excluded due to an excessive error rate of >10%. The final sample consisted of twenty-four participants (five male, twenty-two right-handed, mean age = 24.54 years, age range = 20–36 years).

Apparatus and stimuli

Stimulus presentation was controlled using Matlab (version 2012a) and Psychtoolbox-3 (version 3.0.10). Participants were seated at a viewing distance of 54 cm from the computer screen. This distance was maintained using a chin rest. Visual stimuli were presented on a standard 100 Hz monitor. They consisted of a diamond (1.3° x 1.3° of visual angle) with a left or right corner removed (0.3°). Depending on the setsize, 3, 6 or 9 elements were displayed at equal distance on an imaginary circle (3.3°) on a black background (luminance: 0 cd/m²). One of the elements was indicated by a different color as the target, while the other 2, 5 or 8 elements served as unicolored distractors. The colors of the target and the distractors were either green versus red (luminance: 23 and 30 cd/m², respectively) or vice versa. The target appeared equally frequent in all four quadrants of the imaginary circle but was shifted by a jitter angle within each quadrant to avoid predictability of the target position. To encourage participants to fixate in the center of the screen, a white fixation cross (0.9°, luminance: 109 cd/m²) was presented there. The warning signal was an auditory sinusoidal tone with a frequency of 800 Hz.

Procedure

Each trial started with the presentation of the fixation cross in the center of the screen for 1,000 ms + *X* (where *X* was a random interval between 0 and 1,000 ms, *M* = 500 ms). Then, the auditory warning signal was presented over headphones for 150 ms, followed by an interstimulus interval of 650 ms for the short FP or 2,250 ms for the long FP. Participants were instructed to use this interval to prepare for the subsequent search task. After the FP interval, the search display appeared for 150 ms. It consisted of a colored diamond (e.g. red) surrounded by diamonds of the opposite color (e.g. green). The participants' task was to find the "pop-out" target and to decide on which side of the target a corner was missing. After the search display disappeared, the participants reported the missing corner by pressing the X or the M key for the left or right side, respectively. If participants did not respond within an interval of 1,850 ms, the German phrase "ZU LANGSAM" ("to slow") was displayed for 300 ms; if they pressed an incorrect key or responded during the search display, the feedback "FEHLER" ("error") or "ZU SCHNELL" ("too fast") was presented. To achieve a constant trial length across all conditions, an additional interval of 1,600 ms was included after the short FP trials.

First, participants completed two test blocks (a short FP block and a long FP block or vice versa) of 12 trials each to familiarize themselves with the FP intervals and the task. They were instructed to respond as quickly and as accurately as possible. They then completed 8 blocks of 48 trials each. After each block, participants were informed of their performance (percentage of correct responses) and were encouraged to take a short break.

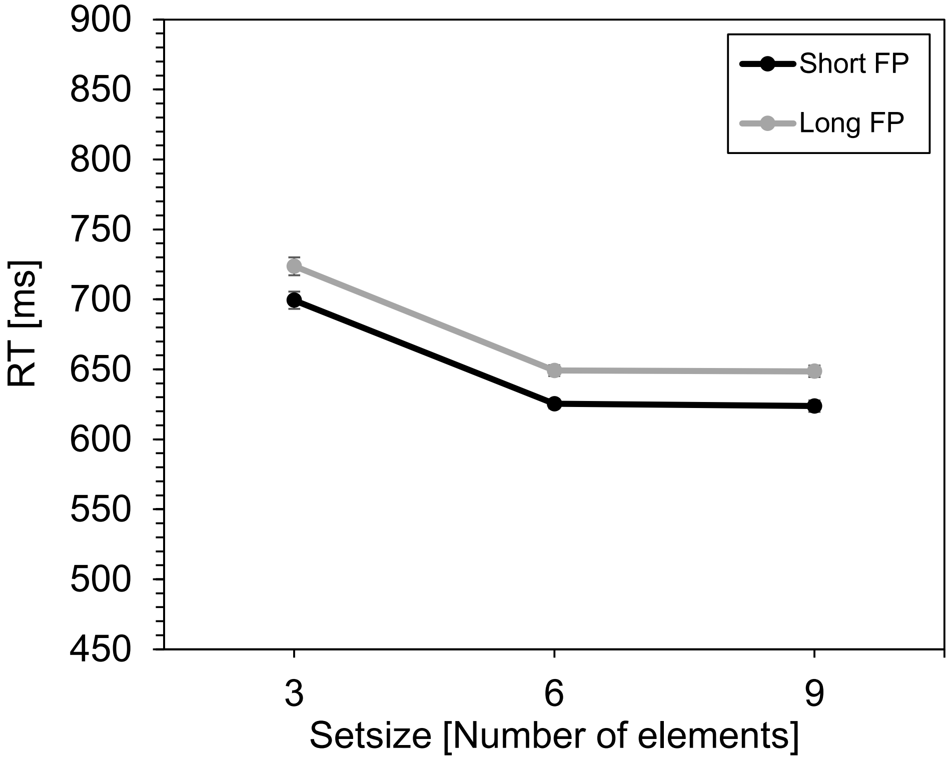
The FP interval was fixed within a block but varied from block to block. The FP of the first block was counterbalanced across all participants. Setsize varied randomly from trial to trial. Each participant completed 384 experimental trials (64 trials for each FP and setsize condition). The color of the target, the side of the missing corner, and the quadrant in which the target appeared were counterbalanced across trials.

Data analysis

The statistical analyses were performed in JASP (Version 0.13.1) and Matlab (MathWorks R2017b). We performed repeated-measures analyses of variance (rmANOVAs) to examine the effect of FP and setsize on mean RT and mean error rate. Practice trials were excluded from the analysis of the mean RT. Trials with incorrect

Figure 2-3

Mean reaction time for short and long foreperiod conditions in Experiment 1



Note. Mean reaction time (RT) as a function of setsize for 3, 6 or 9 elements in the short foreperiod (FP) condition (black line) and the long FP condition (gray line). Error bars denote +/- one standard error of the mean for within-subjects designs, being calculated according to Cousineau (2005) and a correction by Morey (2008).

responses and trials with RTs shorter than 200 ms or longer than 1,500 ms were excluded. An rmANOVA with the factors FP (short or long) and setsize (3, 6 or 9 elements) was then performed on the mean RT and on the mean error rate.

2.2.2 Results

The analysis of mean RT revealed a main effect of FP, $F(1,23) = 25.57$, $p < .001$, $\eta_p^2 = .53$ (see Figure 2-3). Participants responded faster to targets in the short FP condition (M = 649 ms, SD = 92 ms) than in the long FP condition (M = 674 ms, SD = 97 ms). For the main effect of setsize and the interaction of FP and setsize, Mauchly's test of sphericity indicated that the assumption of sphericity was violated, $\chi^2(2) = 13.55$, $p = .001$, therefore, Greenhouse-Geisser corrected degrees of freedom are reported. The analysis of RT revealed an effect of setsize, $F(1.37,31.51) = 100.65$, $p < .001$, η_p^2

Figure 2-4

Mean error rate for short and long foreperiod conditions in Experiment 1

Note. Mean error rote as a function of setsize for 3, 6 or 9 elements in the short foreperiod (FP) condition (dark bar) and the long FP condition (light bar). Error bars denote +/- one standard error of the mean for within-subjects designs, being calculated according to Cousineau (2005) and a correction by Morey (2008).

= .81. Participants responses were faster for search displays with 6 elements (*M* = 637 ms, *SD* = 8 ms) than with 3 elements (*M* = 712 ms, *SD* = 95 ms), *t*(23) = 12.19, p_{bonf} < .001, *d* = 2.49. The post-hoc *t*-test revealed no significant difference between 6 and 9 element displays (*M* = 636 ms, *SD* = 87 ms), *t*(23) = .19, p_{bonf} = 1.00. Most importantly, there was no interaction between FP and setsize, *F*(1.34,30.89) = .01, *p* = .96.

For the mean error rate, the error rate was higher in the 3 elements condition (*M* = 3.50 %, *SD* = 3.09 %) than in the 6 elements condition (*M* = 1.90 %, *SD* = 2.27 %) and in the 9 elements condition (*M* = 2.40 %, *SD* = 2.65 %), *F*(2,46) = 11.74, *p* < .001 (see Figure 2-4). Most importantly, there was no difference in the mean error rate between the FP conditions, *F*(1,23) = 1.66, *p* = .21, nor in the interaction between FP and setsize, *F*(2,46) = 1.31, *p* = .28.

2.2.3 Discussion of Experiment 1

The aim of Experiment 1 was to test whether temporal preparation influences bottom-up processes in a visual search task. Therefore, target salience was varied using a setsize manipulation and the degree of temporal preparation was manipulated using a constant FP paradigm. First, consistent with previous studies (Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014a, 2014b), there was an influence of temporal preparation on visual search: participants responded faster to the pop-out target after a short FP than after a long FP. Second, participants' responses were faster for a target surrounded by more distractors (i.e., 6 or 9 elements) than for targets surrounded by fewer distractors (i.e., 3 elements; see also other studies for such a result, such as Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; Mazza et al., 2009). Most importantly, contrary to our hypothesis, we did not observe an interaction between FP and setsize in RT. Temporal preparation allowed for faster overall responses in the visual search task, but this was independent of target salience. This null result provides no evidence that temporal preparation improves bottom-up processing. Therefore, it is more likely that temporal preparation affects spatial selection indirectly rather than directly (see 2.4 General Discussion of Study 1 for a detailed discussion).

Nevertheless, caution should be exercised in interpreting null results, as they do not provide direct evidence for an indirect influence of temporal preparation. An alternative explanation would be that temporal preparation directly influences spatial selection, but this could not be measured in the current experiment. Possible reasons for this could be experimental limitations in the design of the experiment or theoretical implications about how temporal preparation affects stimulus processing. For example, one possible explanation could be that, due to the design of Experiment 1, participants did not rely exclusively on target salience but used other strategies to detect the target. Although it was a pop-out in the color dimension, the variability of the target was very low because there were only two possible options: either a red target surrounded by green distractors or vice versa. It is possible that some participants took advantage of this top-down knowledge by setting up two possible target sets in order to search for the target based on these features. To reduce this possibility, in Experiment 2 the variability of the pop-out feature was increased by adding another target dimension (i.e., shape; see below for details). This was done to prevent the use of a top-down strategy and to increase bottom-up processing of the target.

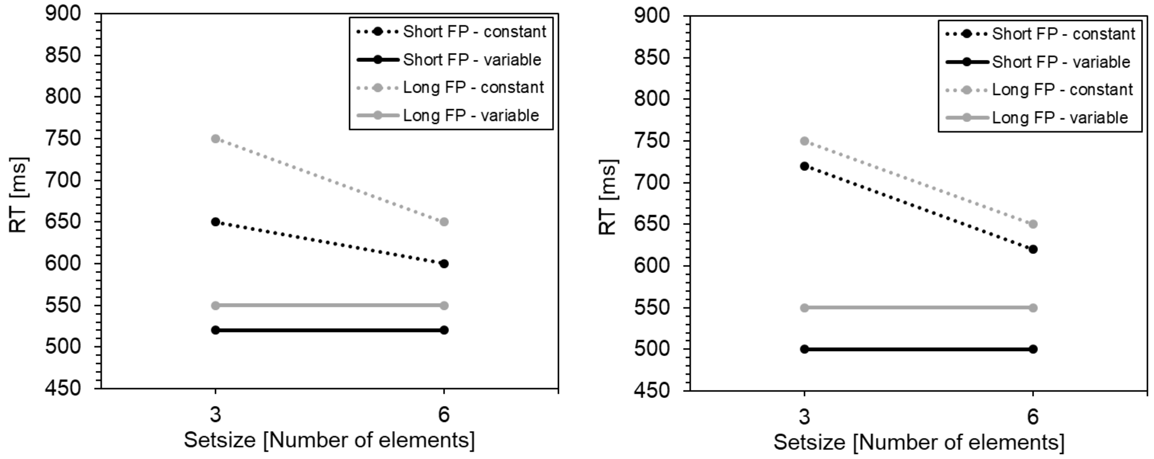
Alternatively, another possible explanation could be that temporal preparation directly influences spatial selection, not by improving bottom-up processing, but by improving other processes, such as top-down processing. To test this, Experiment 2 consisted of a series of trials in which participants were explicitly provided with top-down knowledge about the target-defining feature. The aim was to investigate whether temporal preparation influences top-down processing in spatial selection.

2.3 Experiment 2 – Influence of temporal preparation on bottom-up and top-down processing

To test whether temporal preparation directly influences spatial selection, a second experiment was conducted to observe the effects on bottom-up and top-down processes. In one half of the experiment, the aim was to explicitly test whether temporal preparation affects top-down processes in a visual search task. Therefore, the target-defining feature was kept constant in this half of the experiment. By informing participants which feature would be constant and therefore relevant in the next block, participants were encouraged to use their top-down knowledge to search for the target, in addition to the bottom-up salience of the target itself. For example, participants were explicitly told that the target in the next blocks would always be a green pop-out stimulus. The idea was that participants would use this information about the target feature in a top-down manner, e.g., by giving more weight to the relevant feature. Previous research has shown that this can be observed in a flat search slope that is

Figure 2-5

Illustration of the hypotheses for reaction time in the short and long foreperiod conditions in Experiment 2



Note. Expected pattern of reaction time (RT) for an influence on bottom-up processing (left) and top-down processing (right) as a function of set size (3 or 6 elements) in the short foreperiod (FP) condition (black lines) and the long FP condition (gray lines) for the half of the experiment with a constant target (solid lines) or a variable target (dotted lines). If temporal preparation facilitates bottom-up processing, this should be reflected in faster RTs in the variable target condition, but especially for low salient targets (i.e., the 3-element condition). If temporal preparation facilitates top-down processing, this should be reflected in the constant target condition, independent of setsize.

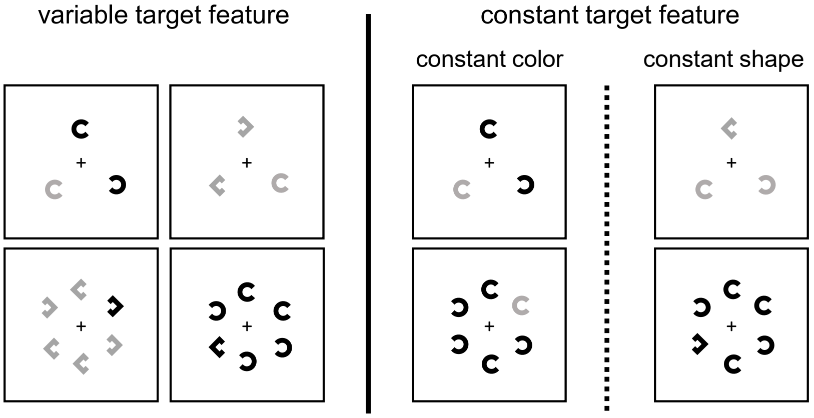
independent of the number of surrounding distractors (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; Wolfe et al., 2003). Furthermore, the manipulation of target salience (i.e., the manipulation of setsize) was repeated to address bottom-up processing. To increase the pop-out effect of the target, another target dimension was added. The target could be a pop-out not only in the color dimension, but also in the shape dimension, i.e., a circle surrounded by diamonds, or vice versa. This made the possible target feature even less predictable, increasing the need to rely on the bottom-up salience of the target.

Consistent with Experiment 1, an effect of FP on RT was expected in the visual search task. Depending on the constancy of the target feature, the hypothesis for an effect of setsize differed: while RT should be independent of setsize for a constant target feature, RT should decrease with increasing setsize for a variable target feature. Most interesting was the interaction between these factors: If temporal preparation

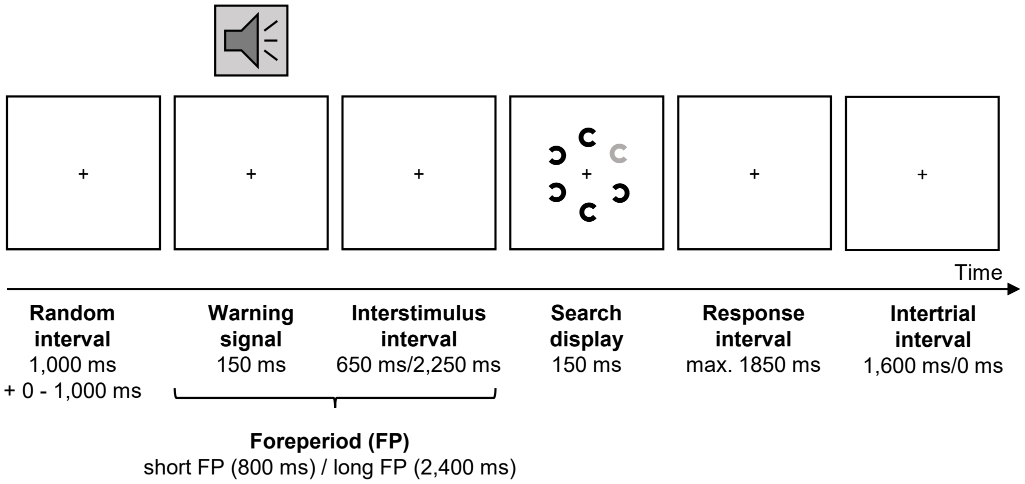
Figure 2-6

Search display and experimental procedure of Experiment 2

A – Search display



B – Experimental procedure



Note. (A) The search display in all trials consisted of a pop-out target of either shape or color surrounded by either two or five homogeneously colored and shaped distractors (3 or 6 elements condition, respectively). In the variable target feature condition (left) all trials were intermixed and therefore the target could be a color pop-out (i.e., a red target surrounded by green distractors or vice versa) or a shape pop-out (i.e., a diamond surrounded by circular distractors or vice versa). In the constant target feature condition (right), participants were informed that the target in all trials would be defined by a specific feature for the next block (e.g., a red target surrounded by green distractors). After two blocks for each foreperiod condition, the target feature changed to the other dimension (e.g., a diamond-shaped target surrounded by circle-shaped distractors), but was always a pop-out in that feature for the next blocks. (B) The timing of the stimulus presentation was analog to Experiment 1.

influences top-down processing, the FP effect should be stronger in the constant target feature condition. On the other hand, if temporal preparation influences bottom-up processing, the FP effect should be strongest in the variable target feature condition, depending on target salience: as setsize decreases, target salience should decrease and the FP effect should increase.

2.3.1 Experimental procedure

Participants

Thirty-four new participants took part in Experiment 2, fulfilling the same requirements as in Experiment 1. Two participants were replaced due to poor performance (error rate of > 10% errors in one half of the experiment). The final sample consisted of thirty-two participants (seven male, twenty-nine right-handed, mean age = 23.25 years, age range = 19–29 years).

Apparatus and stimuli

All experimental parameters of the stimuli were the same as in Experiment 1, except as noted below.

The target was surrounded by either two distractors (i.e., 3 elements condition) or by five distractors (i.e., 6 elements condition). In addition to the use of diamonds as stimuli, another shape was added: circles (1.2° diameter of visual angle). In order to approximate the pop-out effect of color with the pop-out effect of shape, the stimuli were no longer completely filled with color, but only their outlines were colored. Thus, instead of a missing corner, all stimuli had a gap in their outline (see Figure 2-6, upper part).

Procedure

The timing of the stimulus presentation was the same as in Experiment 1 (see Figure 2-6, lower part). The participants' task was to indicate on which side of the target there was a gap by pressing a key. The target could be a pop-out in one of the two dimensions of color or shape (e.g., a diamond surrounded by circles), but it was never salient in both dimensions.

In one half of Experiment 2, the target feature was variable (e.g., the target was unpredictably either green or red, changing from trial to trial), while in the other half, the target feature was constant (e.g., a green pop-out target on each trial). In blocks with a constant target, participants were informed at the beginning which feature defined the target. The FP changed from block to block, while the target feature was

Table 2-1

Exemplary representation of the blocks and trials completed during a session

Block	Trials (no.)	FP condition[b]	Target feature[b]
1[a]	16	Short FP	Variable
2[a]	16	Long FP	Variable
3	64	Short FP	Variable
4	64	Long FP	Variable
5	64	Short FP	Variable
6	64	Long FP	Variable
7[a]	16	Short FP	Constant (e.g. color – red)
8[a]	16	Long FP	Constant (e.g. color – red)
9	64	Short FP	Constant (e.g. color – red)
10	64	Long FP	Constant (e.g. color – red)
11[a]	16	Short FP	Constant (e.g. shape – circles)
12[a]	16	Long FP	Constant (e.g. shape – circles)
13	64	Short FP	Constant (e.g. shape – circles)
14	64	Long FP	Constant (e.g. shape – circles)

Note. Participants completed alternating blocks (64 trials each) in the short and long FP conditions. The target feature was constant in one half of the experiment and variable in the other half. Prior to each change in the constancy of the target feature, participants completed a block of practice trials (16 trials each) in both of the FP conditions.

[a] These blocks were not included in the analyses as they served as test trials for participants to familiarize themselves with the task.

[b] The sequence of FP condition and target feature constancy shown here is exemplary. The starting condition of FP and target feature constancy was counterbalanced across participants.

constant in either the first or last half of the experiment (see Table 2-1 for more details). The order of FP and target feature was counterbalanced across participants. Each participant completed a total of 512 experimental trials (64 for each target feature, FP, and setsize condition).

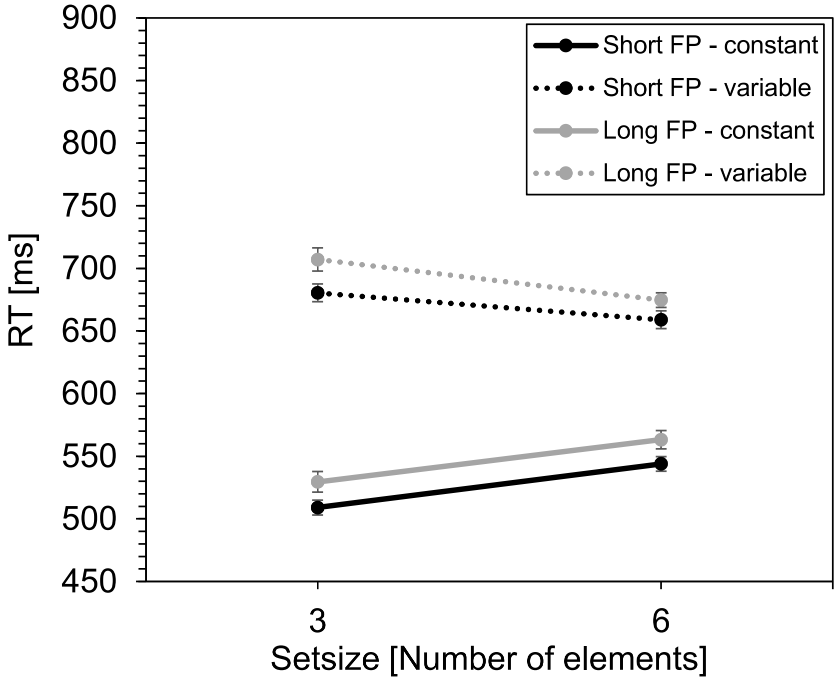
2.3.2 Results

RmANOVAs with the factors FP (short or long), setsize (3 or 6 elements), and target feature constancy (variable or constant) were conducted on mean RT and mean error rate.

Analysis of mean RT revealed a main effect of FP, *F*(1,31) = 17.93, $p < .001$, $\eta_p^2 = .37$ (see Figure 2-7). Participants responded faster to targets in the short FP condition (*M* = 598 ms, *SD* = 100 ms) than in the long FP condition (*M* = 619 ms, *SD* = 104 ms). Further, there was an effect of target feature constancy, *F*(1,31) = 152.25, $p < .001$, $\eta_p^2 = .83$. Participants responded faster in the half of the experiment in which the target feature was constant (*M* = 536 ms, *SD* = 61 ms) than in the half in which it was variable (*M* = 680 ms, *SD* = 83 ms). There was no main effect of setsize, *F*(1,31) = 1.59, $p = .22$, but as hypothesized an interaction between setsize and target feature constancy, *F*(1,31) = 77.35, $p < .001$, $\eta_p^2 = .71$. While mean RT decreased with

Figure 2-7

Mean reaction time for short and long foreperiod conditions in Experiment 2



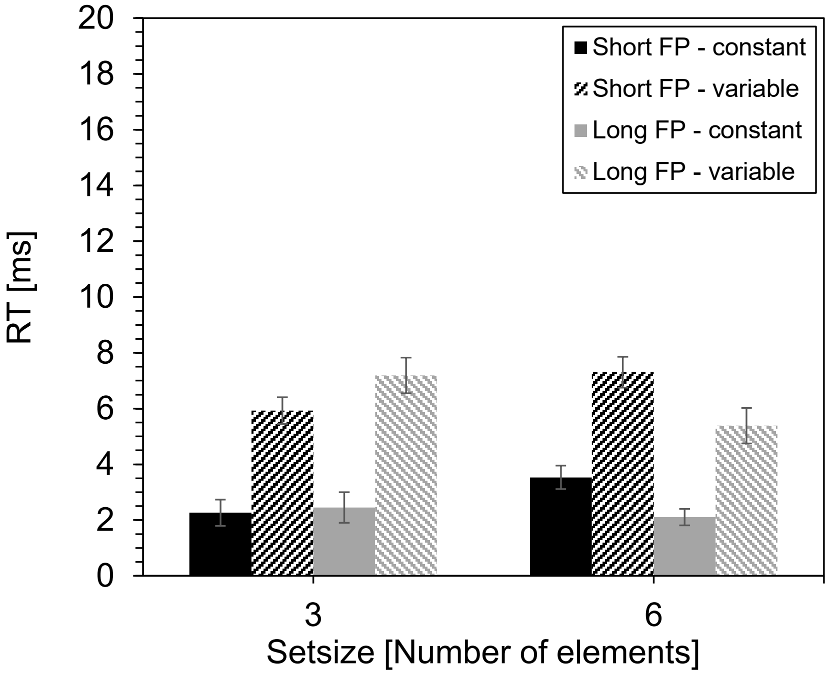
Note. Mean reaction time (RT) as a function of setsize for 3 or 6 elements in the short FP condition (black lines) and the long FP condition (gray lines) for the half of the experiment with a constant target (solid lines) or a variable target (dotted lines). Error bars denote +/- one standard error of the mean for within-subjects designs, being calculated according to Cousineau (2005) and a correction by Morey (2008).

increasing setsize in the variable target feature condition, *t*(31) = 5.93, $p_{bonf} < .001$, this effect was reversed in the constant target feature condition, *t*(31) = -7.55, $p_{bonf} < .001$. No other interactions reached significance (*p* > .14).

There was no main effect of FP, *F*(1,31) = 1.61, *p* = .21, or setsize, *F*(1,31) = .14, *p* = .71, on the mean error rate (see Figure 2-8). Further, participants made more errors on trials with a variable target feature (*M* = 6.45%, *SD* = 4.33%) than on trials with a constant target feature (*M* = 2.59%, *SD* = 2.95%), *F*(1,31) = 36.72, *p* < .001, η_p^2 = .54. A significant interaction between FP and setsize, *F*(1,31) = 23.44, *p* < .001, η_p^2 = .43, showed that the error rate was higher for trials in short FP blocks (*M* = 5.42%, *SD* = 4.17%), than in long FP blocks for the 6 elements condition (*M* = 3.74%, *SD* = 3.79%), *t*(31) = 3.73, $p_{bonf} = .003$, while this was not significant for the 3 elements condition, *t*(31) = -1.61, $p_{bonf} = .68$. No other interactions reached significance (*p* > .29).

Figure 2-8

Mean error rate for short and long foreperiod conditions in Experiment 2



Note. Mean error rate as a function of setsize for 3 or 6 elements in the short FP condition (dark bars) and the long FP condition (light bars) for the half of the experiment with a constant target (filled bars) or a variable target (dashed bars). Error bars denote +/- one standard error of the mean for within-subjects designs, being calculated according to Cousineau (2005) and a correction by Morey (2008).

2.3.3 Discussion of Experiment 2

The aim of Experiment 2 was to test whether temporal preparation influences bottom-up processes and, in a separate half of the experiment, additionally top-down processes in spatial selection. Consistent with Experiment 1, RT was faster after a short FP interval whereas RT was longer after a long FP interval. Therefore, it can be hypothesized that temporal preparation accelerated responses in the visual search task. Most importantly, this FP effect was not modulated by bottom-up salience, i.e., setsize, nor by top-down relevance, i.e., information about the target-defining feature. Therefore, the results of Experiment 2 do not provide evidence that temporal preparation directly influences either bottom-up processing or top-down processing in spatial selection.

2.4 General Discussion of Study 1

Taken together, both experiments replicate the beneficial effect of temporal preparation on visual search under spatial uncertainty observed in previous studies (Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014a, 2014b). First, it was of interest to clarify whether this beneficial effect of temporal preparation was due to an influence on bottom-up processing in spatial selection. To test this, the salience of the target was manipulated by varying the number of distractors surrounding the target. Since salience is a bottom-up property of a stimulus, the aim of this manipulation was to find an interaction between temporal preparation and target salience as an indicator of an influence of temporal preparation on bottom-up processing. Contrary to this hypothesis, there was no interaction between temporal preparation and target salience in RT in Experiment 1. Also, further enhancing the bottom-up properties of the target by increasing its variability did not show evidence for a selective influence of temporal preparation as a function of target salience in Experiment 2. Taken together, the results of both experiments do not support the idea that temporal preparation influences spatial selection by directly influencing bottom-up processing. This observation is consistent with a study by Seibold and Rolke (2014a), who investigated the influence of temporal preparation in an attentional capture paradigm. In this particular study, a task-irrelevant distractor popped out amongst the target and other distractors due to its abrupt onset. Interestingly, temporal preparation influenced spatial selection of the target, but this was independent of the degree of distraction of the attentional capture.

This result mirrors the observations in the current experiment and can be interpreted in favor of an indirect influence of temporal preparation on spatial selection.

Furthermore, an additional question of this study was whether temporal preparation influences top-down processing of the target. Contrary to this hypothesis, top-down information about the target-defining feature did not enhance the FP effect. Therefore, the results do not provide evidence that temporal preparation selectively enhances top-down processing in spatial selection. Initial evidence supporting the idea that temporal preparation can influence top-down processes in general was provided by a study using a variable FP paradigm (Schröter et al., 2014). In this study, the FP effect in a discrimination task was larger when participants could predict the upcoming discrimination task (i.e., letter or color discrimination) than when they could not. This finding can be interpreted in the sense that temporal preparation not only affects discrimination processes in general, but also selectively enhances task-specific processes. With respect to the current study, their results differ from those of Experiment 2 in that the task requirements were kept constant, but the top-down activation of relevant target features and thus the stimulus processing itself were varied. These differences may explain that temporal preparation has a different influence on top-down processes depending on the level at which it is located. Stronger evidence is provided by a study that used a cueing paradigm to investigate the relationship between temporal and feature expectancies (Kingstone, 1992). There, an interaction between valid and invalid temporal and feature cues on RT suggests a relationship between temporal preparation and expectation of target features. Latter could be interpreted as pre-activation of relevant target features in accordance with current top-down goals. In this study, it was particularly interesting that a violation of one expectancy dimension (e.g., feature expectation) in the form of an invalid cue also reduced the beneficial effect on the other valid dimension (e.g., temporal expectation). This may highlight a fundamental difference between the temporal cueing paradigm, in which attention is guided on the basis of trial-by-trial cues that also contain invalid information, and the constant FP paradigm, in which temporal preparation is induced by a constant, always valid relationship between the warning signal and the imperative signal. Nevertheless, there is evidence that temporal preparation can influence top-down processes at different levels, and it remains to be seen whether this can be transferred to spatial selection.

Regarding the main question of how temporal preparation affects spatial selection, the answer is still unclear. This question arose from the observation that temporal preparation modulates the N2pc and thus an index of spatial selection under spatial uncertainty (Hackley et al., 2007; Seibold & Rolke, 2014b; see also Chapter 1). In contrast, there is also evidence from studies that have combined temporal and spatial attention in cueing paradigms that spatial certainty (or spatial attention) appears to be necessary for the use of temporal preparation (Doherty et al., 2005; Rohenkohl et al., 2014). However, although they disagree on whether spatial certainty is a prerequisite for a beneficial influence of temporal preparation, all these studies point in the direction that temporal preparation specifically influences spatial selection. Another approach to explain these results, as well as the contrary observations, is that temporal preparation accelerates early visual processing and that this effect propagates to later processes such as spatial selection, as described in the early onset hypothesis (Rolke, 2008; Rolke et al., 2016; see Chapter 1 for more details). Since this acceleration is not specific to the processes contributing to spatial selection, one might assume that it should show up as an additive result in RT. In this sense, the results of the current experiments are more consistent with studies that did not observe a direct effect of temporal preparation on spatial selection in RT (Seibold & Rolke, 2014b) or in ERPs (Rolke et al., 2016). Ultimately, however, this would suggest that temporal preparation has an indirect influence on spatial selection, independent of bottom-up or top-down processing.

From the present RT study, no direct conclusions can be drawn as to how exactly temporal preparation influences spatial selection. The measurement of RT has the unavoidable disadvantage that we can only observe the average result of all processes that could be affected by temporal preparation. To find out exactly which processes do benefit from temporal preparation, a more precise technique is needed, such as that used in previous studies of spatial selection. The following chapters introduce such an approach by using ERPs to determine how temporal preparation affects spatial selection. Chapter 3 reports an ERP study that examined how temporal preparation affects spatial selection via an influence on bottom-up processing. Chapter 4 attempts to clarify how temporal preparation affects the spatial selection of a top-down relevant target and a salient singleton distractor. This will allow conclusions to be drawn as to whether temporal preparation influences spatial selection by facilitating bottom-up and/or top-down processing.

The following chapter (Chapter 3) consists of a paper which was published in *Brain Research* in 2022 and which was co-authored by Prof. Dr. Bettina Rolke and Dr. Verena C. Seibold. The numbering of the footnotes has been adjusted and the numbering of the figures and the headlines has been supplemented with the chapter number.

The official citation that should be used in reference to the following chapter is:

Balke, J., Rolke, B., & Seibold, V. C. (2022). Temporal preparation accelerates spatial selection by facilitating bottom-up processing. *Brain Research*, *1777*, 147765. https://doi.org/10.1016/j.brainres.2021.147765

3. Study 2: Temporal preparation accelerates spatial selection by facilitating bottom-up processing

Abstract

Temporal preparation facilitates spatial selection in visual search. This selection benefit has not only been observed for targets, but also for task-irrelevant, salient distractors. This result suggests that temporal preparation influences bottom-up salience in spatial selection. To test this assumption, we conducted an event-related-potential (ERP) study in which we measured the joint effect of temporal preparation and target salience on the N2pc as an index of spatial selection and the N1 as an index of perceptual discrimination. To manipulate target salience, we employed two different setsizes (i.e., a small or large number of homogeneous distractors). To manipulate temporal preparation, we presented a warning signal before the search display, and we varied the length of the interval (foreperiod) between warning signal and search display in different blocks of trials (constant foreperiod paradigm). Replicating previous results, we observed that the N1 and the N2pc arose earlier in case of good temporal preparation. Importantly, the beneficial effect on the N2pc onset latency was stronger when the target salience was initially low (i.e., small setsize). This result provides evidence that temporal preparation influences bottom-up processing and, thereby, facilitates spatial selection.

3.1 Introduction

More than a century ago, Woodrow (1914) started uncovering the role of temporal preparation by investigating how participants use temporal information to prepare for an upcoming stimulus. Temporal preparation is an important cognitive function as it enables us to anticipate the moment in time when a future event is most likely to occur and, by this, to optimize stimulus processing and responding. One classic approach in the experimental investigation of temporal preparation is the so-called *constant foreperiod paradigm* (e.g., Klemmer, 1956; Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Sanders, 1966, 1975; Woodrow, 1914). Here, a warning signal predicts the occurrence of an imperative stimulus or target. The interval including the warning signal until the occurrence of the target – the so-called foreperiod (FP) – is constant within one block. On basis of this constant temporal relationship between warning signal and target, participants learn to predict the temporal occurrence of the target (Klemmer, 1956; Niemi & Näätänen, 1981). The typical result pattern observed in the constant FP paradigm is that reaction time (RT) is shorter in blocks with a rather short FP compared to those with a rather long FP (Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Woodrow, 1914). For instance, Müller-Gethmann et al. (2003) observed that RT was especially short for FPs ranging between 200 and 800 ms and then increased for longer FPs up to 6,400 ms.[3] This increase in RT for longer FPs has been explained in terms of an imperfect time-keeping ability (Gottsdanker, 1975; Niemi & Näätänen, 1981), assuming that the estimation of the exact moment in time when a target appears is less precise for long time intervals than for short ones. Therefore, temporal uncertainty is higher in long FP blocks than in short FP blocks. While the beneficial effect of temporal preparation has been replicated in various studies using different paradigms (Coull & Nobre, 1998; Lange & Röder, 2006; Niemi & Näätänen, 1981; Sanabria et al., 2011), different tasks (Correa et al., 2004; Sanders, 1980; Simon & Slaviero, 1975) as well as different modalities (Lange & Röder, 2006; Müller- Gethmann et al., 2003), the exact mechanisms that underlie this beneficial effect are still being debated. While most earlier studies focused on influences of temporal preparation on late motor processes (Hasbroucq et al., 1999; Mattes & Ulrich, 1997; Sanders, 1980; Spijkers, 1990; Tandonnet et al., 2003), more recent studies have provided converging evidence that temporal preparation additionally influences pre-motor processes and stimulus perception (Bausenhart et al., 2007; Correa et al., 2006; Hackley et al., 2007; Müller-Gethmann et al., 2003; Rolke, 2008). Furthermore, it has been shown that not only

---

[3] Apart from the basic observation that RT in the constant FP paradigm increases for longer FPs, studies including a broad range of different FPs (Klemmer, 1956; Los & Schut, 2008; Müller-Gethmann et al., 2003; Woodrow, 1914) and a comparison condition without any warning signal (Müller-Gethmann et al., 2003) have provided evidence for a U-shaped FP-RT function. Specifically, these studies have revealed a steep initial decrease in RT for very short FPs (i.e., less than 200 ms), followed by an RT optimum between 200 and 800 ms (Müller-Gethmann et al., 2003) before RT then slowly increases again until it reaches an asymptote for considerably long FPs (for an overview, see Niemi & Näätänen, 1981). This pattern of results has been typically explained in a way that the build-up of a temporally prepared state takes some time and then gradually decreases until an upper limit (see again Niemi & Näätänen, 1981). Furthermore, the steep descent in RT for very short FPs has been attributed to an immediate facilitation being caused by an increase in arousal rather than temporal preparation (Bertelson, 1967; Los & Schut, 2008; Ulrich & Mattes, 1996).

perception in general, but also selective processes within perception benefit from temporal preparation. In particular, this latter effect has been shown in studies using visual search tasks and measuring the effect of temporal preparation on the N2posterior-contralateral (N2pc) component of the event-related potential (ERP; Balke et al., 2021; Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014b). The N2pc is a posterior negativity in the ERP contralateral to an attended stimulus, which arises at about 200 to 300 ms after the onset of the search display and is regarded as an index of spatial selection of attended stimuli (for reviews, see, e.g., Eimer, 2014; Luck, 2012). The N2pc is most commonly measured in pop-out search tasks in which participants search for a target that differs from all other stimuli (the distractors) in at least one feature (e.g., colour). Seibold and Rolke (2014b) showed that good temporal preparation leads to a more pronounced and earlier arising target-evoked N2pc, suggesting that temporal preparation increases the efficiency of spatial selection of a target. Balke et al. (2021) replicated and extended this finding by investigating whether temporal preparation influences spatial selection not only of the target, but also of task-irrelevant salient distractors. In that study, participants searched for an orientation pop-out target (i.e., a tilted line) amongst homogenous oriented distractors (i.e., horizontal or vertical lines). Furthermore, in each trial, one of the distractors had a unique colour (i.e., red or blue) which differed from the colour of all other stimuli. Importantly, given that participants were instructed to search for an orientation target, the uniquely coloured distractor was completely task-irrelevant as it was defined in a different dimension than the target. Consistent with previous studies, Balke et al. (2021) observed an effect of temporal preparation on RT and the target N2pc. In particular, participants responded faster, and onset latency of the target N2pc was shorter in case of good temporal preparation. The most important result of that study, however, was that temporal preparation did not only affect spatial selection of the target, but also affected spatial selection of the uniquely coloured distractor. In particular, the N2pc evoked by the uniquely coloured distractor was more pronounced in case of good temporal preparation. Summarized, the results of previous studies show that temporal preparation facilitates spatial selection in visual search. Furthermore, this effect is not confined to task-relevant stimuli (i.e., the target), but it is also observed for task-irrelevant stimuli (i.e., a uniquely coloured distractor; see Balke et al., 2021). On grounds of these findings, the question arises *how* temporal preparation may facilitate spatial selection. According to current models of visual search, spatial selection is affected by at least three types of influences: goal-driven influences, selection history (or selection experiences), and bottom-up salience (e.g., Awh et al., 2012; Evans et al., 2011; Lamy & Zoaris, 2009; Liesefeld & Müller, 2021; Theeuwes, 2010; Wolfe, 2021; Wolfe et al., 2003; Yantis, 1993). Goal-driven influences are influences that are assumed to be under active control of an observer such as intentions or task goals. For instance, if an observer's goal (or task set) is to search for a specific stimulus (e.g., a red circle), he or she can actively orient attention towards that specific stimulus. Furthermore, selection history is an influence that arises due to an observer's experiences in previous search episodes. For instance, if a target has been repeatedly presented in the same colour, spatial selection in subsequent episodes will be biased towards this stimulus colour (Maljkovic & Nakayama, 1994). Finally, bottom-up salience is an influence on spatial selection that is caused by low-level properties of a stimulus such as the contrast of a stimulus relative to its surround (Lamy & Zoaris, 2009; Nothdurft, 2000, 2005). Importantly and in contrast to goal-driven influences, bottom-up salience can affect spatial selection irrespective of the task relevance of a stimulus (e.g., Hickey et al., 2006; Liesefeld et al. 2017; Theeuwes, 1991). This theoretical distinction together with the results of Balke et al. (2021) provide a first hint regarding *how* temporal preparation may facilitate spatial selection. Specifically, the observation that temporal preparation modulates the N2pc not only of targets, but also of task-irrelevant salient distractors, suggests that temporal preparation influences spatial selection in a non-selective manner, that is, irrespective of the task-relevance of a stimulus. Within the framework of the above outlined models of visual search, this non-selective effect can be best explained in terms of an influence of temporal preparation on bottom-up salience rather than goal-driven processes. Note that this suggestion does not imply that temporal preparation itself is a bottom-up influence but rather that it modulates bottom-up salience and this, in turn, affects spatial selection. On grounds of this line of reasoning, the aim of this study was to investigate specifically whether temporal preparation influences bottom-up salience. To this end, we combined a FP paradigm with a pop-out visual search task. We presented a circular search display consisting of simple geometric shapes (diamonds), with either the left or the right corner being cut away. All diamonds except for one were of the same colour (i.e., either red or green), and participants were asked to search for this uniquely coloured diamond (the target). To specifically measure the effect of temporal preparation on bottom-up salience, we varied the salience of the target. Stimulus salience presumably constitutes one bottom-up property which affects spatial selection of a stimulus independently of goal-driven factors (e.g., Folk & Remington, 2008; Theeuwes, 2010; Wolfe, 1994). One way to experimentally manipulate stimulus salience is to vary the number of homogenous distractors, which surround the target in a pop-out search task. For instance, in a study by Maljkovic and Nakayama (1994) the target (a uniquely coloured item) was surrounded by either a small (i.e., two) or a large (i.e., eleven) number of homogenous distractors. The typical result pattern that is observed in this approach is that RT to targets decreases as the number of homogenous distractors increases (e.g., Bacon & Egeth, 1991; Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; Rangelov et al., 2017). Furthermore, it has been shown that the target N2pc, known as an indicator of spatial selection, is directly sensitive to this manipulation (Mazza et al., 2009). One possible explanation of these findings is that a larger number of homogenous distractors might increase the probability for perceptual grouping (Bacon & Egeth, 1991; Duncan & Humphreys, 1989; Mazza et al., 2009) so that distractors may be faded out more easily. Alternatively, suppressive interactions between similar stimuli (i.e., homogenous distractors) might be stronger in displays with a larger number of homogenous distractors due to the higher display density (Rangelov et al., 2017). Importantly and irrespective of the underlying mechanism, a larger number of homogenous distractors will directly increase the target salience. Based on this assumed direct relation between the number of homogenous distractors and target salience, we presented the target either with three distractors (i.e., 4 elements condition) or 19 distractors (i.e., 20 elements condition), resulting in conditions of low and high target salience, respectively. As an index of spatial selection of the target, we measured the N2pc (Eimer, 1996; Mazza et al., 2009; Seibold & Rolke, 2014b). To manipulate temporal preparation, we used a constant FP paradigm analogous to previous studies (Balke et al., 2021; Seibold & Rolke, 2014b): we presented an auditory warning signal which preceded the onset of the search display in separate blocks of trials by either a short FP (i.e., 800 ms) or a long FP (i.e., 2,400 ms). Our hypotheses were as follows: first, we expected to find an effect of setsize on the target N2pc (see Mazza et al., 2009). Second, we expected that temporal preparation facilitates spatial selection of the target, which should be reflected in a more pronounced and/or earlier arising N2pc (Balke et al., 2021; Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014b). Our focus, however, was on the influence of temporal preparation on setsize. If temporal preparation facilitates bottom-up salience in spatial selection and if it increases target salience, we expected to observe a more pronounced FP effect on the N2pc when the salience of the target is low compared to when it is high. This hypothesis is rooted in the assumption that the potential for an improvement of perceptual processes is higher if these processes are not already at their optimum (see also Correa et al., 2006). To further investigate the influence of temporal preparation on perceptual processes, we explored the effect of temporal preparation on the N1 in addition to the N2pc. The N1 has been described as an indicator of discrimination processes (Hopf et al., 2002; Mangun & Hillyard, 1991; Vogel & Luck, 2000), and it has been shown to be sensitive to temporal preparation (Balke et al., 2021; Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014b). To monitor the effect of temporal preparation on discrimination processes, we varied the discrimination requirements associated with the target. In separate halves of the experiment, we asked participants to either report the display side at which the target was presented (localization task) or to indicate whether the left or right corner of the target that was cut away (discrimination task). Since discrimination requirements were higher in the discrimination task compared to the localization task, we expected to observe a stronger effect of temporal preparation on the N1 in the discrimination task than in the localization task. Finally, we measured behavioural performance in addition to ERPs (i.e., RT to targets and accuracy). With respect to RT, we expected to replicate the basic FP effect, that is, shorter RT for the short FP condition than for the long FP condition (e.g., Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Rolke, 2008; Seibold and Rolke, 2014a, 2014b). In addition, we expected to observe an effect of setsize and of task on RT. Specifically, RT should be shorter for the large setsize (i.e., 20 elements condition) than for the small setsize (i.e., 4 elements condition; see Bacon & Egeth, 1991; Bravo & Nakayama, 1992; Mazza et al., 2009), and RT should be shorter for the localization task than for the discrimination task (Mazza et al., 2007; Töllner et al., 2012).

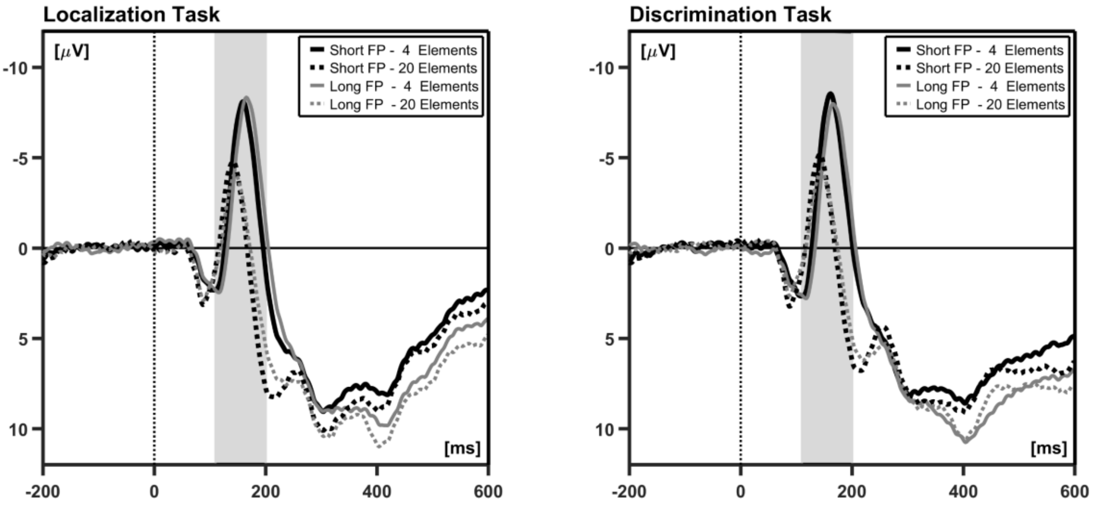
3.2 Results

3.2.1 RT and accuracy

Analysis of mean RT for correct responses showed main effects of task, $F(1, 23) = 457.61$, $p < .001$, $\eta_p^2 = .95$, and setsize, $F(1, 23) = 79.70$, $p < .001$, $\eta_p^2 = .78$. Subjects responded faster in the localisation task (M = 409 ms, SD = 56 ms) than in the discrimination task (*M* = 601 ms, *SD* = 66 ms), and they responded faster in the 20 elements (large setsize) condition (*M* = 492 ms, *SD* = 111 ms) than in the 4 elements (small setsize) condition (*M* = 518 ms, *SD* = 116 ms). Furthermore, the analysis of RT showed a main effect of FP, *F*(1, 23) = 18.31, *p* < .001, η_p^2 = .44, as participants responded faster to targets in the short FP (*M* = 497, *SD* = 116 ms) than in the long FP condition (*M* = 513 ms, *SD* = 112 ms). Furthermore, none of the interactions in RT was significant (all *p*s > .26). Analogous to the analysis of RT, the analysis of error rates revealed main effects of task, *F*(1, 23) = 9.08, *p* = .006, η_p^2 = .28, and setsize, *F*(1, 23) = 4.69, *p* = .041, η_p^2 = .17. Participants made more errors in the discrimination task (*M* = 3.5% error rate, *SD* = 3.3%) than in the localization task (*M* = 1.4%, *SD* = 4.0%), and they made more errors in the 4 elements condition (*M* =

Figure 3-1

Grand-average ERP (N1) evoked by the search display



Note. Grand-average ERP (N1) evoked by the search display at posterior electrode sites (i.e., pooled electrode sites O1, O2, Oz, P3, P4, PO3, PO4, PO7, PO8, POz, Pz, P7 and P8) as a function of foreperiod (FP) and setsize for the localization task (left panel) and the discrimination task (right panel). The black lines denote the short FP condition, and the light grey lines denote the long FP condition; the solid lines denote the 4 elements condition and the dotted lines denote the 20 elements condition. In this figure and the subsequent figure, time (in ms) is displayed on the x-axis, and voltage (in µV) is displayed on the y-axis. Negative voltage is plotted upward. The short-dashed vertical line indicates the onset of the search display. The grey shaded area indicates the time window that was used for measurement of the N1.

2.8%, *SD* = 3.8%) than in the 20 elements condition (*M* = 2.1%, *SD* = 3.8%). In contrast, there was no FP effect on the error rates, *F*(1, 23) = 0.98, *p* = .33. Furthermore, none of the interactions in the error rates was significant (all *p*s > .33).

3.2.2 N1

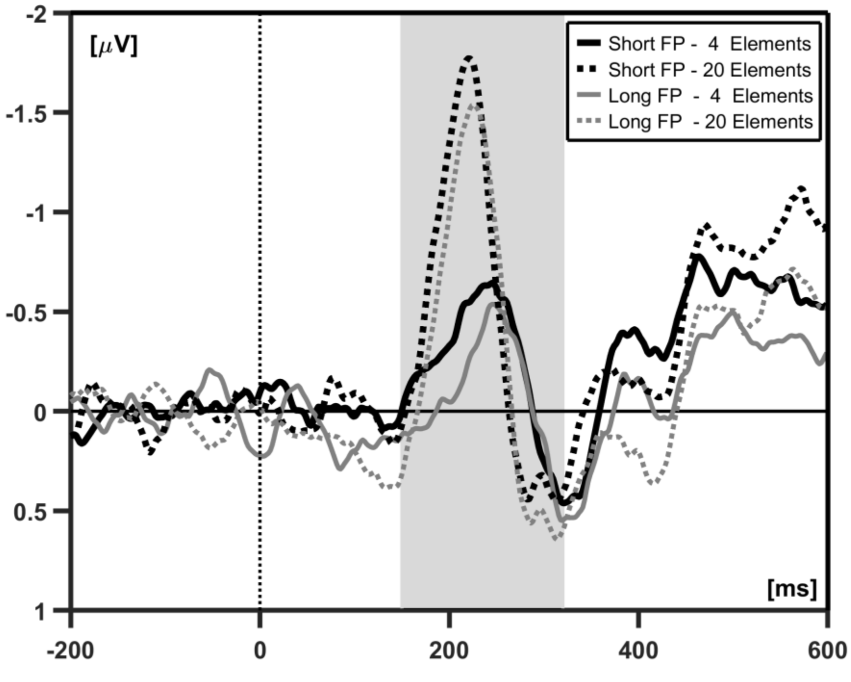
The ERP evoked by the search display is illustrated in Fig. 1. The analysis of N1 amplitude showed a main effect of setsize, *F*(1, 23) = 74.44, *p* < .001, $\eta_p^2 = .76$, as the N1 was more pronounced in the 4 elements condition (*M* = –6.60 μV, *SD* = 3.13 μV) than in the 20 elements condition (*M* = –3.32 μV, *SD* = 2.69 μV). N1 amplitude was neither modulated by FP, *F*(1, 23) = 0.19, *p* = .66, nor by task, *F*(1, 23) = 0.90, *p* = .35. Furthermore, none of the interactions reached significance (all *p*s > .21). The analysis of N1 onset latency revealed pronounced effects of both setsize, $F_C(1, 23) = 4.42$, *p* = .047, $\eta_p^2{}_C = .16$, and FP, $F_C(1, 23) = 11.11$, *p* = .003, $\eta_p^2{}_C = .33$. The N1 onset latency was reduced in the 20 elements condition (*M* = 137 ms, *SD* = 5 ms) as compared to the 4 elements condition (*M* = 143 ms, *SD* = 3 ms). Furthermore, the N1 arose earlier in the short FP condition (*M* = 136 ms, *SD* = 4 ms) than in the long FP condition (*M* = 143 ms, *SD* = 3 ms). Again, there was no effect of task on N1 onset latency, $F_C(1, 23) = 0.02$, *p* = .90, nor were there any significant interactions (all *p*s > .20).

3.2.3 N2pc

The contra- minus ipsilateral difference waves at pooled electrode sites PO3/4 and PO7/8 for each FP and setsize condition is illustrated in Fig. 2. As is evident from Fig. 2, a N2pc emerged at about 150 ms after the onset of the search display. One-tailed *t*-tests against zero revealed that the N2pc was reliable in all FP and setsize conditions (all *p*s < .001). The subsequent analysis of N2pc mean amplitude revealed a main effect of setsize, *F*(1, 23) = 24.14, *p* < .001, $\eta_p^2 = .51$. The N2pc was more pronounced in the 20 elements condition (*M* = –1.53 μV, *SD* = 1.11 μV) than in the 4 elements condition (*M* = –0.70 μV, *SD* = 0.54 μV). Furthermore, the N2pc was numerically larger in the short FP condition (*M* = –1.23 μV, *SD* = 0.87 μV) than in the long FP condition (*M* = –1.00 μV, *SD* = 1.04 μV) even though the FP main effect was not significant, *F*(1, 23) = 4.20, *p* = .052, $\eta_p^2 = .15$. There was no interaction of FP and setsize on N2pc mean amplitude, *F*(1, 23) = 0.04, *p* = .84. The analysis of N2pc onset latency again revealed a main effect of setsize, $F_C(1, 23) = 115.29$, *p* < .001, $\eta_p^2{}_C = .83$. The N2pc arose earlier in the 20 elements condition (*M* = 180 ms, *SD* = 5 ms) than in the 4 elements condition (*M* = 226 ms, *SD* = 14 ms). Furthermore, N2pc onset latency was modulated by FP, $F_C(1, 23) = 13.07$, $p = .001$, $\eta_p{}^2{}_C = .36$, reflecting an earlier arising N2pc in the short FP condition (*M* = 194 ms, *SD* = 19 ms) as compared to the long FP condition (*M* = 212 ms, *SD* = 27 ms). Most interestingly, there was an interaction of setsize and FP on the N2pc onset latency, $F_C(1, 23) = 4.99$, $p = .036$, $\eta_p{}^2{}_C = .18$. Post-hoc analyses of this interaction revealed that the FP effect was present in both the 20 elements condition, $F_C(1, 23) = 7.67$, $p = .011$, $\eta_p{}^2{}_C = .25$, and the 4 elements condition, $F_C(1, 23) = 10.64$, $p = .003$, $\eta_p{}^2{}_C = .32$, but it was larger in the 4 elements condition (difference long FP – short FP: *M* = 28 ms, *SD* = 2 ms) than in the 20 elements condition (difference: *M* = 10 ms, *SD* = 1 ms).

Figure 3-2

Difference wave (N2pc) evoked by the search display



Note. Grand-average contra-minus ipsilateral difference wave evoked by the search display at posterior electrode sites (i.e., pooled PO7/8 and PO3/4) as a function of foreperiod (FP) and setsize. The black lines denote the short FP condition, and the light grey lines denote the long FP condition; the solid lines denote the 4 elements condition and the dotted lines denote the 20 elements condition. The grey shaded area indicates the time window that was used for measurement of the N2pc.

3.3 Discussion

The main aim of the present study was to test whether temporal preparation influences bottom-up salience in spatial selection. We combined a constant FP paradigm with a setsize manipulation in a visual search task in which participants were asked to search for a colour pop-out target. To reveal a potential effect of temporal preparation on bottom-up salience in spatial selection, we measured the N2pc evoked by the target. In addition, we explored whether temporal preparation specifically facilitates discrimination processes. To investigate this question, we varied the task that had to be performed on the target (localization versus discrimination) and we measured the joint effect of task, setsize and FP on the N1 as an indicator of visual discrimination processes. In line with previous studies, we observed an effect of FP on RT as participants responded faster to a target following a short FP than to one following a long FP (e.g., Seibold & Rolke, 2014a, 2014b). Apart from the effect of FP, we observed an effect of setsize on RT. Participants responded faster in the large setsize condition (i.e., 20 elements) than in the small setsize condition (i.e., 4 elements; see Bacon & Egeth, 1991; Bravo & Nakayama, 1992; Mazza et al., 2009). These RT effects were flanked by corresponding effects on the N2pc. The N2pc arose earlier after the short FP than after the long FP indicating that the efficiency of spatial target selection was affected by temporal preparation (see Balke et al., 2021; Rolke et al., 2016; Seibold & Rolke, 2014b, for a similar effect). Moreover, the N2pc was more pronounced and arose earlier in the large setsize condition than in the small setsize condition. This effect of setsize on the N2pc is consistent with a previous ERP study (Mazza et al., 2009) and indicates that target selection benefits from a larger number of homogenous distractors. Overall, these results replicate previous findings and show that our experimental manipulations of temporal preparation and stimulus salience were effective. Importantly, apart from the isolated effects of FP and setsize on the N2pc, we observed an interaction of the two factors on N2pc onset latency as the FP effect was larger in the small setsize condition than in the large setsize condition. This result provides first evidence that the effect of temporal preparation on the efficiency of spatial selection is stronger if target salience is low. The N1 analysis revealed several effects: the N1 arose earlier following the short FP than following the long FP. This result replicates the observations of previous studies (Balke et al., 2021; Rolke et al., 2016; Seibold & Rolke, 2014b) and provides support for the idea that temporal preparation accelerates early visual processing (Correa et al., 2006; Müller-

Gethmann et al., 2003; Rolke, 2008). In contrast to this facilitating effect of FP, we did not observe an effect of task on the N1, nor did we observe an interaction of task and FP, even though RT was modulated by task. From a theoretical point of view, the absence of a task effect on the N1 may indicate that differences in discrimination requirements associated with the target may not emerge before the spatial selection of the target. Indirect support for this assumption can be found in the observation that the N2pc did not differ between discrimination and localization in previous studies (Mazza et al., 2007; Töllner et al., 2012, 2013) nor in the current study. Accordingly, the N1 in our study may reflect processes that do not differ between localization and discrimination such as, for instance, the discrimination of basic stimulus features for all stimuli in the search display. The idea of a rather late, post-selective effect of discrimination requirements can also be found in current models of visual search (Töllner et al., 2012; Wolfe, 2021). For instance, in the guided search model (Wolfe, 2021), the fine discrimination of target features (i.e., in the present study whether the target was cut on its left or right side) requires recurrent processes that reach back from higher stages to low level visual processing after the target has been selected by spatial attention. It should be noted, however, that this explanation for the missing task effect on the N1 remains speculative because it is based on the interpretation of a null result (the absence of a main effect of task). Furthermore, and even more importantly, the missing task effect does not allow to answer the question whether a task that needs a further discrimination of target features benefits more from temporal preparation than a task that requires only localization of a target. Whereas the N1 was not modulated by task, it was affected by setsize: the N1 arose earlier, and its amplitude was reduced in the large setsize condition compared to the small setsize condition. We did not predict a setsize effect on the N1 a priori since most ERP studies on visual search focus on the N2pc so that empirical evidence on the N1 in this context is generally sparse. Yet, studies investigating the N1 in non-search tasks have shown that the amplitude and the latency of the N1 are directly sensitive to variations of perceptual processing requirements (Fort et al., 2005; Jentzsch et al., 2007). Therefore, effects measured in the N1 in these tasks have been typically linked to basic perceptual processes, in particular stimulus discrimination processes (Fedota et al., 2012; Vogel & Luck, 2000). From this perspective, the N1 setsize effect observed in this study may be explained in terms of perceptual differences between the two setsize conditions. For instance, one obvious perceptual difference between the displays in the two setsize conditions is the higher density of the elements in the large setsize condition compared to the small setsize condition. The higher density of the elements in the large setsize condition may increase the likelihood for perceptual grouping (Bacon & Egeth, 1991; Mazza et al., 2009). Such a grouping process might in turn result in the perception of a circular grouped object in the large setsize condition in contrast to the perception of rather ungrouped distributed elements in the small setsize condition. The perception of a single grouped object might be easier or require fewer processing resources than the perception of multiple separate elements (Hyde & Spelke, 2012). Accordingly, perceptual grouping may be one possible explanation for the observation that the N1 arose earlier and was less pronounced in the large setsize condition compared to the small setsize condition (for similar effects of grouping on the N1 see Chicherov et al., 2014; Han et al., 2001; Hyde & Spelke, 2012). However, given the lack of empirical evidence on the N1 in visual search, this explanation remains speculative, and further systematic research is needed to clarify the mechanisms that underly the setsize effect on the N1 in visual search. Regarding our main question, that is, whether temporal preparation influences bottom-up salience, the results are clear: FP interacts on the N2pc with the effect of setsize, an experimental variable that is considered to change bottom-up salience in spatial selection. We additionally observed that FP and setsize reduced the latency of the N1, suggesting that temporal preparation did not only affect spatial selection but also the speed of early perceptual processing in general. In our view, this overall pattern of result suggests that temporal preparation may optimize visual processing via two mechanisms: first, temporal preparation might accelerate early perceptual processing as formulated in the *early onset hypothesis* (Rolke, 2008; Rolke et al., 2016) and, second, temporal preparation might optimize processes that contribute to spatial selection. In principle, there are several ways in which temporal preparation could optimize spatial selection. For instance, in the prominent Guided Search model (Wolfe, 1994) spatial selection is conceptualized as a process in which spatial attention selects stimuli for further in-depth processing depending on their activation value on a location-based activation map. Specifically, stimuli at locations with a higher activation value are more likely to be selected than stimuli at locations with a low activation value. Accordingly, one straightforward way how temporal preparation could influence spatial selection is by changing the activation value in the location-based activation map. Alternatively, and as an extension to this model, temporal preparation could also influence the build-up time of the activation map (see e.g., Lleras et al., 2020, for the idea that preattentive processing is temporally variable).[4] In this scenario, temporal preparation would not affect the activation value within the activation map itself, but rather affects how fast the activation map is available. Importantly, both the activation value and the build-up rate can be assumed to depend on the signal-to-noise ratio: specifically, if the signal-to-noise ratio in the activation map for one specific stimulus location is high, the activation value of that stimulus location is also high, and this should lead to a more efficient selection of stimuli at that specific location by spatial attention. Furthermore, if the signal-to-noise ratio during the build-up of the activation map is high this may increase the speed by which the activation map becomes available. This means that any variable that increases the signal-to-noise ratio either in the activation map itself or during the build-up of the activation map should have an impact on spatial selection. Such an increase might be accomplished by strengthening the signal (see e.g., Ling et al., 2009, for such a mechanism in the context of spatial attention) and/or by reducing noise (see e.g., Ling et al., 2009, for such a mechanism in the context of feature-based attention; for a formal model on these mechanisms see Lu & Dosher, 2005). If one assumes that temporal preparation enhances the signal-to-noise ratio, it seems furthermore plausible that the effect of temporal preparation is larger in a condition where the signal-to-noise ratio is rather low, that is, in case of low stimulus salience. This assumption is reflected in the interactive pattern of results obtained for N2pc onset latency in the current study: the effect of temporal preparation was larger in the small setsize condition than in the large setsize condition. The idea that temporal preparation might change the signal-to-noise ratio in visual processing is consistent with the results of previous studies investigating temporal preparation in the context of perceptual discrimination tasks. Here, it has been shown that temporal preparation facilitates visual stimulus processing to a larger extent when stimulus processing is difficult, for instance, when a mask is superimposed on the stimulus (Rolke, 2008) or when stimulus contrast is lowered (Jepma et al., 2012, Experiment 2). So, it appears that the influence of temporal preparation on stimulus processing is stronger when target quality is low and there is sufficient room for an improvement of perceptual processing. One line of evidence that this improvement might be accomplished by a change of the signal-to-noise ratio has been provided by Bausenhart et al. (2010). These authors examined the influence of temporal

---

[4] We thank Heinrich R. Liesefeld for suggesting this alternative possibility.

preparation on different components of decision processes by means of speed-accuracy trade-off (SAT) functions. One result was that temporal preparation led to an earlier onset of the SAT function suggesting that temporal preparation reduced the time required for stimulus encoding. In addition, and important for the interpretation of the present results, temporal preparation increased the asymptote of the SAT function, which suggests that it improved overall stimulus discriminability over and above its initial effect on stimulus encoding. From a theoretical perspective, this latter result can be explained in terms of an increase in the signal-to-noise ratio (see Bausenhart et al., 2010). Summarized, the results of Bausenhart et al. (2010) support our interpretation of the ERP results in the current study, that is, that temporal preparation may operate on stimulus processing via first, an acceleration of early visual processing and second, an increase in the signal-to-noise ratio. Even though an account which assumes that temporal preparation operates via two mechanisms provides a straightforward explanation for why the effects of temporal preparation and stimulus salience interact during spatial selection (as reflected by the N2pc), but not during early visual processing (as reflected by the N1), this pattern of results could, in principle, be explained in terms of one single mechanism as well. According to this alternative account, temporal preparation exclusively accelerates early visual processing, and this effect simply propagates to the process of spatial selection. The additive effect of temporal preparation might turn into an interactive effect if one makes the assumptions that firstly, spatial selection is a discrete step which has a minimum constant onset latency and, secondly, the time point at which spatial selection starts is influenced by stimulus salience (Bachman et al., 2020; Gaspar & McDonald, 2014; Töllner et al., 2011). In principle, the acceleration of early visual processing by temporal preparation should add up to the effect of stimulus salience, and both should accelerate spatial selection. However, because the time point of spatial selection might be already close to the minimum onset latency for highly salient targets, the additional gain in selection speed being caused by temporal preparation might be smaller for highly salient targets than for low salient ones. This, in turn, would be reflected in an interaction between FP and setsize on the onset latency of the N2pc, as observed in our study. Since both accounts would lead to the same result pattern in our experimental setup, we cannot dissociate between them on grounds of the present study. Importantly, however, this does not change the interpretation of our main finding: irrespective of which specific process is facilitated by temporal preparation, the observation that temporal preparation interacts in its effect with stimulus salience clearly argues in favour of the idea that temporal preparation influences bottom-up processing in spatial selection. In summary, the present study shows that the beneficial effect of temporal preparation on the N2pc, as an indicator of spatial selection of the target, was stronger when the target's salience was low than when it was high. This result together with the facilitating effect of temporal preparation on the N1, suggests that temporal preparation influences bottom-up processing and thereby increases the efficiency of spatial selection.

3.4 Experimental procedure

3.4.1 Participants

Thirty-six healthy subjects, mainly students of the University of Tuebingen, participated either for payment (30 €) or course credits. In accordance with the 2013 Declaration of Helsinki by the World Medical Association, all participants gave written informed consent before the experiment. The overall study protocol had been approved by the ethics committee of the Faculty of Science (University of Tuebingen). Eight participants were excluded from the data analysis due to excessive blink artefacts (see below); four participants were excluded due to an undetectable N2pc. All participants reported to have normal or corrected-to-normal vision as well as normal colour vision. The final sample consisted of 24 participants (seven male, all right-handed, mean age = 21.87 years[5], age range = 19–31 years). Based on a sensitivity analysis using MorePower 6.0 (Campbell & Thompson, 2012), this sample size should provide 80 % power for detecting an effect size of $\eta_p^2 = 0.27$ in a 2 × 2 repeated-measures ANOVA (significance level $\alpha = 5$ %).

---

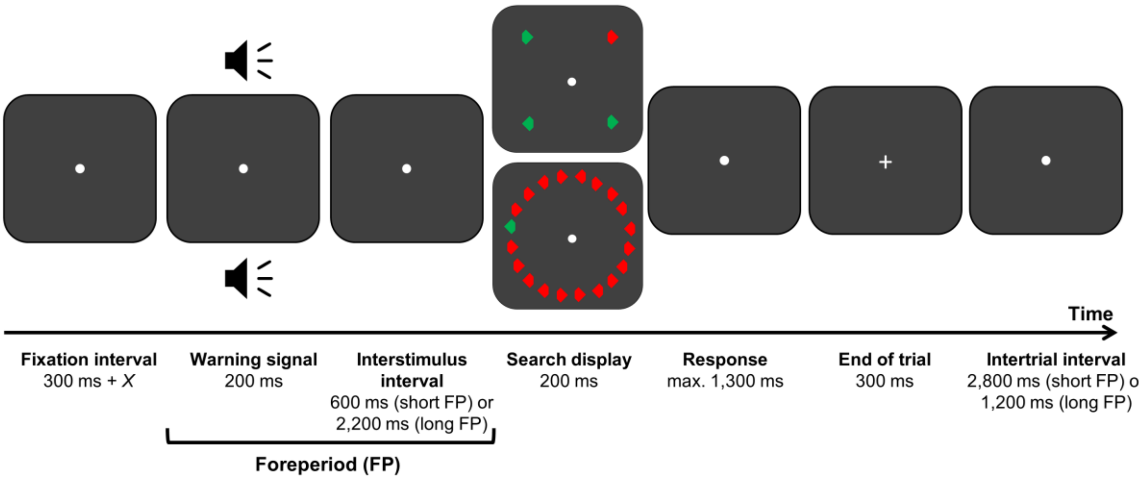
[5] Due to a computer crash, the age information for one participant was not saved correctly. The mean age is therefore calculated on grounds of the remaining participants (*N* = 23).

3.4.2 Apparatus and stimuli

Stimulus presentation was controlled by Experimental Runtime System (BeriSoft, Frankfurt am Main, Germany), running on a standard DOS computer. Visual stimuli were presented on a 20-inch CRT monitor. The viewing distance was fixed to 57 cm via a chin rest. Auditory stimuli were presented via loudspeakers left and right to the screen. An 800-Hz sine tone (SPL approximately 60 dB) served as warning signal. All visual stimuli were displayed on a black background (RGB: 0, 0, 0; luminance: less than 0.01 cd/m^2). The search display was adapted from Mazza et al. (2007). It consisted of four or 20 equally distant diamonds (size: 1.1◦ × 0.9◦ of visual angle). The diamonds were presented on an imaginary circle of 5◦ of visual angle

Figure 3-3

Schematic illustration of the trial procedure



Note. At trial onset, a fixation point appeared at the center of the screen. An auditory warning signal, presented for 200 ms, marked the onset of a foreperiod (FP) of either 800 or 2,400 ms (short or long FP condition). Upon termination of the FP, the search display was displayed for 200 ms. It consisted of a pop-out colour target surrounded by either three or 19 homogenously coloured distractors (4 elements or 20 elements condition, respectively). Participants' task was either to report the display side where the target was presented (localization task) or to indicate the side of the target that was cut away (discrimination task). The end of each trial was marked by the appearance of a cross at fixation for 300 ms. After a variable intertrial interval, the next trial started.

arranged around a white fixation point (RGB: 256, 256, 256; luminance: 76 cd/m^2; size: 0.2° × 0.2° of visual angle), which was presented at the screen center. The fixation point was replaced by a white cross (diameter: 0.5° × 0.5° of visual angle) to indicate the end of each trial. The target was a pop-out in the dimension colour, that is, a red diamond (RGB: 210, 33, 33; luminance: 8 cd/m^2) among green diamonds (RGB: 51, 138, 51; luminance: 8 cd/m^2) or vice versa. The target could appear at one of 12 positions on the imaginary circle (except for the four positions on the top and the bottom of the imaginary circle). The three or 19 distractors were distributed uniformly to the remaining positions. Each diamond had a 0.2° corner cut on its left or right side. Participants responded with their right index and middle fingers by pressing one of two keys on a custom-made response device allowing for low-latency RT measurement. The response device was positioned in front of the participant so that the two keys could easily be operated with the right hand.

3.4.3 Procedure

The trial procedure is illustrated in Fig. 3. The fixation point was presented for 300 ms plus a variable interval, which was included to maximize temporal uncertainty and stress the importance of the warning signal. The variable interval was drawn from an exponential random function and rounded to ms, with a mean of 1,000 ms (min = 0 ms, max = 12,500 ms). Then, the auditory warning signal was presented for 200 ms, followed by an inter-stimulus interval (ISI) of 600 ms (short FP block) or 2,200 ms (long FP block). After the ISI, the search display was presented for 200 ms, followed by a response interval of 1,300 ms in which only the fixation point was presented on the screen. The end of each trial was indicated by replacing the fixation point with a white cross for 300 ms. During practice trials, an error feedback was given on incorrect responses by presenting the German word ‘Fehler!’ (‘Error!’) above the white cross for 300 ms. Before the onset of the next trial, an inter-trial interval of 1,200 ms was presented. In case of a short FP block, an interval of 1,600 ms was added to the inter-trial interval to keep the overall block length comparable for the two FP conditions (see Bausenhart et al., 2007). An experimental session lasted about 3.5 h. Participants were seated in a comfortable chair in a dimly lit, soundproof chamber. After application of the electroencephalogram (EEG), participants first received oral and written task instructions. During one half of the experiment, participant performed a localization task and indicated whether the target appeared on the left or right display side. In the other half of the experiment, participants performed a discrimination task and indicated whether the left or right corner of the target was cut away. Before the start of each experimental half, participants went through two practice blocks with 16 trials each (one block for each FP) to familiarize themselves with the task at hand (i.e., localization or discrimination). Participants were instructed to respond as fast and as accurately as possible. Furthermore, they were advised to use the warning signal in an active manner to prepare for the temporal occurrence of the search display. To minimize artefacts in the EEG being caused by eye movements, participants were encouraged to keep fixation throughout each trial and to restrict blinks and other eye-movements to the inter-trial interval and the breaks between blocks. Participants were given accuracy feedback (percentage of correct responses) at the end of each block, and they were encouraged to take a short break. Participants completed 768 experimental trials in total, corresponding to 96 trials in each of the eight experimental conditions (FP × setsize × task). The experimental trials were presented in 16 blocks of 48 trials each. Setsize (4 or 20 elements), target colour (red or green), the target's missing corner (left or right), the side of the search display containing the target (left or right) as well as the target position (six possible positions on each side of the search display), varied randomly within blocks. The FP (short or long) changed after every second block, whereas the task (localization or discrimination) changed after one half (i.e., eight blocks) of the experiment. The order of the two FPs (short – long or long – short) and the order of the two tasks (localization – discrimination or discrimination – localization) were counterbalanced across participants.

3.4.4 EEG recording

The EEG was recorded via a BIOSEMI Active Two amplifier system with standard Ag/AgCl electrodes from 26 electrode positions according to the extended 10–20 (10–10) system (i.e., electrode positions Fpz, Fp1, Fz, F3/F4, F7/F8, FC3/4, Cz, C3/C4, T7/T8, Pz, P3/P4, P7/P8, PO3/4, PO7/8, Oz, and O1/O2; see American Electroencephalographic Society, 1994). The horizontal electro-oculogram (hEOG) was recorded via electrodes placed at the outer canthi of each eye; the vertical electro-oculogram (vEOG) was recorded via an electrode placed below the left eye and the electrode at position Fp1. Two additional electrodes (Common Mode Sense active electrode and Driven Right Leg passive electrode) served as ground and on-line reference electrode (cf. www. biosemi/faq/cms&drl.htm). Two electrodes placed on the left and right mastoid were used for off-line re-referencing. The EEG and the EOG were recorded with a sampling rate of 512 Hz (amplifier bandpass: DC–100 Hz).

3.4.5 Data analysis

All ERP preprocessing steps were performed in Brain Vision Analyzer 2 (Brain Products, Herrsching, Germany), and the statistical analyses were performed in JASP (Version 0.11.1) and Matlab (MathWorks R2019b). We conducted repeated-measures analyses of variances (rmANOVAs) to examine the effect of FP, setsize, and task on RT, accuracy, and on N1 and N2pc amplitudes and onset latencies. Furthermore, we conducted one-sample *t*-tests against zero to determine the presence of a reliable N2pc. As measures of effect size, we report η_p^2 for significant effects in rmANOVAs.

Behavioral data

Practice trials were excluded from the analysis of behavioral data. Furthermore, trials with incorrect responses and trials with RTs that deviated more than 2.5 *SD* from the mean of each participant in each FP condition (*M* = 2.65 %) were excluded from the RT analysis (for similar outlier criteria see, e.g., Balke et al., 2021; Rolke et al., 2016). Separate rmANOVAs with the factors FP (short or long), setsize (4 or 20 elements), and task (localization or discrimination) were then conducted on mean RT and mean error rate.

ERP data

Practice trials and trials with incorrect responses were excluded from the ERP analysis. All electrodes were re-referenced offline to the average of the left and right mastoid. To reliably detect horizontal and vertical eye movements, bipolar EOG channels were calculated from the two hEOG and the two vEOG channels, respectively. A Butterworth Zero Phase filter (cut-off values of 0.1 and 30 Hz for high-pass and low-pass filtering, respectively; slope: 12 dB/oct) was applied to both EEG and EOG channels. Then, the data of all channels were segmented into epochs ranging from -200 ms to +600 ms relative to the onset of the search display. The interval from -200 ms to 0 ms relative to the onset of the search display served as the pre-stimulus baseline. Analogous to previous ERP studies in the context of visual search (e.g., Barras & Kerzel, 2017; Brisson et al., 2009; Feldmann-Wüstefeld & Schubö, 2016; Seibold & Rolke, 2014b), we used an absolute threshold for artifact rejection. Specifically, segments affected by vertical eye movements (vEOG exceeding ± 80 µV), horizontal eye movements (hEOG exceeding ± 30 µV) or any other artifacts (voltage exceeding ± 80 µV at any other electrode) were excluded from the analysis. Participants for whom less than 50% of the trials in one experimental condition (i.e., less than 48 trials) were left after artifact rejection were excluded (*N* =

8). The average of segments that remained after artifact rejection was comparable between the two FP conditions (i.e., 83.5 % for the short FP and 83.3 % for the long FP condition). For the analysis of the N1, we averaged the retained segments for each participant and each combination of FP (i.e., short or long), setsize (i.e., 4 or 20 elements), and task (i.e., localization or discrimination). N1 amplitude and latency was quantified at a posterior electrode pool (i.e., pooled electrodes O1, O2, Oz, P3, P4, PO3, PO4, PO7, PO8, POz, Pz, P7 and P8) where discriminative processes in the N1 are typically measured (Hopf et al., 2002; Luck & Hillyard, 1995; Vogel & Luck, 2000). For the analysis of the N2pc, we separated the retained segments for left and right targets for each participant. As previous studies have already shown that the N2pc does not vary as a function of the task (i.e., localization or discrimination; e.g., Mazza et al., 2007; Töllner et al., 2012, 2013), we conducted a pre-planned control analysis in order to check whether the N2pc in our study was affected by task. Specifically, we analyzed the effect of all three experimental factors (i.e., task, FP, and setsize) on N2pc amplitude and onset latency. Replicating previous studies, we did not observe any effect of task or interactions of task with other factors on the N2pc.[6] Therefore, for our main analysis we averaged across the factor task and we calculated the contra-minus ipsilateral ERP difference wave at electrode sites PO7/8 and PO3/4 for each combination of FP (i.e., short or long) and setsize (i.e., 4 or 20 elements). Analogous to previous studies (e.g., Balke et al., 2021; Feldmann-Wüstefeld & Schubö, 2016; Heuer & Schubö, 2020), we averaged the resulting ERP difference wave over the two electrodes sites to optimize the signal-to-noise ratio for the measurement of N2pc onset latency. N1 and N2pc amplitudes were estimated via peak-centered mean amplitude (time window: ± 25 ms around peak latency), which is advantageous in case an experimental variable affects ERP latency in addition to ERP amplitude as being reported in previous FP studies (Balke et al., 2021; Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014b). We used an automatized peak-picking algorithm (as implemented in Brain Vision Analyzer 2) using a local maximum criterion for peak detection. To get appropriate time windows for peak detection that are not biased

---

[6] In this pre-planned control analysis, we conducted separate three-way rmANOVAs with factors task (localization or discrimination), FP (short or long), and setsize (4 or 20 elements) for N2pc amplitude and N2pc onset latency. These analyses did not reveal main effects of task on N2pc amplitude, $F(1, 23) = 0.90$, $p = .35$, or on N2pc onset latency, $F_C(1, 23) = 0.54$, $p = .47$, nor did they reveal any interactions of the factor task with other factors (N2pc amplitude: all *p*s > .47; N2pc onset latency: all *p*s > .28).

towards specific experimental conditions, we determined the respective time-windows for N1 and N2pc peak detection in the grand-average ERP across all participants and all experimental condition (see Luck & Gaspelin, 2017). This approach resulted in time windows of 110–200 ms for measurement of the N1, and 150–320 ms for measurement of the N2pc. In addition to N1 and N2pc amplitude, we determined N1 and N2pc onset latency. For this purpose, we used the jackknife approach (Miller et al., 1998) in combination with an absolute amplitude criterion. We chose an absolute amplitude criterion instead of a relative one because the former one is less affected by large amplitude differences that may exist between experimental conditions (see Seiss et al., 2009). Specifically, in case of large amplitude differences between experimental conditions – as it is the case for the two setsize conditions in our study (see Figs. 1 and 2) – a relative amplitude criterion can lead to an overestimation of onset latency for large-amplitude components and thus to an underestimation of the true latency differences between conditions (Seiss et al., 2009). To ensure that the chosen absolute criterion appropriately captured the N2pc for all participants and experimental conditions, we determined ERP onset latency via an iterative procedure. In a first step, we defined a starting value of –5.00 µV for the N1 and of –0.50 µV for the N2pc based on the grand average ERP in that specific setsize condition in which the ERP component was smallest (i.e., the 20 elements condition for the N1 and the 4 elements condition for the N2pc). In a second step, we iteratively lowered this starting value in steps of + 0.05 µV until a corresponding ERP amplitude value was detectable in the jackknifed ERPs for all experimental conditions and all participants. This procedure resulted in absolute onset criteria of –3.85 µV for the N1 and –0.45 µV for the N2pc. Finally, we conducted separate two-way rmANOVAs on N2pc amplitude and onset latency with the factors FP and setsize as well as separate three-way rmANOVAs on N1 amplitude and onset latency with the factors task, FP and setsize. For all jackknife-based analyses, we corrected the resulting *F*-values using the formula $F_C = F / (n - 1)^2$, where F_C denotes the corrected *F*-value, and *n* denotes the number of participants (see Ulrich & Miller, 2001). Furthermore, we corrected the corresponding effect size η_p^2 using the formula $\eta_p^2{}_C = F_C \times df_{effect} / (F_C \times df_{effect} + df_{error})$, where $\eta_p^2{}_C$ denotes the corrected η_p^2 value, df_{effect} denotes the degrees of freedom for the effect, and df_{error} denotes the degrees of freedom for the error.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the German Research Foundation (DFG; grant number SE2576/1-1). We thank Meret Häusler and Melina Häßler for their assistance in data acquisition. Furthermore, we thank Heinrich R. Liesefeld and another anonymous reviewer for their helpful suggestions on a previous version of this manuscript.

The following chapter (Chapter 4) consists of a paper which was published in *Biological Psychology* in 2021 and which was co-authored by Prof. Dr. Bettina Rolke and Dr. Verena C. Seibold. The numbering of the footnotes has been adjusted and the numbering of the figures and the headlines has been supplemented with the chapter number.

The official citation that should be used in reference to the following chapter is:

Balke, J., Rolke, B., & Seibold, V. C. (2021). Reduction of temporal uncertainty facilitates stimulus-driven processes in spatial selection. *Biological Psychology*, *159*, 108028. https://doi.org/10.1016/j.biopsycho.2021.108028.

4. Study 3: Reduction of temporal uncertainty facilitates stimulus-driven processes in spatial selection

Abstract

Previous studies have shown that the reduction of temporal uncertainty facilitates target selection in visual search. We investigated whether this beneficial effect is caused by an effect on stimulus-driven processes or on goal-driven processes in spatial selection. To discriminate between these processes, we employed a visual search task in which participants searched for a shape target while ignoring a color singleton distractor. As an index of stimulus-driven processes, we measured the N2pc evoked by the singleton distractor (N_D). As indices of goal-driven processes, we measured the N2pc evoked by the target (N_T) and the distractor positivity (P_D) evoked by the singleton distractor, respectively. We observed that reducing temporal uncertainty modulated the amplitude of N_D and the onset latency of the N_T, but did not modulate the amplitude of the P_D. These results are consistent with the view that a reduction of temporal uncertainty influences non-selective, stimulus-driven processes in spatial selection.

4.1 Introduction

Preparation is an important cognitive capability that enables humans to act in a flexible way in a constantly changing environment. Although preparation can basically refer to different aspects of upcoming events (i.e., what kind of event will happen or where it will happen; see, e.g., Leuthold e al., 2004; Requin et al., 1991), one of its core facets is *temporal preparation*, that is, the preparation for *when* an event will happen.[7] This type of preparation enables us to optimize our limited window of

---

[7] In the literature, the term *temporal preparation* has sometimes been used interchangeably with the term *alertness*. Yet, from our viewpoint, alertness and temporal preparation can be dissociated both conceptually and empirically from each other: First, whereas the concept of temporal preparation refers to the built-up of a temporal expectancy and preparation for a specific moment in time (e.g., Bausenhart et al., 2007; Rolke & Ulrich, 2010), alertness refers to a general increase in response readiness that has been closely related to an increase in arousal rather than temporal expectancy (e.g., Posner & Petersen, 1990; Weinbach & Henik, 2013). Second, studies including different experimental methods such as computational modelling approaches (Petersen et al., 2017; Vangkilde et al., 2012), functional imaging (Hackley et al., 2009), and conflict tasks (e.g., Weinbach & Henik, 2013) suggest that temporal

attention (Joseph et al., 1997; Shaw & Shaw, 1977) by focusing on those specific time points when relevant stimuli will most likely occur (Miniussi et al., 1999). The exact mechanisms that underlie temporal preparation are still debated; nonetheless, experimental research has provided convincing evidence that temporal preparation influences already perceptual processing of stimuli (Bausenhart et al., 2006; Correa et al., 2006; Müller-Gethmann et al., 2003; Rohenkohl et al., 2012; Rolke & Hofmann, 2007; Seibold & Rolke, 2014b; for a recent review, see Nobre & van Ede, 2018). In the present study, we investigated how temporal preparation influences spatial selection of visual stimuli.

In general, temporal preparation has been investigated using different experimental approaches (Coull & Nobre, 1998; Lange & Röder, 2006; Niemi & Näätänen, 1981; Sanabria et al., 2011). For instance, in the so-called temporal cueing paradigm, a symbolic cue provides explicit information about the likely temporal occurrence of an imperative stimulus (see, e.g., Correa et al., 2004; Griffin et al., 2001; Rohenkohl & Nobre, 2011). The typical observation in this paradigm is that participants respond faster and more accurate to the imperative stimulus if the temporal information provided by the cue is correct (valid) than if it is incorrect (invalid). This finding is explained in terms of a process of temporal orienting of attention. Specifically, it is assumed that participants use the explicit information provided by the cue to voluntarily orient attention towards the expected moment in time (e.g., Correa et al., 2004; Coull & Nobre, 1998; Miniussi et al., 1999).

Apart from paradigms that rely on explicit temporal information to study temporal preparation, there are also paradigms in which temporal preparation is varied rather implicitly. This rather implicit manipulation is implemented, for instance, in the so-called foreperiod (FP) paradigm, in which a warning signal is presented before an imperative stimulus, and the time interval between both stimuli – the FP – is varied (see, e.g., Klemmer, 1956; Los & Van den Heuvel, 2001; Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Sanders, 1966, 1975; Steinborn et al., 2008; Woodrow, 1914). In the focus of the present study is one variant of the FP paradigm: the so-called *constant FP paradigm*. In this paradigm, the FP is kept constant within a block of trials but varies across blocks of trials so that participants can learn to estimate the temporal

---

preparation and alertness exert dissociable effects on stimulus processing. From this perspective, we think that the term temporal preparation is more appropriate in this context than the term alertness.

occurrence of the imperative stimulus. The classical finding in this paradigm is that reaction time (RT) is shorter following a short FP (e.g., 800 ms) than a long one (e.g., 2,400 ms; Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Woodrow, 1914). This finding is explained in terms of a direct relationship between FP length and temporal uncertainty (Klemmer, 1956; Niemi & Näätänen, 1981). Specifically, it is assumed that participants' temporal estimates are more precise for shorter than for longer time intervals due to an imperfect time-keeping ability (Gottsdanker, 1975; Näätänen & Merisalo, 1977; Treisman, 1964). Consequently, temporal uncertainty is reduced for short FP blocks in comparison to long FP blocks.

Experimental studies have generally shown that this reduction of temporal uncertainty does not only affect the speed of responding – as indexed by RT (e.g., Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981; Woodrow, 1914) – but also the accuracy of responding (e.g., Bausenhart et al., 2007; Rolke, 2008; Rolke & Hofmann, 2007). For instance, Rolke (2008) has shown that perceptual sensitivity in discriminating masked stimuli is higher if participants can anticipate the occurrence of these stimuli. Furthermore, researchers measuring the dynamics of stimulus processing by means of event-related potentials (ERPs) have shown that the reduction of temporal uncertainty does not only lead to an earlier onset of the stimulus-locked lateralized readiness potential (e.g., Hackley et al., 2007; Müller-Gethmann et al., 2003; Seibold & Rolke, 2014b), an ERP index of the duration of pre-motoric processes (e.g., Smulders & Miller, 2012), but even modulates early ERPs such as the visual and auditory N1 (Hackley et al., 2007; Rolke et al., 2016; Seibold, et al., 2011; Seibold & Rolke, 2014b). These results have led to the notion that temporal uncertainty directly affects stimulus perception (e.g., Rolke & Ulrich, 2010).

Following this notion of a perceptual processing effect, more recent studies have focused on the question whether temporal uncertainty also influences selective processes within stimulus perception. Here, the underlying idea is that the reduction of temporal uncertainty may not only facilitate perceptual processing in a non-specific manner, but may specifically facilitate selective processes that privilege some stimuli over others, based on, for instance, their spatial position or specific stimulus features. One straightforward approach to this question is to investigate the effect of temporal uncertainty in visual search (Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014a, 2014b). In this type of task, a task-relevant visual stimulus (the target) must be selected from competing visual stimuli (the distractors) by means of spatial attention (for reviews, see, e.g., Eckstein, 2011; Theeuwes, 2014; Wolfe, 2010). For instance, in a study by Seibold and Rolke (2014b) participants had to select a target that differed from the distractors in its unique color (pop-out search). To investigate the effect of temporal uncertainty on spatial selection of the target, the authors measured the effect of a constant FP manipulation (with FPs of 800 and 2,400 ms) on the N2posterior-contralateral (N2pc). This ERP component is characterized by a lateralized voltage difference over posterior electrode sites that typically arises within 200–300 ms after search display onset. Due to its time-course and its topography, the N2pc has been linked to spatial selection of target (or target-similar) stimuli (for reviews, see, e.g., Eimer, 2014; Luck, 2012). Comparing the N2pc between the two FP conditions, Seibold and Rolke (2014b) observed that the N2pc evoked by the target arose earlier and was more pronounced when temporal uncertainty was low (i.e., in the 800-ms FP condition). This basic finding of a modulation of the N2pc has also been reported in other studies (Hackley et al., 2007; Rolke et al., 2016), and suggests that the reduction of temporal uncertainty may not only facilitate stimulus perception in general, but may also affect spatially selective processing.

From the viewpoint of theories on selective attention (e.g., Fecteau & Munoz, 2006) and visual search (e.g., Found & Müller, 1996; Wolfe, 1994), this effect of temporal uncertainty corresponds to an enhancing effect on stimulus processing (e.g., Wolfe, 1994). Importantly, however, the specific mechanisms that underlie this enhancement are still unclear. In principle, enhanced target processing, as reflected in a more pronounced N2pc in the short FP condition (Hackley et al., 2007; Seibold & Rolke, 2014b), can be attributed to two different processes: *stimulus-driven* processes and *goal-driven* processes (e.g. Connor et al., 2004; Folk & Remington, 2008; Found & Müller, 1996; Wolfe, 1994; for reviews, see, e.g., Chan & Hayward, 2013; Fecteau & Munoz, 2006; Theeuwes, 2010; Wolfe, 2010). Stimulus-driven processes, on the one hand, refer to bottom-up processes that guide spatial attention towards stimuli depending on their salience, that is, their local contrast (or distinctness) in basic features relative to their surround. For instance, a stimulus that has a unique color (i.e., a color that differs from that of all other stimuli) has a higher local contrast in the dimension color than other stimuli and is therefore more likely to be selected by spatial attention. In line with this assumption, ERP studies including a manipulation of stimulus salience have revealed a larger N2pc for more salient stimuli (e.g., Mazza et al., 2009; Töllner et al., 2011).

Goal-driven processes, on the other hand, refer to top-down controlled processes that operate via a weighting process and are directly dependent on the actual goal or task of a participant. For instance, if the participant searches for a target that is defined by a specific feature (e.g., red) or dimension (e.g., color), the respective feature or dimension will be up-weighted, which will then increase the likelihood that the target is selected by spatial attention (or subjected to enhanced processing). Importantly, this goal-driven up-weighting of features or dimensions is also reflected in the amplitude of the N2pc: For instance, a larger N2pc has been observed for targets associated with a higher reward (Kiss et al., 2009) as well as distractors that possess a target feature (Seiss et al., 2009, Experiment 1). Furthermore, and in addition to enhancement, goal-driven processes also entail a suppression or down-weighting of features (or dimensions) that are associated with distractors (see Sawaki & Luck, 2010; see also Gaspelin & Luck, 2018). Due to this additional process, distractors will either not be selected by spatial attention at all, or – in case they have been selected – they will be quickly suppressed (see, e.g., Feldmann-Wüstefeld & Schubö, 2013, 2016; Liesefeld et al., 2017). In the ERP, this process of distractor suppression is reflected in the emergence of the so-called distractor positivity (P_D), a contralateral positivity relative to a salient distractor (Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2013, 2016; Hickey et al., 2009; see Luck, 2014, for a short review).

On grounds of this theoretical distinction between stimulus-driven and goal-driven processes, we aimed at investigating how the reduction of temporal uncertainty facilitates spatial selection, as reflected in a larger N2pc in the study of Seibold and Rolke (2014b). More specifically, we wanted to clarify whether a reduction of temporal uncertainty specifically enhances task-relevant stimuli (which would correspond to a goal-driven enhancement) or whether it enhances processing of task-irrelevant stimuli as well (which would correspond to a stimulus-driven enhancement). In addition, we also examined for the first time whether temporal uncertainty may influence suppression, as another important component of goal-driven selection. For this purpose, we employed a visual search task that has already been used successfully in a previous study (Feldmann-Wüstefeld & Schubö, 2016) to separate these processes. Participants were asked to search for a singleton target differing in one feature dimension (i.e., its orientation) from all other stimuli and to discriminate its specific value on that dimension (i.e., whether it was tilted towards the left or right). At the same time, participants had to ignore an additional singleton which differed from all other stimuli in another feature dimension (i.e., its color). This specific task setup enabled us to measure both goal-driven and stimulus-driven contributions in spatial selection: Specifically, spatial selection of the target is determined by goal-driven processes (i.e., because the orientation value “tilt” is task-relevant and should receive a higher weight), and, potentially, also by stimulus-driven processes (i.e., because a unique orientation may be a pop-out by itself). In contrast, spatial selection of the singleton distractor should be determined by stimulus-driven processes only (i.e., because a unique value on the dimension color – despite being task-irrelevant – should result in a high salience value and, therefore, cause the distractor to pop out from its surround). Finally, on grounds of the notion that goal-driven processes also entail distractor suppression (e.g., Gaspelin & Luck, 2018), stimulus-driven spatial selection of the singleton distractor should be followed by goal-driven suppression.

To uncover the contribution of stimulus-driven and goal-driven processes to spatial selection in our study, we measured lateralized ERPs and systematically varied the position of the target and the color distractor. Specifically, in order to replicate the basic effect of temporal uncertainty on the N2pc (e.g., Seibold & Rolke, 2014b), we measured the N2pc evoked by the target (which we refer to as N_T) as an index of spatially selective processing of the target. For this purpose, we included a condition in which only the target was presented laterally, whereas the distractor was presented on the vertical midline (target-lateral condition). Furthermore, we measured the distractor-evoked N2pc (which we refer to as N_D) as an index of spatially-selective processing of salient distractors (Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2016; Hickey et al., 2006). For this purpose, we included a condition in which the target was presented on the vertical midline and the color distractor was presented at a lateral position (distractor-lateral condition). Importantly, because color in our study was not a task-defining dimension, spatially selective processing of the singleton distractor, as indexed by the N_D, should mainly reflect the contribution of stimulus-driven processes, independent of the top-down task set (Hickey et al., 2006; Theeuwes, 1992; see also Theeuwes, 2010). Furthermore, and as outlined above, spatially selective processing of the singleton distractor is terminated by goal-driven, active suppression (e. g., Gaspelin & Luck, 2018; Sawaki & Luck, 2010). In our study, this should be reflected in the emergence of a P_D in the distractor-lateral condition (Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2013, 2016; Hickey et al., 2009).

With respect to the effect of temporal uncertainty on spatial selection, we expected different outcomes depending on whether it influences stimulus-driven or goal-driven processes. First, if temporal uncertainty operates via stimulus-driven enhancement, its effect should translate into a processing advantage for salient stimuli (i.e., stimuli with a higher stimulus contrast). In the context of our study, this means that temporal uncertainty should affect both spatial selection of the target and the singleton distractor, because both stimuli are singletons in a certain dimension (i.e., orientation and color). Therefore, the reduction of temporal uncertainty should modulate both the amplitude of the N_T and the N_D in a way that both event-related lateralizations (ERLs) are more pronounced in the short FP condition than in the long FP condition. In contrast, if temporal uncertainty operates via goal-driven enhancement, only spatial selection of the target should be affected, whereas spatial selection of the singleton distractor should remain unaffected. In this case, the N_T should be more pronounced in the short FP condition than in the long FP condition, whereas no amplitude modulation should be observed for the N_D. Second, if temporal uncertainty operates via goal-driven distractor suppression, this should be reflected in the P_D in our study. That is, the P_D should be more pronounced in the short FP condition than in the long FP condition. Finally, to control for the effectiveness of our manipulation and to additionally measure potential effects of temporal uncertainty on early visual processing (see, e. g., Rolke et al., 2016), we also measured FP effects on RT and the visual N1, which provides an index of early visual processing (Luck, 2014). In this respect, we expected to observe the basic constant FP effect on RT, that is, shorter RT in the short FP condition than in the long FP condition (see, e.g., Müller-Gethmann et al., 2003). Furthermore, we expected to observe a more pronounced N1 in the short FP condition than in the long FP condition (see, e.g., Rolke et al., 2016; Seibold & Rolke, 2014b).

4.2 Method

4.2.1 Participants

Thirty-two healthy volunteers, mainly students of the University of Tuebingen, participated either for payment (30 €) or course credits. In accordance with the 2013 Declaration of Helsinki by the World Medical Association, all participants gave written informed consent before the experiment. The overall study protocol had been approved by the ethics committee of the Faculty of Science (University of Tuebingen).

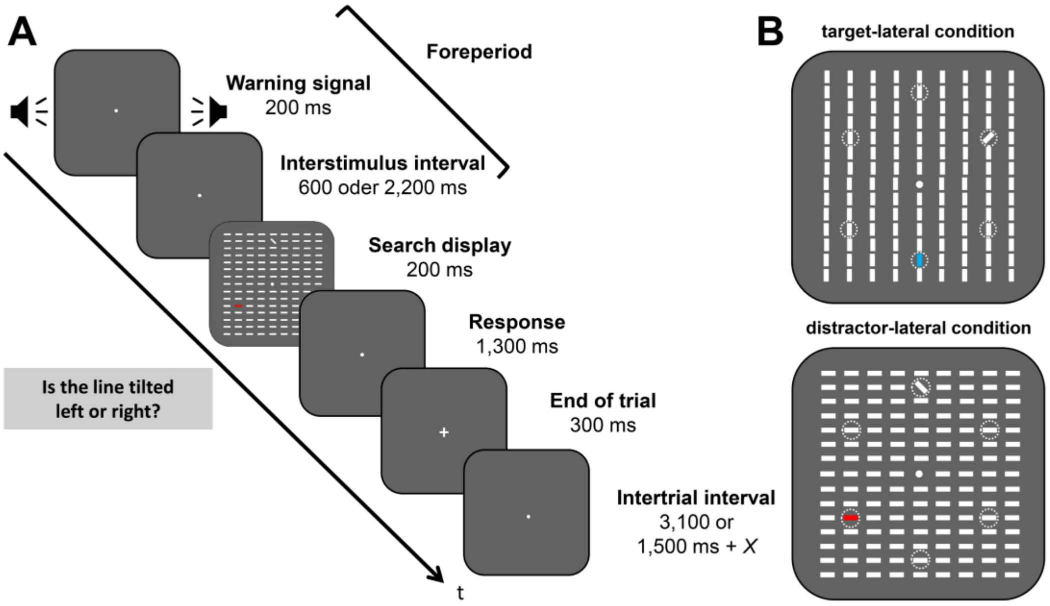
Six participants were excluded from the analysis due to excessive blink artefacts (see below); two participants were excluded because of excessive alpha activity and a not detectable N2pc. The final sample consisted of 24 participants (nine male, all right-handed, mean age = 21.96 years, age range = 18–30 years). The resulting sample size is comparable to the sample sizes in previous ERP studies investigating the FP effect on spatial selection (i.e., Rolke et al., 2016; Seibold & Rolke, 2014b) and ERP studies on visual search with similar stimuli and search tasks (Feldmann-Wüstefeld & Schubö, 2013, 2016; Liesefeld et al., 2017). Based on a formal sensitivity analysis using G*Power (Faul et al., 2007), this final sample size should provide 80 % power for detecting an effect size of $d_Z = .60$ in a two-tailed dependent *t*-test, which would correspond to a n_p^2 of approximately .26 in a one-way repeated-measures ANOVA (see Brysbaert, 2019, p. 12, on how to estimate n_p^2 from d_Z). All participants reported to have normal or corrected-to-normal vision and no color blindness.

4.2.2 Apparatus and stimuli

Stimulus presentation was controlled by Experimental Runtime System (BeriSoft, Frankfurt am Main, Germany), running on a standard DOS computer. Visual stimuli were presented on a standard 20-inch CRT monitor. The viewing distance was fixed to 57 cm via a chin rest. Auditory stimuli were presented via loudspeakers left and right to the screen. A 800-Hz sine tone (SPL approximately 60 dB) served as warning signal. All visual stimuli were displayed on a dark background (grey RGB: 133, 133, 133, luminance: 9 cd/m2). A small white dot (diameter: 0.1◦ × 0.1◦ of visual angle; RGB: 256, 256, 256; luminance: 72 cd/m2), presented at the center of the screen, served as fixation point. The fixation point was replaced by a white cross (diameter: 0.3◦ × 0.3◦ of visual angle) to indicate the end of each trial. The search display was adapted from Feldmann-Wüstefeld and Schubö (2016): It consisted of 458 white lines (size: 0.1◦ × 0.7◦ of visual angle) arranged in a 27 × 17 matrix (size: 27.3◦ × 16.5◦ of visual angle) with the middle position replaced by the fixation point. The distractors were either horizontally or vertically aligned lines. Each search display contained a target as well as a singleton distractor. The target was an orientation singleton, that is, a line that was tilted 45◦ either to the left or to the right. The singleton distractor was a color singleton, that is, a horizontal or vertical line that was colored either in red (RGB: 233, 33, 33; luminance: 10 cd/m2) or in blue (RGB: 108, 100, 256; luminance: 10 cd/m2). The target and the singleton distractor were positioned on two of six matrix positions on an imaginary circle with a radius of 6◦ of visual angle around the fixation

Figure 4-1

Schematic illustration of the trial procedure (A) and the search display (B)



Note. Left panel (A): Schematic illustration of the trial procedure. At trial onset, a fixation point appeared at the center of the screen. An auditory warning signal, presented for 200 ms, marked the onset of a foreperiod (FP) of either 800 or 2,400 ms. Upon termination of the FP, the search display was displayed for 200 ms. It consisted of 458 lines arranged in a 27 × 17 matrix. Except for the target and the singleton distractor, all lines were white and oriented either horizontally or vertically. The target differed in its orientation from the other items (i.e., being tilted either 45◦ to the left or to the right), whereas the singleton distractor differed in its color (i.e., being either red or blue). Participants were required to respond to the orientation of the target within 1,500 ms. The end of each trial was marked by the appearance of a cross at fixation for 300 ms. After a variable intertrial interval, the next trial started. Right panel (B): Schematic illustration of the target-lateral condition (upper panel) and the distractor-lateral condition (lower panel). Both the target and the singleton distractor were presented randomly on two out of six display positions that were arranged on an imaginary circle. In the target-lateral condition, the target was presented either to the left or right of fixation, whereas the distractor was presented either above or below fixation. In the distractor-lateral condition, the target was presented either above or below fixation, whereas the singleton distractor was presented either to the left or to right of fixation. (Note that the figure does not exactly reproduce the original display layout.)

dot (see Fig. 1B). With this setup, two possible positions were on the vertical midline and the remaining four positions were lateral (two on the left and two on the right display side). In one third of the trials, the target was presented on one of the vertical midline positions while the singleton distractor was presented on one of the four lateral positions (distractor-lateral condition). In another third of the trials, this assignment was reversed so that the singleton distractor was presented vertically and the target was presented laterally (target-lateral condition). To balance the positions of the target and the singleton distractor within the search display, both stimuli were presented laterally (i.e. on different display sides) in the remaining third of the trials.

Participants responded to the orientation of the target by pressing two external keys with their left and right index fingers. The two keys were positioned in front of the participant and were aligned to the center of the screen.

4.2.3 Procedure

The trial procedure is illustrated in Fig. 1A. Each trial started with the presentation of the fixation point for 300 ms plus a variable interval. The variable interval was drawn from an exponential random function and rounded to ms, with a mean of 1,000 ms (min = 0 ms, max = 12,500 ms). This random interval was included to maximize temporal uncertainty and stress the importance of the warning signal (see also Seibold & Rolke, 2014b). Then, the auditory warning signal was presented for 200 ms. Depending on the FP, either an inter-stimulus interval of 600 ms (short FP) or an inter-stimulus interval of 2,200 ms (long FP) followed. After the inter-stimulus interval, the search display was presented for 200 ms, followed by a response interval of 1,300 ms in which only the fixation point was presented on screen. The end of each trial was indicated by replacing the fixation point with a white cross for 300 ms. During practice trials, an error feedback was given on incorrect responses by presenting the German word ‘Fehler!’ (‘Error!’) above the white cross. Before the onset of the next trial, an inter-trial interval of 1, 200 ms was presented. In case of a short FP block, an interval of 1,600 ms was added to the inter-trial interval to keep overall block length comparable for the two FP conditions (see Bausenhart et al., 2007).

An experimental session lasted about 3.5 h. Participants were seated in a comfortable chair in a dimly lit, soundproofed chamber. After EEG application, participants first received oral and written task instructions. They were instructed to indicate the orientation of the target as fast and as accurate as possible by means of a button press. Furthermore, they were advised to use the warning signal to prepare for the temporal occurrence of the search display. To minimize artefacts in the EEG being caused by eye movements, participants were encouraged to keep fixation throughout each trial and to restrict blinks and other eye-movements to the inter-trial interval and breaks between blocks. After the instruction, participants went through two practice blocks with 32 trials each (one for each FP). Afterwards, they completed 768 experimental trials in total, which were divided into 24 blocks of 32 trials each. Participants were given accuracy feedback (percentage of correct responses) at the end of each block and they were encouraged to take a short break.

Target and singleton distractor position (target lateral, distractor lateral, or both stimuli lateral), target orientation (tilted to the left or to the right), singleton distractor color (red or blue), and singleton distractor orientation (vertical or horizontal) varied randomly within blocks. The FP (short or long) changed after every sixth block. The order of the two FPs (short – long or long – short) was counterbalanced across participants. Furthermore, the response button assignment was counterbalanced across participants: Half of the participants pressed the upper key if the target was tilted 45◦ to the left and the lower key if the target was tilted 45◦ to the right, whereas the other half of the participants received the reversed assignment.

4.2.4 EEG recording

The EEG was recorded via a BIOSEMI Active Two amplifier system with 26 Ag/AgCl electrodes, including 18 electrode sites from the international 10–20 system (i.e., Fpz, Fz, F3/F4, F7/F8, Cz, C3/C4, T7/T8, Pz, P3/P4, P7/P8, and O1/O2) and eight additional electrode sites (i.e., Fp1, FC3/FC4, PO3/PO4, PO7/PO8, and Oz). Horizontal electro-oculograms (hEOG) were recorded from electrodes at the outer canthi of each eye, vertical electro-oculograms (vEOG) were recorded via an electrode placed below the left eye and electrode site Fp1. Two additional electrodes (Common Mode Sense active electrode and Driven Right Leg passive electrode) served as ground and on-line reference electrode (cf. www.biosemi/faq/cms&drl.htm). Two electrodes placed on the left and right mastoid served for off-line re-referencing. During recording, we constantly monitored the signal quality at the mastoid sites; in case of a substantial decline in signal quality, we improved the signal quality (i.e., by reattaching the electrode) during the block breaks. This was the case for one participant. The EEG and EOG recordings were recorded with a sampling rate of 512 Hz (amplifier bandpass: DC–100 Hz).

4.2.5 Data analysis

All ERP preprocessing steps were performed in Brain Vision Analyzer 2 (Brain Products, Herrsching, Germany), and the statistical analyses were performed in SPSS (IBM Statistics 25, 2017) and Matlab (MathWorks R2017b). We conducted repeated-measures analyses of variances (rmANOVA) to examine the effect of FP on RT and ERP amplitudes and latencies, and we conducted one-sample *t*-tests against zero to determine whether the observed ERLs (i.e., the N_T, N_D and P_D) were reliable. As measures of effect size, we report n_p^2 and Cohen's d_Z (see Lakens, 2013) for significant effects in rmANOVAs and *t*-tests, respectively.

Behavioral data

Practice trials were excluded from all analyses. Furthermore, trials with incorrect responses and trials with RTs that deviated more than 2.5 *SD* from the mean of each participant in each FP condition (*M* = 2.61 %) were excluded from the RT analysis (for similar outlier criteria see, e.g., Feldmann-Wüstefeld & Schubö, 2013; Rolke et al., 2016). Separate rmANOVAs with the factor FP (short or long) were then conducted on mean RT and error rates.

ERP data

Only correct responses were included in the ERP analysis. All electrodes were re-referenced offline to the average of the left and right mastoid. To detect horizontal and vertical eye movements, bipolar EOG channels were calculated from the two hEOG and two vEOG channels, respectively. A Butterworth Zero Phase filter (0.1–30 Hz, 12 dB/oct slope) was applied to both EEG and EOG channels. Then, the data of all channels were segmented into epochs from □ 200 ms to 600 ms after search display onset. The interval from □ 200 ms to 0 ms relative to search display onset served as the pre-stimulus baseline. Analogous to previous ERP studies in the context of visual search (e.g., Barras & Kerzel, 2017; Brisson et al., 2009; Feldmann-Wüstefeld & Schubö, 2016; Seibold & Rolke, 2014b) we used an absolute threshold for artifact rejection. Specifically, segments affected by vertical eye movements (vEOG exceeding ±80 μV), horizontal eye movements (hEOG exceeding ±30 μV) or any other artifacts (voltage exceeding ±80 μV at any other electrode) were excluded from the analysis. An additional visual inspection revealed that the EEG signal at electrode sites PO3, PO4, PO7, and PO8 was noisy in some blocks for some participants. Since these electrode sites were most relevant for measurement of lateralized ERP components (see below), we removed the corresponding segments for these participants manually.

Participants who had less than 50 % of the trials in one experimental condition (i.e., less than 64 trials) after artifact rejection were disqualified (*N* = 8). After artifact rejection, an average of 80.8 % of the segments was retained in the short FP condition (80.8 % for the N1, 80.3 % for the N_T, and 81.4 % for the N_D and P_D), and 80.9 % of the segments in the long FP condition (80.9 % for the N1, 80.3 % for the N_T, and 81.5 % for the N_D and P_D).

For the analysis of the N1, segments for short and long FP conditions were averaged across the target-lateral and distractor-lateral conditions for each participant. Electrodes PO3, PO4, PO7, PO8, O1 and O2 were then pooled to determine N1 amplitude. N1 amplitude was estimated via peak-centered mean amplitude values to account for N1 latency differences that have been observed in FP paradigms (see, e.g., Hackley et al., 2007; Seibold & Rolke, 2014b). On grounds of the grand-average across participants and FP conditions (see Luck & Gaspelin, 2017), we chose a time window of 120–220 ms for peak detection. An automatized peak-picking algorithm with a local maximum criterion was used for peak detection. Then, N1 mean amplitude was calculated as mean voltage within ±25 ms around the peak.

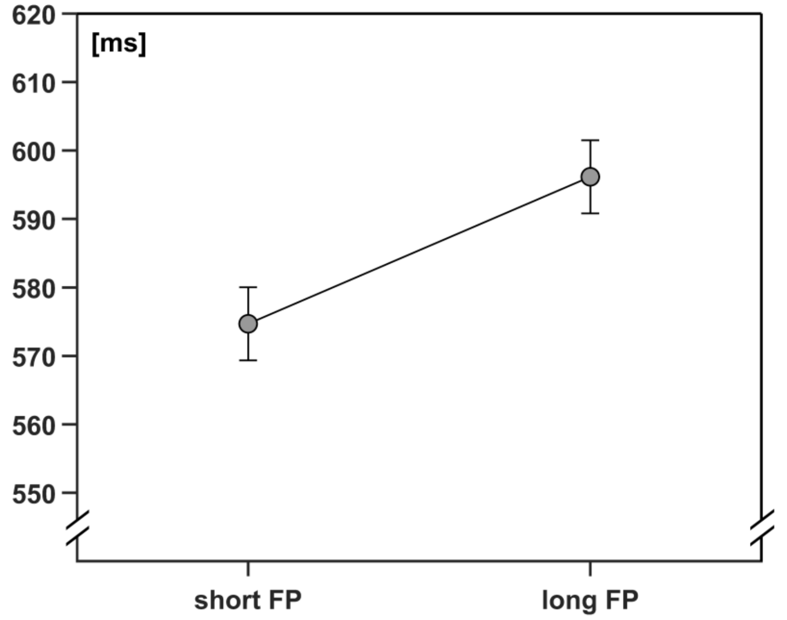
For the analysis of the N_T, N_D and P_D, segments for left and right targets (target-lateral condition), and left and right distractors (distractor-lateral condition), respectively, were averaged for each participant and FP condition. We then calculated the contra-minus ipsilateral difference wave at posterior electrode sites (electrode sites PO7/8 and PO3/4). These electrode sites were chosen based on the topography of the N_T and P_D that has been reported in previous studies (e.g., Hickey et al., 2009). Equivalent to previous studies (e.g., Feldmann-Wüstefeld & Schubö, 2016; Heuer & Schubö, 2020; Oemisch et al., 2017) and to further increase the signal-to-noise ratio for determining ERP onset latency, we pooled the resulting ERP difference wave across electrode sites PO7/8 and PO3/4. ERL (i.e., N_T, N_D and P_D) amplitude was again estimated via peak-centered mean amplitude (time window: ±25 ms around peak latency). The time windows for peak detection were determined in the grand-average ERL across participants and FP condition, separately for the distractor-lateral and the target-lateral conditions (see Luck & Gaspelin, 2017). This approach resulted in time windows of 180–320 ms for the N_T (target-lateral condition), 170–270 ms for the N_D (distractor-lateral condition), and 240–340 ms for the P_D (distractor-lateral condition).

In addition to ERL amplitude, we analyzed ERL onset latency for each component. For this purpose, we used the jackknife approach (Miller e al., 1998) in combination with a relative amplitude criterion, which has been shown to provide an especially accurate estimate of ERL onset latency (see Kiesel et al., 2008). Specifically, we determined ERL onset latency using a relative amplitude criterion of 50 % of ERL peak amplitude (see also Seibold & Rolke, 2014b).

Before the analysis of ERL amplitude and latency, we first examined whether the N_T, the N_D, and the P_D reliably differed from zero. We then subjected ERL amplitude and latency to separate one-way rmANOVAs with the factor FP (short or long). For all jackknife-based analyses, we corrected the F-value for the main effect of FP using the formula $F_C = F / (n - 1)^2$, where F_C denotes the corrected F-value, and n denotes the number of participants (see Ulrich & Miller, 2001). Furthermore, we corrected the corresponding effect size n_p^2 using the formula $n_p^2{}_C = F_C \times df_{effect} / (F_C \times df_{effect} + df_{error})$, where $n_p^2{}_C$ denotes the corrected n_p^2 value, d*feffect* denotes the degrees of freedom for the effect and df_{error} denotes the degrees of freedom for the error.

Figure 4-2

Mean reaction time (RT) as a function of foreperiod (FP)



Note. Mean reaction time (RT) as a function of foreperiod (FP). Error bars denote +/- one standard error of the mean for within-subjects designs, being calculated according to Cousineau (2005) and a correction by Morey (2008).

4.3. Results

4.3.1 RT and error rate

The analysis of mean RT for correct responses revealed a main effect of FP, $F(1, 23) = 8.57$, $p = .008$, $n_p^2 = .27$. Mean RT was overall shorter in the short FP condition ($M = 574$ ms, $SD = 76$ ms) than in the long FP condition ($M = 596$ ms, $SD = 91$ ms; see Fig. 2). There was no FP effect on mean error rate, $F(1, 23) = .048$, $p = .83$ (short FP condition: $M = 2.26$ %, $SD = 2.01$ %; long FP condition: $M = 2.31$ %, $SD = 1.96$ %).[8]

4.3.2 N1

The ERP evoked by the search display is illustrated in Fig. 4-3. The N1 was more pronounced in the short FP condition ($M = -1.84$ µV, $SD = 4.26$ µV) than in the long FP condition ($M = -.77$ µV, $SD = 4.20$ µV), $F(1, 23) = 7.69$, $p = .011$, $n_p^2 = .25$. Furthermore, the N1 arose earlier in short FP condition ($M = 146$ ms, $SD = 1$ ms) than in the long FP condition ($M = 157$ ms, $SD = 1$ ms), $F_C(1, 23) = 13.04$, $p < .001$, $n_p^2{}_C = .36$.

4.3.3 N_T (target-lateral condition)

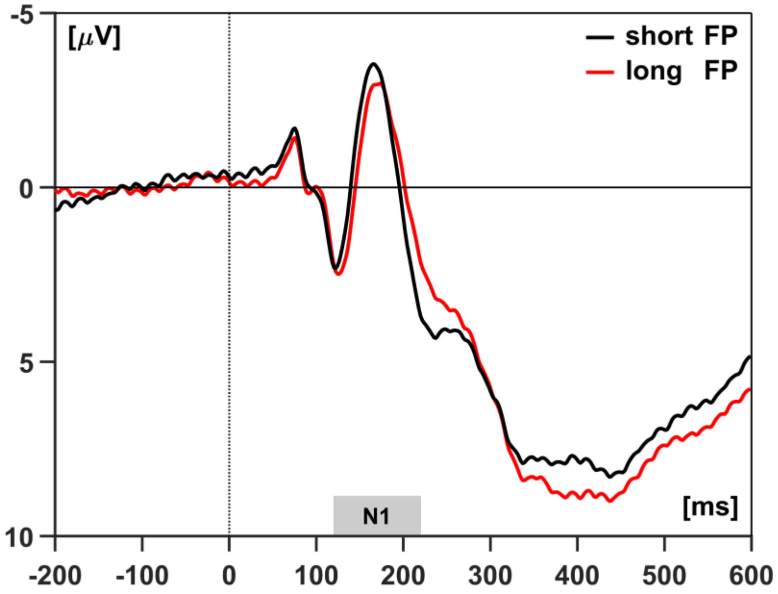
The ERL for the target-lateral condition is illustrated in Fig. 4-4, left panel. As expected, a more-negative going voltage emerged at contralateral electrode sites around 180 ms after search display onset. This N_T was reliable in both the short FP condition, $t(23) = 7.87$, $p < .001$, $d_Z = 1.61$, and the long FP condition, $t(23) = 7.32$, $p < .001$, $d_Z = 1.49$. The analysis of N_T mean amplitude did not reveal a FP main effect, $F(1, 23) = .45$, $p = .51$. In contrast, the analysis of N_T onset latency showed that the N_T

---

[8] Since an additional check indicated deviations from the assumption of normally distributed errors for N_T and N_D onset latency in the long FP condition and for error rate in both FP conditions, we conducted additional nonparametric (i.e., Wilcoxon) tests on the FP effect for these dependent variables. These nonparametric tests revealed the same results as the corresponding parametric tests: there was a FP effect on N_T onset latency, $W = 78$, $p = .039$, but not on N_D onset latency, $W = 107$, $p = .23$, nor was there a FP effect on error rate, $W = 84$, $p = .74$. In sum, these results show that FP effect was not affected by deviations from normality

Figure 4-3

Grand-average ERP evoked by the search display as a function of foreperiod



Note. Grand-average ERP (N1) evoked by the search display at posterior electrode sites (i.e., pooled electrode sites PO3, PO4, PO7, PO8, O1, and O2) as a function of foreperiod (FP). The black line denotes the short FP condition, whereas the red line denotes the long FP condition. In this figure and all subsequent figures, time (in ms) is displayed on the x-axis, and voltage (in μV) is displayed on the y-axis. Negative voltage is plotted upward. The short-dashed vertical line indicates the onset of the search display. The grey shaded area indicates the time windows for measurement of the N1.

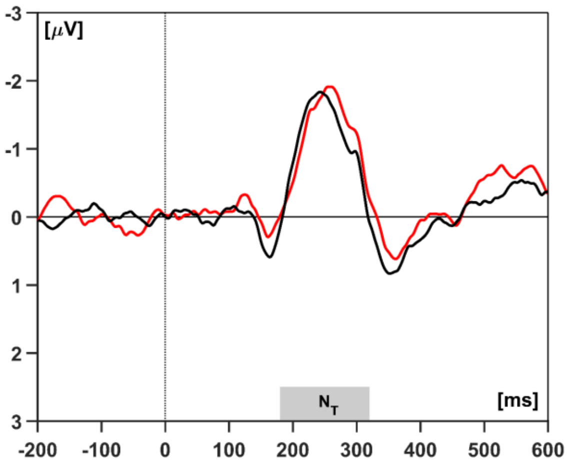
arose earlier in the short FP condition (M = 205 ms, SD = 1 ms) than in the long FP condition (M = 213 ms, SD = 1 ms), $F_C(1, 23) = 4.94$, $p = .036$, $\eta_p{}^2{}_C = .18$.

4.3.4 N$_D$ and P$_D$ (distractor-lateral condition)

Analogous to the target-lateral condition, a more-negative going voltage emerged at contralateral electrode sites around 180 ms after search display onset. As illustrated in Fig. 4, right panel, this N$_D$ was followed by a P$_D$, that is, a more positive-going voltage around 230 ms after search display onset. *T*-Tests against zero substantiated the observation of a reliable N$_D$ in the short FP condition, $t(23) = 4.31$, $p < .001$, $d_Z = .88$, and the long FP condition, $t(23) = 2.15$, $p = .042$, $d_Z = .44$. Similarly,

Figure 4-4

Grand-average difference wave evoked by the search display as a function of foreperiod



Note. Grand-average contra-minus ipsilateral difference wave evoked by the search display at posterior electrode sites (i.e., pooled PO7/8 and PO3/4) as a function of foreperiod (FP) and search condition (left panel: target-lateral condition; right panel: distractor-lateral condition). The black line denotes the short FP condition, whereas the red line denotes the long FP condition. The grey shaded areas indicate the time windows that were used to determine the peak of the NT (target-lateral condition), as well as the ND and PD (distractor-lateral condition).

a reliable P_D was evoked in both the short FP condition, *t* (23) = 8.61, *p* < .001, d_Z = 1.76, and the long FP condition, *t*(23) = 10.40, *p* < .001, d_Z = 2.12. The analysis of N_D amplitude showed a main effect of FP, *F*(1, 23) = 5.84, *p* = .024, n_p^2 = .20. The N_D was more pronounced in the short FP condition (*M* = - .82 µV, *SD* = .93 µV) than in the long FP condition (*M* = - .31 µV, *SD* = .70 µV). There was no difference in N_D onset latency between the two FP conditions, F_C(1, 23) = .14, *p* = .71. The analyses of P_D amplitude did not reveal a FP main effect, *F*(1, 23) = .23, *p* = .64, nor did the analysis of P_D onset latency, F_C(1, 23) = .01, *p* = .92. An analogous result emerged, when we restricted our statistical analyses to electrode sites PO7/8 which is used in some studies (e.g. Barras & Kerzel, 2017; Feldmann-Wüstefeld & Schubö, 2013) for the measurement of the P_D: Neither P_D amplitude, *F* (1, 23) = .09, *p* = .77, nor P_D onset latency, *F*(1, 23) < .01, *p* = .98, was significantly affected by FP.

4.3.5 Exploratory analyses

On grounds of the suggestions from two anonymous reviewers, we conducted two further exploratory analyses. First, we investigated the functional relationship between attentional selection, as reflected in the ERLs in our study, and behavior by correlating the two measures (see, e. g., Liesefeld et al., 2017). Second, we investigated whether distractor selection, as reflected in the ND, and its modulation by FP may differ qualitatively between fast and slow responses by means of a median split (see, e.g., Feldmann-Wüstefeld & Schubö, 2016). It should be noted, however, that our sample size was not pre-planned for these types of analyses.

For the correlation analysis, we calculated Pearson correlations between the amplitudes and latencies of the N_T, the N_D, as well as the P_D and median RT. We used median RT instead of mean RT because the former measure has been considered to be more suitable when examining correlations between RT and ERP latencies (see Luck, 2014). Furthermore, to ensure that we did not miss any potential effects for ERP latency, we calculated fractional area latency in addition to the jackknife-based onset latencies (using a criterion of 50 % of component area between on- and offset of the respective component; see Liesefeld et al., 2017). For both measures, we then derived estimates of individual latencies for each participant from the jackknife-based latencies (see Smulders, 2010). We observed a positive correlation between N_T amplitude and median RT ($r = .45$, $p = .013$). In contrast, we did not observe a significant correlation of N_D or P_D amplitude with median RT (both ps > .32), nor did we observe any correlation between ERP latencies and median RT (all ps > .14).

Second, we conducted median splits by both participants and trials. For the median split by participants, we sorted participants into two equally sized groups of fast and slow responders, based on the median RT. Then we ran a rmANOVA on N_D amplitude including the within-subjects factor FP (short, long) and the between-subjects factor responder group (fast, slow). For the median split by trials, we split the trials for each participant into fast and slow responses, based on his or her median RT in each FP condition. Then we ran a rmANOVA including the within-subject factors FP (short, long) and response speed (fast, slow). With respect to the overall effect of response speed, we observed no modulation of ND amplitude, neither for the median split by trials, $F(1, 23) = .74$, $p = .40$, nor for the median split by participants, $F(1, 22) = 1.26$, $p = .27$. With respect to the effect of FP, we observed a larger N_D in the short FP condition than in the long FP condition for both the median split by participants,

$F(1, 22) = 5.77$, $p = .025$, $n_p^2 = .21$, and the median split by trials, $F(1, 23) = 5.31$, $p = .031$, $n_p^2 = .19$. Finally, although there was a trend towards an interaction of FP and response speed on N_D amplitude for the median split by trials, $F(1, 23) = 4.27$, $p = .05$, $n_p^2 = .16$, no indication for an interaction was observed for the median split by participants, $F(1, 22) = .73$, $p = .40$. In summary, both analyses replicated the effect of FP on N_D amplitude, as observed in our main analysis.

4.4. Discussion

The aim of the present study was to clarify how the reduction of temporal uncertainty facilitates spatial selection as observed in several previous studies (Hackley et al., 2007; Rolke et al., 2016; Seibold & Rolke, 2014b). On grounds of established models of spatial selection in visual search (e.g., Connor et al., 2004; Folk & Remington, 2008; Found & Müller, 1996; Theeuwes, 2010; Wolfe, 1994), we hypothesized that the reduction of temporal uncertainty can facilitate spatial selection either via an influence on stimulus-driven processes or via an influence on goal-driven processes. To separate these two processes, we employed a visual search task in which participants discriminated the orientation of a target while ignoring a uniquely colored distractor, and we varied temporal uncertainty via constant FPs. By measuring ERLs evoked by the lateral singleton distractor (N_D and P_D) and the lateral target (N_T), respectively, we aimed at measuring how stimulus-driven and goal-driven processes are influenced by temporal uncertainty. In line with previous studies (e.g., Seibold & Rolke, 2014b), we observed FP effects on both RT and the visual N1. Participants responded faster in the short FP condition than in the long FP condition. Furthermore, the N1 was more pronounced and its latency was reduced in the short FP condition in comparison to the long FP condition. This latter result may indicate that early, perceptual processing of visual stimuli is already affected by temporal uncertainty (Rolke et al., 2016; Seibold & Rolke, 2014b). Such an interpretation, however, remains tentative because the assumption that the N1 reflects basic visual discrimination processes (Vogel & Luck, 2000) has become a point of discussion more recently (see, e.g., Van der Lubbe et al., 2016). Accordingly, the N1 modulation might be influenced by a superimposition of stimulus-preceding ERPs (i.e., the contingent negative variation; see, e.g., Correa et al., 2006) or differences in phase-locked responses (e.g., Van der Lubbe et al., 2016), and experimental effects on the N1 might be difficult to be traced back to one causative factor. For these reasons, we will focus on the FP effect on the ERLs, because these components should be unaffected by an overlap from stimulus-preceding effects which might differ between the two FPs (see also Hackley et al., 2007).

With respect to the ERLs, we replicated the basic results reported by Feldmann-Wüstefeld and Schubö (2016). Specifically, lateral targets evoked a large N_T, indexing spatially selective processing of the target (e.g., Hickey et al., 2009). Furthermore, lateral distractors evoked a N_D and a subsequent P_D, which indicates that the distractor was subjected to spatially selective processing, too (e.g., Feldmann-Wüstefeld & Schubö, 2016), and this process was actively terminated via goal-driven suppression (Hickey et al., 2009; Sawaki & Luck, 2010). Together, these results show that our experimental setup was effective in measuring an effect of temporal uncertainty on stimulus processing as well as ERP signatures of stimulus-driven and goal-driven processes involved in spatial selection.

With respect to our main question, that is, how the reduction of temporal preparation modulates spatial selection, we will first discuss the results for distractor-lateral condition: The first important result was the observation that the distractor-evoked N_D was larger in the short FP condition than in the long FP condition. To our knowledge, this is the first empirical demonstration of a direct effect of temporal uncertainty on spatial selection of a salient, yet task-irrelevant distractor. We interpret this modulation of N_D amplitude in terms of stronger processing of salient stimuli regardless of their task-relevance, which would be consistent with a view according to which the reduction of temporal uncertainty facilitates stimulus-driven processes in spatial selection. The observation of an N_D amplitude modulation, however, is not consistent with a view according to which temporal uncertainty influences spatial selection via goal-driven processes: Because stimulus color was not a target-defining feature in our task the singleton distractor should not have benefited from goal-driven processes in our study. Second, and inconsistent with a goal-driven view, we did not observe any influence of temporal uncertainty on the distractor-evoked P_D.

In our opinion, this result provides the first empirical evidence that temporal uncertainty may not influence distractor suppression as one important mechanism in goal-driven spatial selection. In sum, the observation that the reduction of temporal uncertainty increased N_D amplitude and the absence of a corresponding effect on the P_D is most consistent with the view that temporal uncertainty influences spatial selection via stimulus-driven rather than goal driven processes. Furthermore, from a broader perspective, this result argues for a view according to which the reduction of temporal uncertainty facilitates stimulus processing via enhancement rather than suppression.

Whereas the ERP results in the distractor-lateral condition favor an effect of temporal uncertainty on stimulus-driven processes over goal-driven processes, the results in the target-lateral condition seem less clear-cut. In contrast to the distractor-evoked ND, the target-evoked N_T was not enhanced in its amplitude by the reduction of temporal uncertainty. Instead, reducing temporal uncertainty affected N_T latency as it arose earlier in the short FP condition than in the long FP condition. At first sight, this pure latency effect may seem inconsistent with both an influence of temporal uncertainty on stimulus-driven and goal-driven processes given that we hypothesized that any influence on the two processes should be reflected in ERP amplitude modulations. One explanation for this specific result could be that the N_T latency modulation reflects the propagation of an early perceptual processing benefit. According to this explanation, the reduction of temporal uncertainty leads to a global acceleration of visual processing either before or at the level of spatial selection (see Rolke et al., 2016). This explanation, however, is not consistent with the observation that only the latency of the N_T, but neither the latency of the N_D nor the subsequent P_D was influenced by temporal uncertainty. Therefore, we like to consider another possible explanation, which is also in line with the view that the reduction of temporal uncertainty influences stimulus-driven processes in spatial selection. This alternative explanation rests upon the assumption that stimulus-driven and goal-driven processes do not affect spatial selection at the same time point, but that stimulus-driven processes contribute to spatial selection at an earlier time point than goal-driven processes, or that the contribution of stimulus-driven processes is less enduring. If this was the case and if temporal uncertainty influenced exclusively stimulus-driven processes, then only the early part of the N_T should be enhanced in its amplitude, whereas the later part of the N_T should remain unaffected. Importantly, such a lagged onset of stimulus- and goal-driven contributions would show up as a latency shift in the average ERP. Although this explanation is clearly post-hoc, it is supported descriptively by a direct comparison of the temporal expansion of the N_D and the N_T. As can be derived from Fig. 4, the N_D in our study seems to overlap mainly with the early part of the N_T. Given that the N_D in our study should mainly reflect stimulus-driven processes, its temporal overlap with the early part of the N_T would be consistent with the idea that stimulus-driven contributions to spatial selection may be reflected in the early part of the N_T. Furthermore, this result suggests that spatial selection of the target and the singleton distractor started at about the same time in our study (at least descriptively). In summary, the pattern of results we observed for the N_D, the P_D, and the N_T is most consistent with the idea that temporal uncertainty affects stimulus-driven processes in spatial selection.

The enhancement of stimulus-driven processes by the reduction of temporal uncertainty includes the possibility that processing of distractors and, thus, their potential to capture spatial attention is also enhanced. Importantly, this attentional capture effect would be reflected in the N_D because this ERP component is also regarded as an index of the extent to which distractors are spatially selected (see, e.g., Barras & Kerzel, 2017; Feldmann-Wüstefeld & Schubö, 2013, 2016; Hickey et al., 2006; Lee et al., 2018; Liesefeld et al., 2017; Seiss et al., 2009). From this viewpoint, the observation that the N_D was larger in the short FP condition suggests that the reduction of temporal uncertainty might amplify attentional capture. Yet, despite stronger processing of the distractor in the short FP condition, RT to the target was still faster in this condition in comparison to the long FP condition. At first sight, this RT advantage in the short FP condition may seem paradoxical as one might expect the reversed RT pattern, that is, longer RT in the short FP condition if attentional capture is stronger in this condition. How is it possible that stronger distractor processing is nonetheless associated with an RT advantage? Although we can only speculate on this issue, we think that several explanations are possible. One explanation could be that stronger processing of the singleton distractor came along with stronger processing of the target as it was also a singleton (i.e., on the orientation dimension). Hence, and as reasoned in the Introduction, it seems conceivable that stimulus-driven processes contributed to spatially selective processing of both the distractor and the target in our study. Accordingly, more efficient target selection may compensate for attentional capture by the distractor, which in turn may allow for faster responding to the target's orientation.

A second, additional explanation could be that enhanced distractor processing, as indexed by the larger N_D in the short FP condition, does not directly translate into a corresponding RT effect. Some preliminary evidence in support of this possibility may be found in our exploratory correlation analysis: In line with previous studies (e.g., Drisdelle et al., 2016; Weymar et al., 2011), this analysis revealed a positive correlation between N_T amplitude and RT, suggesting that the effectiveness of spatially selective processing of the target directly influenced how fast participants responded to the target's response-relevant feature. In contrast, the correlation analysis did not reveal a correlation between N_D amplitude and RT (nor did it reveal a correlation between P_D amplitude and RT). Although the empirical evidence on the relationship between N_D amplitude and RT is still sparse, previous research did not reveal a correlation of N_D amplitude with mean RT either (Liesefeld et al., 2017), but instead indicates that the amplitude of the N_D correlates with the degree of self-reported distractibility (Burra & Kerzel, 2013). From this perspective, it could be argued that the process that underlies the N_D cannot be directly measured in RT, and this may explain why the FP effect on N_D amplitude was not reflected in a corresponding RT effect in the present study. We want to mention, however, that this inference is clearly limited by the fact that our sample size was not optimized for a correlation analysis (see also Drisdelle et al., 2016, regarding the problem of small sample sizes when correlating ERPs and behavioral measures). Accordingly, the absence of a correlation between N_D amplitude and RT in our study may be also due to this limitation.

So far, we have only discussed the FP effect on the N_D and N_T in terms of a facilitating effect of reduced temporal uncertainty, which optimizes attentional allocation to task-relevant and task-irrelevant stimuli. An alternative explanation, however, would be that the modulation of N_D amplitude and N_T latency is caused by different search strategies in short versus long FP blocks. Specifically, in short FP blocks, participants may preferentially pursue a singleton detection strategy, in which they search for any singleton in the display, whereas in long FP blocks, they may preferentially pursue a feature search strategy in which they search for a specific target feature. Accordingly, the observation of an earlier N_T onset in combination with a more pronounced N_D would reflect the fact that searching for a singleton is less effortful, but increases the likelihood of attentional capture by distractors. Yet, from our viewpoint, this alternative explanation is unlikely for several reasons: First, searching for a specific target feature – as is assumed to be the case in feature search mode – would not be viable strategy in our task setup since the specific feature value (i.e., the specific orientation of the target) varied randomly from trial to trial. Second, if participants pursued a feature search strategy in the long FP condition, the color distractor should not capture attention anymore and, therefore, no reliable N_D should have been observed (see Eimer & Kiss, 2008; Eimer et al., 2009). Yet, as described above, a reliable N_D was observed in both the short and the long FP condition. Third and finally, previous studies suggest that participants cannot flexibly switch between singleton detection and feature search strategies (e.g., Lamy & Egeth, 2003). Specifically, Lamy and Egeth (2003) have shown that if participants first use a singleton-detection strategy, they cannot prevent attentional capture in a subsequent block even if they search for a constant target feature. Transferred to the present study, this means that a feature search strategy in the long FP condition would only be possible in the first block and only for those participants that started with a long FP block. At variance with this assumption, however, we did not observe an effect of FP order on N_D amplitude, $F(1, 22) = .36$, $p = .85$, nor an interaction with FP order and FP, $F(1, 22) = .12$, $p = .74$. On grounds of these considerations, we do not think that differential search strategies can explain the FP effect on the N_D and N_T.

Given that our results provide evidence for the idea that temporal uncertainty affects stimulus-driven processes in spatial selection, the question arises how exactly this effect is implemented. As explained in the Introduction, current models of spatial selection assume that stimulus-driven spatial selection is directly determined by a process that computes the relative contrast (or saliency) of a stimulus on different dimensions or features relative to its surround (e.g., Fecteau & Munoz, 2006; Found & Müller, 1996; Wolfe, 1994). In accordance with this theoretical framework, we argue that the reduction of temporal uncertainty changes stimulus contrast, for instance, by increasing the signal-to-noise ratio. Adapting this framework to our study, the difference between signal – defined as stimulus contrast – and noise – defined as the random variation within the perceptual process – is enhanced by the reduction of temporal uncertainty. Importantly, this change in stimulus contrast is independent of the task-relevance of a stimulus. Therefore, it should affect all stimuli in a visual scene to the same extent. What remains to be clarified is how exactly such a non-selective increase in the signal-to-noise ratio is achieved. In this regard, theoretical frameworks that explicitly target modulations of the signal-to-noise-ratio, such as the perceptual template model (PTM; Dosher & Lu, 1998), may provide a good starting point for further research. Specifically, the PTM distinguishes between three main processes that determine the signal-to-noise ratio: a process of stimulus enhancement, a process of external noise exclusion, and a process of internal (multiplicative) noise reduction (see Lu & Dosher, 2005, for a review). Importantly, according to the PTM, these different processes can be distinguished empirically by varying the strength of external noise in unspeeded discrimination tasks and measuring its effect on perceptual thresholds.

Combining this experimental approach with a manipulation of temporal uncertainty may therefore provide a good starting point for investigating how a reduction of temporal uncertainty leads to a non-selective increase in the signal-to-noise-ratio. For instance, on grounds of the results of the present study and the notion that attentional modulations of early ERPs have been directly linked to stimulus enhancement (see, e.g., Itthipuripat et al., 2019), one testable prediction within this framework could be that the reduction of temporal uncertainty increases the signal-to-noise-ratio via a process of stimulus enhancement.

From a broader perspective, the observation that stimulus-driven processes in spatial selection are affected by temporal uncertainty in the constant FP paradigm is reminiscent of a view assuming that temporal preparation generally influences stimulus processing in a global, non-specific manner (e.g., Bertelson, 1967; Los & Agter, 2005; Niemi & Näätänen, 1981). The so-called multiple trace theory of temporal preparation (MTP; Los et al., 2014) implements the possibility to explain non-specific effects. This theory assumes that each trial episode (i.e., each sequence of warning signal, imperative signal and response) leads to the formation of a long-term memory trace. This long-term memory trace contains the joint representation of the attended trial events as well as a temporal profile of (1) inhibition that prevents premature responding during the FP and (2) activation as soon as the imperative stimulus is presented and responded to. Over the course of several trials, the averaged temporal profile of inhibition and activation then determines the degree of temporal preparation in each new trial. Within this model, increasing the degree of temporal uncertainty by increasing FP length in the constant FP paradigm affects the shape of the temporal profile of activation and inhibition. Specifically, the activation-inhibition profile is assumed to have a lower maximum activation and a higher temporal dispersion in case of a long FP so that preparation is overall lower and more variable in this case. Importantly, this change in the temporal profile can occur independently of the specific features of the imperative stimulus. Transferred to the present study, MTP thus provides a straightforward explanation of why reduced temporal uncertainty led to enhanced processing of both the target and the salient distractor.

The finding that temporal uncertainty – as one important determinant of temporal preparation – influences processing of both task-relevant and task-irrelevant stimuli does not necessarily mean, however, that temporal preparation is always non-specific. Rather, there is empirical evidence for specific effects of temporal preparation in several studies in which the FP varied randomly from trial to trial (Schröter et al., 2014; Thomaschke & Dreisbach, 2013; Wagener & Hoffmann, 2010).[9] Specifically, presenting one of two imperative stimuli more frequently after one FP than after another, Wagener and Hoffman (2010) showed that RT to the frequent stimulus-FP combination was faster than RT to the infrequent stimulus-FP combination. Furthermore, Schröter et al. (2014) observed that the FP effect in such a variable FP context was larger when the upcoming task was predictable than when it was not predictable. Moreover, and beyond the context of the FP paradigm, specific temporal preparation effects have also been reported in studies employing explicit temporal cues and combining these cues with spatial or feature-specific cues (Doherty et al., 2005; Kingstone, 1992; Olk, 2014; Rohenkohl et al., 2014). For instance, Kingstone (1992) cued both the likely time point at which the imperative stimulus would appear and the likely form of that stimulus. Importantly, he observed that both cue dimensions (time and form) interacted in their effect on RT. Specifically, RT to the imperative stimulus was fastest when it appeared at the cued time point and had the cued form, and was slowest when the imperative stimulus appeared at the cued time point, but did not have the cued form. Furthermore, Doherty et al. (2005) combined temporal and spatial cueing (see also Rohenkohl et al., 2014) and observed that the visual P1 evoked by the imperative stimulus, an ERP component associated with early spatially-selective processing, was more pronounced when the imperative stimulus was presented both at an expected location and an expected time point than when it was presented only at an expected location, but at an unexpected time point.

Summarizing these findings, it seems reasonable to assume that temporal preparation is not always non-specific, but can be specific, at least if certain conditions are met. One condition might be a change in the activation strength either by increasing the overall frequency of an imperative stimulus (Schröter et al., 2014) or by correlating the imperative stimulus with a specific FP (e.g., Wagener & Hoffman, 2010). Another condition that can be derived from the above-described temporal cueing studies might be the ability to actively build up a common mental representation of temporal and non-

---

[9] In the so-called variable FP paradigm, the FP varies randomly from trial to trial. Accordingly, the specific FP cannot be predicted at the onset of each new trial. Importantly, the conditional probability that the imperative stimulus will occur increases for longer FPs, thereby leading to a downward-sloping RT function (e.g., Klemmer, 1956; Los & Van den Heuvel, 2001; Steinborn & Langner, 2012; Woodrow, 1914; for a review see, e.g., Niemi & Näätänen, 1981).

temporal information as it may be the case when combining explicit temporal cues with explicit cues about other dimensions of the imperative stimulus (e.g., Kingstone, 1992; Rohenkohl et al., 2014; see also Olk, 2014, for a discussion of further conditions in this respect). Investigating these specific conditions in a systematic way will be an important step in order to better understand whether and how temporal preparation influences stimulus processing in a specific or non-specific manner.

To conclude, the present study provides first evidence on how the reduction of temporal uncertainty facilitates spatial selection by measuring ERP indicators of goal-driven and stimulus-driven processes. Contrary to the view of a goal-driven influence, we did not observe an effect of temporal uncertainty on goal-driven distractor suppression (the P_D). Instead, we observed an effect of temporal uncertainty on stimulus-driven spatial selection (the N_D). Our results are thus most consistent with a view assuming that the reduction of temporal uncertainty facilitates spatial selection in a non-selective manner, that is, by enhancing stimulus-driven processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the German Research Foundation (DFG; grant SE2576/1-1). We thank Meret Häusler and Viola Vogl for their assistance in data acquisition and Dr. Elisabeth Hein for her deliberate hints regarding the interpretation of our results. Furthermore, we thank Dr. Van der Lubbe and two anonymous reviewers for their helpful comments on an earlier version of this manuscript.

5. General Discussion

Research has shown that temporal preparation influences spatial selection (Balke et al., 2021, 2022; Hackley et al., 2007; Seibold & Rolke, 2014b). However, how this influence of temporal preparation on spatial selection is mediated is still unknown. Based on current models of visual search (Awh et al., 2012; Itti & Koch, 2001; Liesefeld & Müller, 2021; Wolfe, 1994, 2021), several factors can influence spatial selection (see Chapter 1): bottom-up salience, top-down weighting, and the influence of prior history. Based on previous studies, for this dissertation, bottom-up and top-down processes are of particular interest. Therefore, the aim of this dissertation is to clarify whether temporal preparation influences spatial selection by facilitating bottom-up and/or top-down processing. To this end, a constant FP paradigm was combined with a visual search task in three experimental series. To test whether temporal preparation influences bottom-up processing, a setsize manipulation was used to vary target salience (Studies 1 and 2), or a task-irrelevant but salient distractor was presented in addition to a salient target (Study 3). To test whether temporal preparation influences top-down processing, participants were informed about the feature and dimension defining the target (Study 3) and its constancy (Study 1) to facilitate the formation of a top-down representation. RT (Studies 1, 2, and 3) and the N2pc elicited by the target (Studies 2 and 3), or a singleton distractor (Study 3) were measured. Since the N2pc is an indicator of spatial selection, it was of particular interest whether temporal preparation modulates the N2pc and thus spatial selection depending on either the bottom-up salience or the top-down weighting of a stimulus.

In terms of behavioral measures, RT was faster after a short FP interval than after a long FP interval (Studies 1-3). As this is consistent with previous research (Müller-Gethmann et al., 2003; Niemi & Nääatänen, 1981; Seibold & Rolke, 2014a, 2014b; Woodrow, 1914), this RT pattern serves as evidence that the constant FP paradigm successfully induced temporal preparation. In Study 1, the main goal was to investigate whether temporal preparation influences bottom-up and/or top-down processing in a visual search task and whether this could be observed in participants' responses as measured by RT. In Experiment 1 (Study 1), setsize was manipulated as an indicator of bottom-up processing. The results of Experiment 1 showed that the FP effect did not differ between the setsize conditions, i.e., 3, 6 or 9 elements condition. In Experiment 2 (Study 1), the constancy of target features was manipulated to examine the influence of temporal preparation on top-down processes. The effect of FP on RT did not differ between constant and variable target feature blocks. Taken together, in both experiments of Study 1, there was an effect of FP on RT in the visual search task. However, this effect did not interact with target salience or target feature constancy. Thus, temporal preparation facilitates visual search, but there is no evidence that this is due to a direct influence on bottom-up or top-down processing. Rather, the observed pattern of results suggests that temporal preparation has an additive effect on spatial selection, in addition to bottom-up and top-down influences. In conclusion, the RT results of Study 1 may indicate that temporal preparation accelerates spatial selection globally, i.e., via an indirect influence.

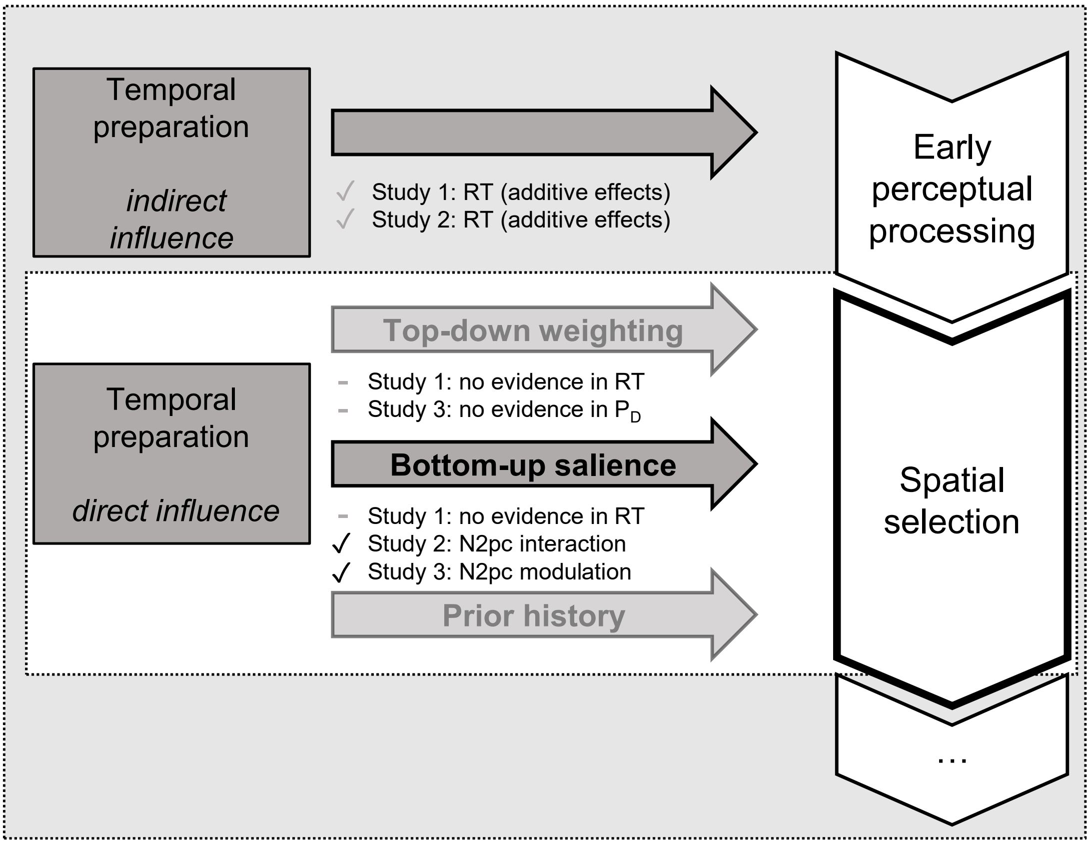
To further investigate whether temporal preparation facilitates spatial selection by an influence on bottom-up or top-down processing, or whether this facilitation is independent of these processes, two ERP studies were conducted to measure the influence of temporal preparation on spatial selection directly. In both studies, there was an effect of FP on N1 onset latency (Studies 2 and 3) as well as on N1 amplitude (Study 3). Consistent with previous research (Rolke et al., 2016; Seibold & Rolke, 2014b), the observed N1 modulation supports the notion that temporal preparation accelerates early visual processing. Furthermore, Study 2 aimed to directly test whether temporal preparation affects bottom-up processing in spatial selection. Replicating previous findings (Hackley et al., 2007; Seibold & Rolke, 2014b), FP did modulate the N2pc: the N2pc arose earlier in the short FP condition compared to the long FP condition. Most importantly, the onset latency of the N2pc revealed an interaction between FP and setsize. The N2pc arose earlier after a short FP compared to a long FP, and this influence of temporal preparation was greater for a small setsize (i.e., 4-element condition) compared to a large setsize (i.e., 20-element condition). Because setsize affects the salience of the target (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; Wolfe et al., 2003), this result suggests that the influence of temporal preparation on spatial selection depends on stimulus salience. In Study 3, the finding that FP modulates the onset latency of the N2pc elicited by the target was replicated. Most importantly, FP also modulated the N2pc elicited by the salient but task-irrelevant singleton distractor, i.e., the amplitude of the distractor N2pc was enhanced. Both stimuli, target and singleton distractor, have in common that they are salient due to their unique feature properties, but they differ in their relevance to the task. Since the N2pc, i.e. the process of spatial selection, was modulated for both stimuli, these results suggest that temporal preparation facilitates spatial selection for salient stimuli regardless of their top-down relevance. Rather, the results of both ERP studies provide evidence that the influence of temporal preparation on spatial selection varies as a function of stimulus salience.

With regard to the main aim of this dissertation, which is to answer the question of how temporal preparation affects spatial selection, the observations of Studies 2 and 3 suggest interesting implications. Most importantly, Study 2 showed that the influence of temporal preparation depends on the salience of the target stimulus. Salience is considered bottom-up because it is determined by the basic feature differences between a stimulus and its surround (Itti & Koch, 2001; Nothdurft, 2000, 2005). Therefore, it can be concluded that temporal preparation affects spatial selection by influencing bottom-up processing. Further evidence for this hypothesis is provided by Study 3, in which temporal preparation affected not only the N2pc of the target but also that of a singleton distractor. The observation that temporal preparation influences spatial selection of this singleton distractor solely on the basis of its bottom-up salience supports the notion that temporal preparation influences spatial selection of all salient stimuli. Importantly, the facilitatory influence of temporal preparation is not restricted to task-relevant stimuli or targets. Thus, the observed pattern of results is most consistent with the idea that temporal preparation influences spatial selection by facilitating bottom-up processing (see lower part of Figure 5-1).

However, it is interesting to note that although both Studies 2 and 3 show an effect of FP on the N2pc that is related to stimulus salience, the N2pc modulations differ between the two studies. In Study 3, the N2pc amplitude of the salient distractor was enhanced by temporal preparation. As discussed in the Introduction, amplitude modulation can be interpreted as a change in the quality of the underlying process (Otten & Rugg, 2005). Cautiously interpreted, this would imply that temporal preparation qualitatively enhances processes associated with the N2pc of the singleton distractor, i.e., the process of spatial selection that distractor. Although it is difficult to define what constitutes a qualitative enhancement of a process, it is obviously different from a pure acceleration of that process. In contrast to an increase in amplitude, a shift in onset latency can be attributed either to a direct acceleration of the current process

Figure 0-1

Illustration of the results of all studies on the influence of temporal preparation on spatial selection



Note. The results of the individual studies allow different conclusions to be drawn about how temporal preparation influences spatial selection. In the reaction time studies, additive effects of temporal preparation and bottom-up salience or top-down weighting can be observed in the visual search task. This suggests that temporal preparation does not have a direct effect on spatial selection, but rather that temporal preparation influences spatial selection indirectly, e.g. via an influence on early perceptual processing (see upper part of the figure). In the results of Studies 1 and 3, there is no evidence that temporal preparation directly influences top-down processing in spatial selection. In contrast, the results of the event-related potential studies suggest that temporal preparation affects the N2pc as a function of target stimulus salience (Study 2) and also modulates the N2pc of irrelevant distractors (Study 3). Both together can be interpreted as temporal preparation directly influencing spatial selection by facilitating bottom-up processing (see lower part of the figure).

or to an acceleration of previous processes, implying an indirect influence. These two alternatives, i.e., a direct or an indirect acceleration, provide different interpretations for the observed results. In particular, temporal preparation shifted the N2pc onset latency elicited by both targets, the orientation pop-out target in Study 3 and the color pop-out target in Study 2. According to the above assumptions, these latency shifts induced by temporal preparation could be explained by the acceleration of spatial selection itself or by the acceleration of a preceding process. The latter interpretation, that temporal preparation globally accelerates perceptual processing and thus indirectly affects spatial selection, is consistent with the early onset hypothesis (Rolke, 2008; Rolke et al., 2016) and will be discussed below. On the other hand, there is the idea that temporal preparation directly accelerates spatial selection. For the interpretation of our results, it is important to note that the N2pc is influenced by both bottom-up and top-down processes, but that these processes influence the N2pc at different times. In Study 3, it is observed that the N2pc elicited by the target and the singleton distractor are similar in their early parts, while they diverge in their later parts (see Figure 4-4). Given that both stimuli pop out from the surrounding stimuli due to their bottom-up salience, but differ in their task-relevance, this observation slightly supports the assumption that bottom-up processes influence the N2pc earlier than top-down processes. This could explain why the influence of temporal preparation is particularly evident in the earlier part of the N2pc elicited by the target in Studies 2 and 3: If temporal preparation directly influences spatial selection by enhancing bottom-up processing, this should lead to a modulation of the earlier part of the target N2pc, which could be reflected in an earlier emerging N2pc. However, this interpretation must be treated with caution, as it is clearly post-hoc and requires further evidence to confirm the underlying assumptions. Crucially, whether one assumes that the influence of temporal preparation on spatial selection should be observed as an increase in amplitude or as a shift in the onset latency of the N2pc, the interpretation of the N2pc modulation remains the same. Regardless of the particular process facilitated by temporal preparation, the observation that temporal preparation interacts with stimulus salience in its effects strongly supports the notion that temporal preparation plays a role in influencing bottom-up processing in spatial selection.

The finding that temporal preparation influences bottom-up processing in spatial selection is an answer to the main question of this dissertation, which is how temporal preparation influences spatial selection. However, not only bottom-up salience, but also other factors influence spatial selection. Therefore, it is of further interest to investigate whether temporal preparation also improves spatial selection by influencing top-down processes. For this purpose, it is interesting to take a closer look at the results of Study 3. First, temporal preparation was shown to affect the N2pc of the target stimulus and the singleton distractor, but the P_D of the distractor in this study remained unaffected by temporal preparation. Given that the P_D has been associated with top-down suppression of the distractor (Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2016; Hickey et al., 2009), the interpretation of this lack of modulation by temporal preparation may provide an initial starting point if interpreted with caution. First, it is important to note that this is a null effect and may simply be due to the fact that the methods, designs, or sample sizes used in this study do not lend themselves to investigating the true effect. Leaving aside this very likely possibility, one could come to the alternative interpretation that temporal preparation does not actually modulate the distractor P_D. There are several possible reasons for this. First, it could be that temporal preparation enhances stimulus processing but does not affect its suppression. This idea is consistent with accounts suggesting that temporal preparation globally accelerates stimulus processing (Rolke, 2008; Rolke et al., 2016). Regardless of the exact process that is affected by temporal preparation, such an approach would assume that the influence of temporal preparation is non-specific to all stimuli, and therefore leads to enhanced processing of these stimuli rather than suppression. Thus, the observation that temporal preparation did not affect the P_D in Study 3 is consistent with the idea that temporal preparation enhances stimulus processing rather than stimulus suppression in spatial selection. Second, it could be hypothesized that temporal preparation does not affect spatial selection by improving top-down processes. This would be supported by the fact that the influence of temporal preparation on the P_D cannot be measured in our experiment. Since the P_D is an indicator of active top-down suppression (Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2016; Hickey et al., 2009), this null finding can be interpreted that temporal preparation does not specifically influence top-down processing. Furthermore, the observed modulation of the distractor N2pc is consistent with the notion that temporal preparation influences the processing of all salient stimuli. However, since there is a modulation of both target and distractor N2pc by temporal preparation, this cannot be taken as evidence that top-down processing specifically benefits from temporal preparation (see Figure 5-1). Furthermore, there is no evidence in the RTs in Study 1 that temporal preparation influences top-down processing, i.e., by observing additive effects of temporal preparation and top-down information about target feature constancy on RT. However, these RT results must be interpreted with caution, as they also do not allow conclusions to be drawn about the influence of temporal preparation on bottom-up processing. Taken together, the results of Studies 1 and 3 provide no evidence that temporal preparation influences spatial selection via an influence on top-down processing or via a suppression of task-irrelevant stimuli.

Further comparing the results observed in the behavioral and ERP studies, the influence of temporal preparation on RT observed in Study 1 was independent of both target salience and target feature constancy. Thus, Study 1 does not provide evidence for the idea that temporal preparation directly influences spatial selection, e.g. by facilitating bottom-up processing. The question arises as to why the results for RTs should lead to different conclusions than those for ERPs. First, it is important to note that although there was an interaction between FP and setsize on N2pc onset latency in Study 2, this interaction did not extend to RT in the same study. Because the experimental manipulations in the first experiment of Study 1 and in Study 2 were similar, the RT results in both experiments are relatively comparable, as both showed only additive effects. Therefore, it seems possible that temporal preparation directly influences spatial selection, as observed in the current ERP studies and in previous studies (Hackley et al., 20007; Seibold & Rolke, 2014b), but that this influence is not measurable in RT. This raises the question of what might account for the lack of interaction between FP and setsize in RT when observed in N2pc onset latency. Many previous studies have shown that temporal preparation influences various processes other than spatial selection, such as early perceptual processing (Correa et al., 2006; Rolke et al., 2016; Seibold & Rolke, 2014b), later processes such as response selection (Hackley et al., 2007; Müller-Gethmann et al., 2003), as well as motor processes (Mattes & Ulrich, 1997; Sanders, 1980; Spijkers, 1990). Given that temporal preparation affects these very different processes, it seems plausible that the beneficial effect of temporal preparation observed in RT is a mixture of all these improved processes. For example, temporal preparation improves response selection (Hackley et al., 2007; Müller-Gethmann et al., 2003), and since this process occurs after spatial selection, it could be that such a subsequent process superimposes the influence of temporal preparation on spatial selection in RT. Therefore, the specific acceleration of low salient stimuli observed in N2pc due to the influence of temporal preparation on bottom-up processing may not be reflected in RT. Furthermore, there is also some evidence that the N2pc amplitude elicited by a singleton distractor does not necessarily correlate with changes in RT (Liesefeld et al., 2017). This observation is consistent with the results of an additional analysis (Study 3), which showed that the N2pc amplitude of the singleton distractor did not correlate with RT. A cautious interpretation of this null effect would suggest that the distractor N2pc does not necessarily reflect RT, and therefore the observed interaction between FP and setsize does not necessarily translate to RT. Taken together, these two assumptions may explain why the results observed in Study 1 on RT are different from those observed in Studies 2 and 3 in the N2pc. Furthermore, it must be considered that the ERP results allow a more detailed view of the underlying processes. Thus, together with the assumption that the influence of temporal preparation on spatial selection might be masked by other processes when measuring RTs, the ERP studies tend to provide more convincing evidence for an influence of temporal preparation on spatial selection through facilitating bottom-up processing.

An alternative approach to the idea that temporal preparation directly influences spatial selection is that the influence of temporal preparation on the latter is more indirect through an influence on early visual processing in general. This approach - proposed in the early onset theory (Rolke, 2008; Rolke et al., 2016) - would also provide an alternative explanation for the observed differences in N2pc onset latency if some additional assumptions are considered. First, temporal preparation affected the N1, as observed in the current Studies 2 and 3, as well as in previous studies (Correa et al., 2006; Rolke & Hofmann, 2007; Seibold & Rolke 2014b). This indicates that temporal preparation influences early visual processing. Furthermore, one would have to assume that this influence on early visual processes is not uniformly transferred to later processes but depends on the salience of a stimulus. For example, one could imagine that spatial selection has a minimum onset time at which it can begin (e.g., a minimum onset of 180 ms). If this time has already been reached for highly salient stimuli (independent of temporal preparation), no additional acceleration is possible due to the influence of temporal preparation on earlier processes. In this example for highly salient stimuli, the N2pc onset would not differ between short and long FPs and would both be e.g. 180 ms because they are already optimized for both conditions. In contrast, low salient stimuli could still benefit from the additional advantage of temporal preparation because the minimum time for spatial selection to begin has not yet been reached. In this example, the N2pc for the low salient stimuli would start at, say, 210 ms and accelerate even further for short FP intervals, resulting in an N2pc onset latency of, say, 200 ms. This would explain how temporal preparation influences spatial selection through a general and therefore indirect influence, but dependent on stimulus salience. In contrast, the influence of temporal preparation on the amplitude of the N2pc (Study 3) is more difficult to reconcile with an indirect approach. If one assumes that temporal preparation accelerates early visual processing but does not directly affect spatial selection, then this change in amplitude should also be a propagating effect evoked by earlier processes. We know that the observed ERP component, in this case the distractor N2pc, is an average across many observations. If these single-trial waves differ in their onset latency, this can lead to a reduction in the amplitude of the averaged ERP waveform compared to the single-trial waveform (see Luck, 2014, for a detailed description of these averaging biases and ways to avoid them). If one assumes that the effects of temporal preparation on earlier processes lead to a reduction in the variability of the onset latency of subsequent processes (e.g., through optimal timing of all processes), then one could explain that this could lead to an increase in amplitude. Against the idea that temporal preparation accelerates early visual processing, and that this is propagated by averaging into an amplitude difference in the N2pc, is the fact that this averaging bias often results in a broader and more spread-out waveform (Luck, 2014). Comparing the difference waves elicited by short and long FP in Study 3 (Figure 4-4), we see that the onset latency is not affected by temporal preparation. Since this argues against an averaging bias, the N2pc amplitude modulation is difficult to reconcile with an indirect influence of temporal preparation on spatial selection. Rather, it seems plausible that temporal preparation directly influences spatial selection.

Returning to the assumption that temporal preparation influences spatial selection by facilitating bottom-up processing, the question arises how this might be embedded in models of visual search (Awh et al., 2012; Itti & Koch, 2001; Liesefeld & Müller, 2021; Wolfe, 1994, 2021). For example, in the guided search model (Wolfe, 1994, 2021), spatial selection describes the process of stimulus selection by spatial attention for further processing based on location-based activation. Bottom-up processing in this model depends on the activation value and thus the salience of a stimulus relative to its surround. More specifically, attention is directed to those locations on the priority map that have a high activation value relative to the surrounding locations. Interestingly, it is not the activation value per se that determines which stimulus is selected for further processing, but the difference between the activation values for different locations. Assuming that temporal preparation affects spatial selection by facilitating bottom-up processing, temporal preparation could alter this activation contrast between the stimulus and the surrounding stimuli. Alternatively, it is possible that temporal preparation optimizes the process of spatial selection by speeding up the construction of activation maps. In this scenario, it is not the activation difference itself that is affected, but the time it takes to build these maps.

However, both possible mechanisms depend on the same concept: the signal-to-noise ratio. The signal-to-noise ratio describes the difference between the signal (defined here as the stimulus itself and its surround) and the noise (the random signal variation within the perceptual process). The signal-to-noise ratio can be increased by increasing the difference in activation between the salient and surround stimuli. This can be achieved by increasing the signal activation of the salient stimulus or by reducing the noise (either by reducing the noise in the system or by reducing the activation of the surround stimuli, see the PTM for a detailed model of this; Dosher & Lu, 1998; Lu & Dosher, 2005). From a neurophysiological perspective, this idea has been discussed within the framework of gain and tuning models in the context of spatial and feature-based attention (Ling et al., 2009; Martinez-Trujillo & Treue, 2004; Reynolds & Chelazzi, 2004). The gain model predicts that attention enhances the neural response to a stimulus at attended locations (spatial attention; Ling et al., 2009) or for attended features (feature-based attention; Ling et al., 2009; Martinez-Trujillo & Treue, 2004). In the context of temporal preparation, one could speculate that gain should increase the stimulus signal specifically during attended time points. On the other hand, the tuning model predicts that attention sharpens the neural response profile to attended locations or features and suppresses the neural response to irrelevant stimuli or noise. In this case, tuning should reduce extraneous noise during attended time, thereby optimizing the signal-to-noise ratio for target stimulus selection. Indeed, it is also plausible that both mechanisms, gain and tuning, work in combination to improve the signal-to-noise ratio. Both mechanisms would lead to the conclusion that temporal preparation affects spatial selection by altering the signal-to-noise ratio, thereby influencing bottom-up processing during spatial selection.

Further, as noted above, it is possible that temporal preparation optimizes the process of spatial selection by speeding up the construction of activation maps. Since higher salience (in the case of bottom-up processing) allows for a higher activation value for a stimulus, signal quality, defined as the difference between the target and surrounding distractors, is improved. As a result, the construction of the activation map containing input with an optimized signal-to-noise ratio may be faster, and consequently the map will be available earlier. Finally, and most importantly in our case, the influence of temporal preparation on bottom-up processing in spatial selection may be due to an improvement in signal-to-noise ratio.

Following this conclusion, the results of Study 2, i.e., earlier onset of the N2pc with good temporal preparation, especially for low salient targets, are fully consistent with this hypothesis: if temporal preparation improves the signal-to-noise ratio, this should be particularly beneficial when the signal-to-noise ratio is initially low, as it was in the low salient target condition. Consistent with this observation are studies that found the effect of temporal preparation to be greater in tasks where the signal-to-noise ratio is low and therefore stimulus processing is difficult (Bausenhart et al., 2010; Jepma et al., 2012; Rolke, 2008). For example, as mentioned in the Introduction, Rolke and Hofmann (2007) investigated the influence of temporal preparation on perceptual processing in a masking study. First, they observed an effect of FP on d', which served as an index of discrimination performance. Most interestingly, the FP effect decreased as the duration of the target stimulus presentation before masking increased. It can be concluded that temporal preparation for targets was particularly beneficial when stimulus processing was most difficult, i.e., when target duration was shortest. Although the influence of temporal preparation in this study is not necessarily due to the process of spatial selection, these results fit well with the assumption that temporal preparation improves the signal-to-noise ratio. Finally, the results of the reported studies can be theorized as an influence of temporal preparation on spatial selection by improving the signal-to-noise ratio, thereby facilitating bottom-up processing.

The theoretical idea that temporal preparation improves the signal-to-noise ratio in spatial selection remains to be tested. A first approach to testing this hypothesis can be derived from the PTM (Dosher & Lu, 1998; Lu & Dosher, 2005). The PTM provides a framework for how signal-to-noise ratio can be improved by proposing the interaction of three processes: stimulus enhancement, external noise exclusion, and internal noise reduction. Assuming that temporal preparation affects spatial selection by influencing one of these processes, one can test this assumption empirically by following the approach of Lu and Dosher (2005). They propose that stimulus enhancement, external noise exclusion and internal noise reduction can be discriminated experimentally as a function of signal strength and external noise (Lu & Dosher, 2005). Based on the results of Study 3, which found no evidence for signal suppression but did find that temporal preparation enhanced the process of spatial selection, it may be of particular interest whether temporal preparation in this model can be reconciled with the idea of stimulus enhancement. In particular, in the PTM, the influence of stimulus enhancement is observed under conditions of low signal strength and low external noise. Thus, by experimentally varying the level of signal strength and external noise, it can be tested whether temporal preparation affects one of the proposed attentional mechanisms. Such a systematic investigation could provide further evidence that temporal preparation improves bottom-up processing in spatial selection and clarify the underlying mechanism, i.e., an increase in the signal-to-noise ratio by stimulus enhancement, external noise exclusion, or internal noise reduction.

Although the exact mechanism requires further research, the results of the presented studies (Studies 2 and 3) suggest that temporal preparation affects spatial selection by facilitating bottom-up processing. However, since the present studies mainly addressed bottom-up processing, it remains to be seen whether other factors, such as top-down goals or prior history, also benefit from temporal preparation to influence spatial selection. As discussed above, it is difficult to interpret whether temporal preparation specifically influences top-down processing in spatial selection. Nevertheless, there is some evidence that temporal preparation may be particularly effective when relevant features of the target are known in advance, allowing for a top-down representation. For example, in a variable FP paradigm, Schröter et al. (2014) found that the FP effect was larger when participants could predict the upcoming task than when they could not. This finding may highlight the fact that temporal preparation specifically improves processes that are controlled by top-down guidance. Even stronger evidence is provided by cueing paradigms in which the use of temporal information or cues is explicitly induced and thus requires top-down processing (Doherty et al., 2005; Kingstone, 1992; Olk, 2014; Rohenkohl et al., 2014). For example, Kingstone (1992) combined temporal and feature expectations in a cueing experiment. Importantly, both cueing dimensions interacted in their effect, i.e., RT was fastest when it appeared at the cued time and had the cued shape. This finding is consistent with other results examining an interaction between temporal and spatial cues (Doherty et al., 2005; Olk, 2014; Rohenkohl et al., 2014; Seibold et al., 2020).

Finally, the results of these cueing studies can be interpreted as an indication that temporal and non-temporal information contribute to the formation of a top-down representation and thus enable selective top-down processing. Whether these results generalize to other paradigms, such as the constant FP paradigm, in which temporal preparation is induced more implicitly, remains to be seen. In particular, further research is needed to clarify whether temporal preparation influences spatial selection by enhancing top-down processing.

Regarding an influence of temporal preparation on spatial selection through the influence of prior history, several studies provide interesting starting points. For example, in the variable FP paradigm, it has been observed that FP in previous trials influences responses in the current trial, leading to longer RTs in the case of a switch (i.e., short FP following a long FP; Los, 2010; Los & van den Heuvel, 2001). Independent of spatial selection, this influence could be interpreted as an interaction of temporal preparation and history effects. For even stronger evidence, Los and colleagues (2021) paired a FP (e.g., long) with a specific warning signal (e.g., tone) in a test phase. In a subsequent experimental phase in which subjects were explicitly told that this coupling was now removed, RTs in a discrimination task were nevertheless faster when the FP was presented with the previously coupled warning signal. Cautiously interpreted, this result could be seen as evidence for interactions between temporal preparation and prior history. It remains to be clarified whether these interactions can be transferred to perceptual processes or even to spatial selection.

In short, the aim of this dissertation was to clarify how temporal preparation influences spatial selection. Therefore, three studies were conducted to investigate whether temporal preparation has a direct influence on spatial selection by facilitating bottom-up and/or top-down processing. Study 1 measured RT to investigate such an influence but found no interactive effect of temporal preparation on either bottom-up or top-down processing. In contrast, and most interestingly, Study 2 found that spatial selection, as measured by the N2pc, was modulated by temporal preparation as a function of target salience. Given that target salience is a bottom-up property, the modulation of N2pc onset latency provides evidence that temporal preparation facilitates bottom-up processing and thereby influences spatial selection. Further support for this hypothesis was observed in Study 3. Temporal preparation did not affect top-down suppression of a task-irrelevant but salient distractor. Instead, temporal preparation affected spatial selection, i.e., the N2pc, of both the target and the singleton distractor. The results of Study 3 suggest that temporal preparation affects spatial selection of all salient stimuli, and thus bottom-up rather than top-down processing. Finally, the present studies are consistent with the view that temporal preparation directly influences spatial selection by facilitating bottom-up processing.

References

American Electroencephalographic Society (1994). Guideline thirteen: Guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 11*(1), 111–113. https://doi.org/10.1097/00004691-199401000-00014

Awh, E., Belopolsky, A.V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences, 16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bachman, M.D., Wang, L., Gamble, M.L., & Woldorff, M.G. (2020). Physical salience and value-driven salience operate through different neural mechanisms to enhance attentional selection. *Journal of Neuroscience, 40*(28), 5455–5464. https://doi.org/10.1523/jneurosci.1198-19.2020

Bacon, W.F., & Egeth, H.E. (1991). Local processes in preattentive feature detection. *Journal of Experimental Psychology: Human Perception and Performance, 17*(1), 77–90. https://doi.org/10.1037/0096- 1523.17.1.77

Balke, J., Rolke, B., & Seibold, V.C. (2021). Reduction of temporal uncertainty facilitates stimulus-driven processes in spatial selection. *Biological Psychology, 159*, 108028. https://doi.org/10.1016/j.biopsycho.2021.108028

Balke, J., Rolke, B., & Seibold, V. C. (2022). Temporal preparation accelerates spatial selection by facilitating bottom-up processing. *Brain research*, 1777, 147765. https://doi.org/10.1016/j.brainres.2021.147765

Barras, C., & Kerzel, D. (2017). Target-nontarget similarity decreases search efficiency and increases stimulus-driven control in visual search. *Attention, Perception, & Psychophysics, 79*(7), 2037–2043. https://doi.org/10.3758/s13414-017-1367-9

Bausenhart, K. M., Rolke, B., Hackley, S. A., & Ulrich, R. (2006). The locus of temporal preparation effects: Evidence from the psychological refractory period paradigm. *Psychonomic Bulletin & Review, 13*(3), 536–542. https://doi.org/10.3758/bf03193882

Bausenhart, K. M., Rolke, B., & Ulrich, R. (2007). Knowing when to hear aids what to hear. *Quarterly Journal of Experimental Psychology, 60*(12), 1610–1615. https://doi.org/10.1080/17470210701536419

Bertelson, P. (1967). The time course of preparation. *Quarterly Journal of Experimental Psychology, 19*(3), 272–279. https://doi.org/10.1080/14640746708400102

Bravo, M.J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics, 51*(5), 465–472. https://doi.org/10.3758/bf03211642

Breska, A., & Deouell, L. Y. (2014). Automatic Bias of Temporal Expectations following Temporally Regular Input Independently of High-level Temporal Expectation. *Journal of Cognitive Neuroscience, 26*(7), 1555–1571. https://doi.org/10.1162/jocn_a_00564

Breska, A., & Deouell, L. Y. (2017). Dance to the rhythm, cautiously: Isolating unique indicators of oscillatory entrainment. *PLOS Biology, 15*(9), e2003534. https://doi.org/10.1371/journal.pbio.2003534

Brisson, B., Leblanc, É., & Jolicoeur, P. (2009). Contingent capture of visual-spatial attention depends on capacity-limited central mechanisms: Evidence from human electrophysiology and the psychological refractory period. *Biological Psychology, 80*(2), 218–225. https://doi.org/10.1016/j.biopsycho.2008.10.001

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with reference tables. *Journal of Cognition, 2*(1), 16. https://doi.org/10.5334/joc.72

Burle, B., Tandonnet, C., & Hasbroucq, T. (2010). Excitatory and inhibitory motor mechanisms of temporal preparation. In A. C. Nobre, & J. T. Coull (Eds.), *Attention and time* (pp. 243–256.). Oxford: University Press. https://doi.org/10.1093/acprof:oso/9780199563456.003.0018

Burra, N., & Kerzel, D. (2013). Attentional capture during visual search is attenuated by target predictability: Evidence from the N2pc, Pd, and topographic segmentation. *Psychophysiology, 50*(5), 422–430. https://doi.org/10.1111/psyp.12019

Campbell, J.I.D., & Thompson, V.A.T. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behavior Research Methods, 44*(4), 1255–1265. https://doi.org/10.3758/s13428-012-0186-0

Chan, L. K., & Hayward, W. G. (2013). Visual search. *Wiley Interdisciplinary Reviews: Cognitive Science, 4*(4), 415–429. https://doi.org/10.1002/wcs.1235

Chicherov, V., Plomp, G., & Herzog, M.H. (2014). Neural correlates of visual crowding. *Neuroimage*, 93, 23–31. https://doi.org/10.1016/j.neuroimage.2014.02.021

Connor, C. E., Egeth, H. E., & Yantis, S. (2004). Visual attention: Bottom-up versus top-down. *Current Biology, 14*(19), R850–R852. https://doi.org/10.1016/j.cub.2004.09.041

Correa, Á. (2010). Enhancing behavioural performance by visual temporal orienting. In A. C. Nobre, & J. T. Coull (Eds.), *Attention and time* (pp. 359–370). Oxford: University Press. https://doi.org/10.1093/acprof:oso/9780199563456.003.0026

Correa, Á., Cappucci, P., Nobre, A. C., & Lupiáñez, J. (2010). The Two Sides of Temporal Orienting. *Experimental Psychology, 57*(2), 142–148. https://doi.org/10.1027/1618-3169/a000018

Correa, Á., Lupiáñez, J., Madrid, E., & Tudela, P. (2006). Temporal attention enhances early visual processing: A review and new evidence from event-related potentials. *Brain Research, 1076*(1), 116–128. https://doi.org/10.1016/j.brainres.2005.11.074

Correa, Á., Lupiáñez, J., Milliken, B., & Tudela, P. (2004). Endogenous temporal orienting of attention in detection and discrimination tasks. *Perception & Psychophysics, 66*(2), 264–278. https://doi.org/10.3758/bf03194878

Correa, Á., Lupiáñez, J., & Tudela, P. (2005). Attentional preparation based on temporal expectancy modulates processing at the perceptual level. *Psychonomic Bulletin & Review, 12*(2), 328–334. https://doi.org/10.3758/bf03196380

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: The neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience, 18*(18), 7426–7435. https://doi.org/10.1523/jneurosci.18-18-07426.1998

Cousineau, D. (2005). Confidence intervals in within-subjects designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology, 1*(1), 42–45. https://doi.org/10.20982/tqmp.01.1.p042

Doherty, J. R., Rao, A., Mesulam, M. M., & Nobre, A. C. (2005). Synergistic effect of combined temporal and spatial expectations on visual attention. *Journal of Neuroscience, 25*(36), 8259–8266. https://doi.org/10.1523/JNEUROSCI.1821-05.2005

Dosher, B. A., & Lu, Z.-L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proceedings of the*

National Academy of Sciences of the United States of America, 95(23), 13988–13993. https://doi.org/10.1073/pnas.95.23.13988

Drisdelle, B. L., West, G. L., & Jolicoeur, P. (2016). The deployment of visual spatial attention during visual search predicts response time: Electrophysiological evidence from the N2pc. *Neuroreport, 27*(16), 1237–1242. https://doi.org/10.1097/wnr.0000000000000684

Duncan, J., & Humphreys, G.W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*(3), 433–458. https://doi.org/10.1037/0033-295x.96.3.433.

Eckstein, M. P. (2011). Visual search: A retrospective. *Journal of Vision, 11*(5), 1–36. https://doi.org/10.1167/11.5.14

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology,* 99(3), 225–234. https://doi.org/10.1016/0013-4694(96)95711-9

Eimer, M. (2014). The time course of spatial attention: insights from event-related brain potentials. In Nobre, A.C., Kastner, S. (Eds.), *The Oxford Handbook of Attention* (pp. 289–317). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199675111.001.0001

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 20*(8), 1423–1433. https://doi.org/10.1162/jocn.2008.20099

Eimer, M., Kiss, M., Press, C., & Sauter, D. (2009). The roles of feature-specific task set and bottom-up salience in attentional capture: An ERP study. *Journal of Experimental Psychology: Human Perception and Performance, 35*(5), 1316–1328. https://doi.org/10.1037/a0015872

Evans, K.K., Horowitz, T.S., Howe, P., Pedersini, R., Reijnen, E., Pinto, Y., Kuzmova, Y., & Wolfe, J.M., (2011). Visual attention. *Wiley Interdisciplinary Reviews: Cognitive Science, 2*(5), 503–514. https://doi.org/10.1002/wcs.127

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. https://doi.org/10.3758/bf03193146

Fecteau, J. H., & Munoz, D. P. (2006). Salience, relevance, and firing: A priority map for target selection. *Trends in Cognitive Sciences, 10*(8), 382–390. https://doi.org/10.1016/j.tics.2006.06.011

Feldmann-Wüstefeld, T., & Schubö, A. (2013). Context homogeneity facilitates both distractor inhibition and target enhancement. *Journal of Vision, 13*(3), 1–12. https://doi.org/10.1167/13.3.11

Feldmann-Wüstefeld, T., & Schubö, A. (2016). Intertrial priming due to distractor repetition is eliminated in homogeneous contexts. *Attention, Perception, Psychophysics, 78*(7), 1935–1947. https://doi.org/10.3758/s13414-016-1115-6

Fedota, J.R., McDonald, C.G., Roberts, D.M., & Parasuraman, R. (2012). Contextual task difficulty modulates stimulus discrimination: Electrophysiological evidence for interaction between sensory and executive processes. *Psychophysiology, 49*(10), 1384–1393. https://doi.org/10.1111/j.1469-8986.2012.01455.x

Folk, C. L., & Remington, R. W. (2008). Bottom-up priming of top-down attentional control settings. *Visual Cognition, 16*(2-3), 215–231. https://doi.org/10.1080/13506280701458804

Fort, A., Besle, J., Giard, M.-H., & Pernier, J. (2005). Task-dependent activation latency in human visual extrastriate cortex. *Neuroscience Letters, 379*(2), 144–148. https://doi.org/10.1016/j.neulet.2004.12.076

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a “dimension-weighting” account. *Perception & Psychophysics, 58*(1), 88–101. https://doi.org/10.3758/Bf03205479

Frowein, H. W., & Sanders, A. F. (1978). Effects of visual stimulus degradation, S-R compatibility, and foreperiod duration on choice reaction time and movement time. *Bulletin of the Psychonomic Society, 12*(2), 106–108. https://doi.org/10.3758/bf03329641

Gaspar, J.M., & McDonald, J.J. (2014). Suppression of salient objects prevents distraction in visual search. *Journal of Neuroscience, 34*(16), 5658–5666. https://doi.org/10.1523/ jneurosci.4161-13.2014

Gaspelin, N., & Luck, S. J. (2018). The role of inhibition in avoiding distraction by salient stimuli. *Trends in Cognitive Sciences, 22*(1), 79–92. https://doi.org/10.1016/j.tics.2017.11.001

Gottsdanker, R. (1975). The attaining and maintaining of preparation. In P. M. Rabbit, & S. Dornic (Eds.), *Attention and performance V* (pp. 33–49). Oxford: Academic Press.

Griffin, I. C., Miniussi, C., & Nobre, A. C. (2001). Orienting attention in time. *Frontiers in Bioscience, 6*(1), d660–d671. https://doi.org/10.2741/griffin

Griffin, I. C., Miniussi, C., & Nobre, A. C. (2002). Multiple mechanisms of selective attention: differential modulation of stimulus processing by attention to space or time. *Neuropsychologia, 40*(13), 2325–2340. https://doi.org/10.1016/s0028-3932(02)00087-8

Hackley, S. A., Langner, R., Rolke, B., Erb, M., Grodd, W., & Ulrich, R. (2009). Separation of phasic arousal and expectancy effects in a speeded reaction time task via fMRI. *Psychophysiology, 46*(1), 163–171. https://doi.org/10.1111/j.1469-8986.2008.00722.x

Hackley, S. A., Schankin, A., Wohlschläger, A., & Wascher, E. (2007). Localization of temporal preparation effects via trisected reaction time. *Psychophysiology, 44*(2), 334–338. https://doi.org/10.1111/j.1469-8986.2007.00500.x

Han, S., Song, Y., Ding, Y., Yund, E.W., Woods, D.L. (2001). Neural substrates for visual perceptual grouping in humans. *Psychophysiology, 38*(6), 926–935. https://doi.org/10.1111/1469-8986.3860926

Hasbroucq, T., Kaneko, H., Akamatsu, M., & Possama, C.-A. (1999). The time-course of preparatory spinal and cortico-spinal inhibition: an H-reflex and transcranial magnetic stimulation study in man. *Experimental Brain Research, 124*(1), 33–41. https://doi.org/10.1007/s002210050597

Herbst, S. K., Obleser, J., & van Wassenhove, V. (2022). Implicit Versus Explicit Timing—Separate or Shared Mechanisms? *Journal of Cognitive Neuroscience, 34*(8), 1447–1466. https://doi.org/10.1162/jocn_a_01866

Heuer, A., & Schubö, A. (2020). Cueing distraction: Electrophysiological evidence for anticipatory active suppression of distractor location. *Psychological Research, 84*(8), 2111–2121. https://doi.org/10.1007/s00426-019-01211-4

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward Changes Salience in Human Vision via the Anterior Cingulate. *The Journal of Neuroscience, 30*(33), 11096–11103. https://doi.org/10.1523/jneurosci.1026-10.2010

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience, 21*(4), 760–775. https://doi.org/10.1162/jocn.2009.21039

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience, 18*(4), 604–613. https://doi.org/10.1162/jocn.2006.18.4.604

Hopf, J.M., Vogel, E., Woodman, G., Heinze, H.J., & Luck, S.J. (2002). Localizing visual discrimination processes in time and space. *Journal of Neurophysiology, 88*(4), 2088–2095. https://doi.org/10.1152/jn.2002.88.4.2088

Hyde, D.C., & Spelke, E.S. (2012). Spatiotemporal dynamics of processing nonsymbolic number: an event-related potential source localization study. *Human Brain Mapping, 33*(9), 2189–2203. https://doi.org/10.1002/hbm.21352

Itthipuripat, S., Sprague, T. C., & Serences, J. T. (2019). Functional MRI and EEG index complementary attentional modulations. *Journal of Neuroscience, 39*(31), 6162–6179. https://doi.org/10.1523/JNEUROSCI.2519-18.2019

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience, 2*(3), 194–203. https://doi.org/10.1038/35058500

Jentzsch, I., Leuthold, H., & Ulrich, R. (2007). Decomposing sources of response slowing in the PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33*(3), 610–626. https://doi.org/10.1037/0096-1523.33.3.610

Jepma, M., Wagenmakers, E.J., & Nieuwenhuis, S. (2012). Temporal expectation and information processing: a model-based analysis. *Cognition, 122*(3), 426–441. https://doi.org/10.1016/j.cognition.2011.11.014

Jones, M. R. (2010). Attending to sound patterns and the role of entrainment. In A. C. Nobre, & J. T. Coull (Eds.), *Attention and time* (pp. 317–330). Oxford: University Press. https://doi.org/10.1093/acprof:oso/9780199563456.003.0023

Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal Aspects of Stimulus-Driven Attending in Dynamic Arrays. *Psychological Science, 13*(4), 313–319. https://doi.org/10.1111/1467-9280.00458

Joseph, J., Chun, M., & Nakayama, K. (1997). Attentional requirements in a ‘preattentive’ feature search task. *Nature, 387*(6635), 805–807. https://doi.org/10.1038/42940

Kiesel, A., Miller, J., Jolicoeur, P., & Brisson, B. (2008). Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods. *Psychophysiology, 45*(2), 250–274. https://doi.org/10.1111/j.1469-8986.2007.00618.x

Kingstone, A. (1992). Combining expectancies. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 44*(1), 69–104. https://doi.org/10.1080/14640749208401284

Kiss, M., Driver, J., & Eimer, M. (2009). Reward priority of visual target singletons modulates event-related potential signatures of attentional selection. *Psychological Science, 20*(2), 245–251. https://doi.org/10.1111/j.1467-9280.2009.02281.x

Klemmer, E. T. (1956). Time uncertainty in simple reaction time. *Journal of Experimental Psychology, 51(*3), 179–184. https://doi.org/10.1037/h0042317

Lamy, D., & Zoaris, L. (2009). Task-irrelevant stimulus salience affects visual search. *Vision Research, 49*(11), 1472–1480. https://doi.org/10.1016/j.visres.2009.03.007

Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2008). Entrainment of Neuronal Oscillations as a Mechanism of Attentional Selection. *Science, 320*(5872), 110–113. https://doi.org/10.1126/science.1154735

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*, 863. https://doi.org/10.3389/fpsyg.2013.00863

Lamy, D., & Egeth, H. E. (2003). Attentional capture in singleton-detection and feature-search modes. *Journal of Experimental Psychology: Human Perception and Performance, 29*(5), 1003–1020. https://doi.org/10.1037/0096-1523.29.5.1003

Lange, K., & Röder, B. (2006). Orienting attention to points in time improves stimulus processing both within and across modalities. *Journal of Cognitive Neuroscience, 18(5)*, 715–729. https://doi.org/10.1162/jocn.2006.18.5.715

Lange, K., Rösler, F., & Röder, B. (2003). Early processing stages are modulated when auditory stimuli are presented at an attended moment in time: An event-related potential study. *Psychophysiology, 40*(5), 806–817. https://doi.org/10.1111/1469-8986.00081

Lee, J., Leonard, C. J., Luck, S. J., & Geng, J. J. (2018). Dynamics of feature-based attentional selection during color-shape conjunction search. *Journal of*

Cognitive Neuroscience, 30(12), 1773–1787. https://doi.org/10.1162/jocn_a_01318

Leuthold, H., Sommer, W., & Ulrich, R. (2004). Preparing for action: Inferences from CNV and LRP. *Journal of Psychophysiology, 18*(2/3), 77–88. https://doi.org/10.1027/0269-8803.18.23.77

Liesefeld, H. R., Liesefeld, A. M., Töllner, T., & Müller, H. J. (2017). Attentional capture in visual search: Capture and post-capture dynamics revealed by EEG. *NeuroImage, 156*, 166–173. https://doi.org/10.1016/j.neuroimage.2017.05.016

Liesefeld, H.R., & Müller, H.J. (2021). Modulations of saliency signals at two hierarchical levels of priority computation revealed by spatial statistical distractor learning. *Journal of Experimental Psychology: General, 150*(4), 710–728. https://doi.org/10.1037/xge0000970.

Ling, S., Liu, T., & Carrasco, M. (2009). How spatial and feature-based attention affect the gain and tuning of population responses. *Vision Research, 49*(10), 1194–1204. https://doi.org/10.1016/j.visres.2008.05.025

Lleras, A., Wang, Z., Ng, G.J.P., Ballew, K., Xu, J., & Buetti, S. (2020). A target contrast signal theory of parallel processing in goal-directed search. *Attention, Perception, & Psychophysics, 82*(2), 394–425. https://doi.org/10.3758/s13414-019-01928-9

Los, S. A. (2010). Foreperiod and sequential effects: theory and data. In A. C. Nobre, & J. T. Coull (Eds.), *Attention and time* (pp. 289–302). Oxford: University Press. https://doi.org/10.1093/acprof:oso/9780199563456.003.0021

Los, S. A., & Agter, F. (2005). Reweighting sequential effects across different distributions of foreperiods: Segregating elementary contributions to nonspecific preparation. *Perception & Psychophysics, 67*(7), 1161–1170. https://doi.org/10.3758/bf03193549

Los, S.A., & Schut, M.L. (2008). The effective time course of preparation. *Cognitive Psychology, 57*(1), 20–55. https://doi.org/10.1016/j.cogpsych.2007.11.001

Los, S. A., & Van den Heuvel, C. E. (2001). Intentional and unintentional contributions to nonspecific preparation during reaction time foreperiods. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 370–386. https://doi.org/10.1037/0096-1523.27.2.370

Los, S. A., Kruijne, W., & Meeter, M. (2014). Outlines of a multiple trace theory of temporal preparation. *Frontiers in Psychology, 5*, 1058. https://doi.org/10.3389/fpsyg.2014.01058

Loveless, N. E. (1973). The contingent negative variation related to preparatory set in a reaction time situation with variable foreperiod. Electroencephalography and *Clinical Neurophysiology, 35*(4), 369–374. https://doi.org/10.1016/0013-4694(73)90193-4

Lu, Z. L., & Dosher, B. A. (2005). External noise distinguishes mechanisms of attention. In L. Itti, G. Rees, & J. K. Tsotsos (Eds.), *Neurobiology of attention* (pp. 448–453). Elsevier Academic Press. https://doi.org/10.1016/b978-012375731-9/50078-1

Luck, S. J. (2012). Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components. In S. J. Luck, & E. Kappenmann (Eds.), *The Oxford handbook of event-related potential components* (pp. 329–360). New York: Oxford University Press.

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT Press.

Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology, 54(1)*, 146–157. https://doi.org/10.1111/psyp.12639

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20*(5), 1000–1014. https://doi.org/10.1037/0096-1523.20.5.1000

Luck, S.J., & Hillyard, S.A. (1995). The role of attention in feature detection and conjunction discrimination: an electrophysiological analysis. *International Journal of Neuroscience, 80*(1–4), 281–297. https://doi.org/10.3109/00207459508986105

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. *Role of features. Memory & Cognition, 22*(6), 657–672. https://doi.org/10.3758/bf03209251

Mangun, G.R., & Hillyard, S.A. (1991). Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. *Journal of Experimental Psychology: Human Perception and Performance, 17*(4), 1057–1074. https://doi.org/10.1037/0096-1523.17.4.1057

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-Based Attention Increases the Selectivity of Population Responses in Primate Visual Cortex. *Current Biology, 14*(9), 744–751. https://doi.org/10.1016/j.cub.2004.04.028

Mattes, S., & Ulrich, R. (1997). Response force is sensitive to the temporal uncertainty of response stimuli. *Perception & Psychophysics, 59*(7), 1089–1097. https://doi.org/10.3758/bf03205523

Mazza, V., Turatto, M., Umiltà, C., & Eimer, M. (2007). Attentional selection and identification of visual objects are reflected by distinct electrophysiological responses. *Experimental Brain Research, 181*(3), 531–536. https://doi.org/10.1007/s00221-007- 1002-4

Mazza, V., Turatto, M., & Caramazza, A. (2009). Attention selection, distractor suppression and N2pc. *Cortex, 45(7)*, 879–890. https://doi.org/10.1016/j.cortex.2008.10.009

Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35(1)*, 99–115. https://doi.org/10.1111/1469-8986.3850816

Miniussi, C., Wilding, E. L., Coull, J., & Nobre, A. C. (1999). Orienting attention in time: Modulation of brain potentials. *Brain, 122*(8), 1507–1518. https://doi.org/10.1093/brain/122.8.1507

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology, 4*(2), 61–64. https://doi.org/10.20982/tqmp.04.2.p061

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics, 57*(1), 1–17. https://doi.org/10.3758/bf03211845

Müller, H. J., Krummenacher, J., & Schubert, T. (2015). Visuelle Suche. In H. J. Müller, J. Krummenacher, & T. Schubert (Eds.), *Aufmerksamkeit und Handlungssteuerung* (pp. 45–56). Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-41825-9_5

Müller-Gethmann, H., Ulrich, R., & Rinkenauer, G. (2003). Locus of the effect of temporal preparation: Evidence from the lateralized readiness potential. *Psychophysiology, 40(4)*, 597–611. https://doi.org/10.1111/1469-8986.00061

Näätänen, R., & Merisalo, A. (1977). Expectancy and preparation in simple reaction time. In S. Dornic (Ed.), *Attention and performance VI* (pp. 115–138). Lawrence Erlbaum.

Näätänen, R., Muranen, V., & Merisalo, A. (1974). Timing of expectancy peak in simple reaction time situation. *Acta Psychologica, 38*(6), 461–470. https://doi.org/10.1016/0001-6918(74)90006-7

Niemi, P., & Näätänen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin, 89*(1), 133–162. https://doi.org/10.1037/0033-2909.89.1.133

Nobre, A. C., & van Ede, F. (2018). Anticipated moments: Temporal structure in attention. *Nature Reviews Neuroscience, 19*(1), 34–48. https://doi.org/10.1038/nrn.2017.141

Nothdurft, H.-C. (2000). Salience from feature contrast: additivity across dimensions. *Vision Research,* 40(10–12), 1183–1201. https://doi.org/10.1016/s0042-6989(00)00031-6

Nothdurft, H.-C. (2005). Salience of feature contrast. In: Itti, L., Rees, G., Tsotsos, J.K. (Eds.), *Neurobiology of Attention* (pp. 233–239). Academic Press. https://doi.org/ 10.1016/b978-012375731-9/50042-2

Oemisch, M., Watson, M. R., Womelsdorf, T., & Schubö, A. (2017). Changes of attention during value-based reversal learning are tracked by N2pc and feedback-related negativity. *Frontiers in Human Neuroscience, 11*, 540. https://doi.org/10.3389/fnhum.2017.00540

Olk, B. (2014). Effects of spatial, temporal and spatiotemporal cueing are alike when attention is directed voluntarily. *Experimental Brain Research, 232*(11), 3623–3633. https://doi.org/10.1007/s00221-014-4033-7

Otten, L. J., & Rugg, M. D. (2005). Interpreting event-related brain potentials. In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (pp. 3-16). MIT Press

Petersen, A., Petersen, A. H., Bundesen, C., Vangkilde, S., & Habekost, T. (2017). The effect of phasic auditory alerting on visual perception. *Cognition, 165*, 73–84. https://doi.org/10.1016/j.cognition.2017.04.004

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*(1), 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Praamstra, P., Kourtis, D., Fei Kwok, H., & Oostenveld, R. (2006). Neurophysiology of Implicit Timing in Serial Choice Reaction-Time Performance. *The Journal of Neuroscience, 26*(20), 5448–5455. https://doi.org/10.1523/jneurosci.0440-06.2006

Rangelov, D., Müller, H.J., & Zehetleitner, M. (2017). Failure to pop out: Feature singletons do not capture attention under low signal-to-noise ratio conditions. *Journal of Experimental Psychology: General, 146*(5), 651–671. https://doi.org/10.1037/xge0000284

Requin, J., Brener, J., & Ring, C. (1991). Preparation for action. In J. R. Jennings, & M. G. H. Coles (Eds.), *Wiley psychophysiology handbooks. Handbook of cognitive psychophysiology: Central and autonomic nervous system approaches* (pp. 357–448). John Wiley & Sons.

Reynolds, J. H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Review of Neuroscience, 27*(1), 611–647. https://doi.org/10.1146/annurev.neuro.26.041002.131039

Rohenkohl, G., & Nobre, A. C. (2011). Alpha oscillations related to anticipatory attention follow temporal expectations. *Journal of Neuroscience, 31*(40), 14076–14084. https://doi.org/10.1523/JNEUROSCI.3387-11.2011

Rohenkohl, G., Cravo, A. M., Wyart, V., & Nobre, A. C. (2012). Temporal expectation improves the quality of sensory information. *Journal of Neuroscience, 32*(24), 8424–8428. https://doi.org/10.1523/JNEUROSCI.0804-12.2012

Rohenkohl, G., Gould, I. C., Pessoa, J., & Nobre, A. C. (2014). Combining spatial and temporal expectations to improve visual perception. *Journal of Vision, 14*(4), 8. https://doi.org/10.1167/14.4.8

Rolke, B. (2008). Temporal preparation facilitates perceptual identification of letters. *Perception & Psychophysics, 70*(7), 1305–1313. https://doi.org/10.3758/PP.70.7.1305

Rolke, B., & Hofmann, P. (2007). Temporal uncertainty degrades perceptual processing. *Psychonomic Bulletin & Review, 14*(3), 522–526. https://doi.org/10.3758/BF03194101

Rolke, B., & Ulrich, R. (2010). On the locus of temporal preparation: Enhancement of pre-motor processes? In A. C. Nobre, & J. T. Coull (Eds.), *Attention and time* (pp. 227–241). Oxford: University Press. https://doi.org/10.1093/acprof:oso/9780199563456.003.0017

Rolke, B., Festl, F., & Seibold, V. C. (2016). Toward the influence of temporal attention on the selection of targets in a visual search task: An ERP study. *Psychophysiology, 53*(11), 1690–1701. https://doi.org/10.1111/psyp.12734

Sanabria, D., Capizzi, M., & Correa, Á. (2011). Rhythms that speed you up. *Journal of Experimental Psychology: Human Perception and Performance, 37*(1), 236–244. https://doi.org/10.1037/a0019956

Sanders, A. F. (1966). Expectancy: Application and measurement. *Acta Psychologica, 25*, 293–313. https://doi.org/10.1016/0001-6918(66)90013-8

Sanders, A. F. (1975). The foreperiod effect revisited. *Quarterly Journal of Experimental Psychology, 27*(4), 591–598. https://doi.org/10.1080/14640747508400522

Sanders, A.F. (1980). Some effects of instructed muscle tension on choice reaction time and movement time. *Attention and Performance VIII, 8*, 59–74.

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics, 72*(6), 1455–1470. https://doi.org/10.3758/APP.72.6.1455

Schröter, H., Birngruber, T., Bratzke, D., Miller, J., & Ulrich, R. (2014). Task predictability influences the variable foreperiod effect: Evidence of task-specific temporal preparation. *Psychological Research, 79*(2), 230–237. https://doi.org/10.1007/s00426-014-0550-z

Seibold, V. C., Balke, J., & Rolke, B. (2023). Temporal attention. *Frontiers in Cognition*, *2*. https://doi.org/10.3389/fcogn.2023.1168320

Seibold, V. C., Dietrich, S., & Rolke, B. (2019). Multidimensional selection by temporal attention and feature-based attention: Evidence from event-related potentials. *Brain Research*, 1722, 146340. https://doi.org/10.1016/j.brainres.2019.146340

Seibold, V. C., Fiedler, A., & Rolke, B. (2011). Temporal attention shortens perceptual latency: A temporal prior entry effect. *Psychophysiology, 48*(5), 708–717. https://doi. org/10.1111/j.1469-8986.2010.01135.x

Seibold, V.C., & Rolke, B. (2014a). Does temporal preparation facilitate visual processing in a selective manner? Evidence from attentional capture. *Acta Psychologica, 151*, 51–61. https://doi.org/10.1016/j.actpsy.2014.05.012

Seibold, V.C., & Rolke, B. (2014b). Does temporal preparation speed up visual processing? Evidence from the N2pc. *Psychophysiology, 51*(6), 529–538. https://doi.org/ 10.1111/psyp.12196.

Seibold, V. C., Stepper, M. Y., & Rolke, B. (2020). Temporal attention boosts perceptual effects of spatial attention and feature-based attention. *Brain and Cognition, 142*, 105570. https://doi.org/10.1016/j.bandc.2020.105570

Seiss, E., Kiss, M., & Eimer, M. (2009). Does focused endogenous attention prevent attentional capture in pop-out visual search? *Psychophysiology, 46*(4), 703–717. https://doi.org/10.1111/j.1469-8986.2009.00827.x

Serences, J. T., & Kastner, S. (2014). A Multi-level Account of Selective Attention. In Nobre, A.C., Kastner, S. (Eds.), *The Oxford Handbook of Attention* (pp. 276–104). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199675111.013.022

Shaw, M. L., & Shaw, P. (1977). Optimal allocation of cognitive resources to spatial locations. *Journal of Experimental Psychology: Human Perception and Performance, 3*(2), 201–211. https://doi.org/10.1037/0096-1523.3.2.201

Simon, R.J., & Slaviero, D.P. (1975). Differential effects of a foreperiod countdown procedure on simple and choice reaction time. *Journal of Motor Behavior, 7*(1), 9–14. https://doi.org/10.1080/00222895.1975.10735008.

Smulders, F. T. Y. (2010). Simplifying jackknifing of ERPs and getting more out of it: Retrieving estimates of participants’ latencies. *Psychophysiology, 47*(2), 387–392. https://doi.org/10.1111/j.1469-8986.2009.00934.x

Smulders, F. T. Y., & Miller, J. O. (2012). The lateralized readiness potential. In E. S. Kappenmann, & S. J. Luck (Eds.), *Oxford handbook of event-related potentials* (pp. 209–230). Oxford University Press.

Spijkers, W.A. (1990). The relation between response-specificity, SR compatibility, foreperiod duration and muscle-tension in a target aiming task. *Acta Psychologica, 75*(3), 261–277. https://doi.org/10.1016/0001-6918(90)90016-9

Steinborn, M. B., & Langner, R. (2012). Arousal modulates temporal preparation under increased time uncertainty: Evidence from higher-order sequential foreperiod effects. *Acta Psychologica, 139*, 65–76. https://doi.org/10.1016/j.actpsy.2011.10.010

Steinborn, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2008). Sequential effects within a short foreperiod context: Evidence for the conditioning account of temporal preparation. *Acta Psychologica, 129*(2), 297–307. https://doi.org/10.1016/j.actpsy.2008.08.005

Tandonnet, C., Burle, B., Vidal, F., & Hasbroucq, T. (2003). The influence of time preparation on motor processes assessed by surface Laplacian estimation. *Clinical Neurophysiology, 114*(12), 2376–2384. https://doi.org/10.1016/s1388-2457(03)00253-0

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50*(2), 184–193. https://doi.org/10.3758/bf03212219

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics, 51*(6), 599–606. https://doi.org/10.3758/BF03211656

Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. *Acta Psychologica, 135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006

Theeuwes, J. (2014). Spatial orienting and attentional capture. In A. C. Nobre, & S. Kastner (Eds.), *The Oxford handbook of attention* (pp. 231–252). Oxford University Press

Thomaschke, R., & Dreisbach, G. (2013). Temporal predictability facilitates action, not perception. *Psychological Science, 24*(7), 1335–1340. https://doi.org/10.1177/0956797612469411

Töllner, T., Conci, M., Rusch, T., & Müller, H. J. (2013). Selective manipulation of target identification demands in visual search: The role of stimulus contrast in CDA activations. *Journal of Vision, 13*(3), 23–23. https://doi.org/10.1167/13.3.23

Töllner, T., Rangelov, D., & Müller, H.J. (2012). How the speed of motor-response decisions, but not focal-attentional selection, differs as a function of task set and target prevalence. *Proceedings of the National Academy of Sciences, 109*(28), E1990–E1999. https://doi.org/10.1073/pnas.1206382109

Töllner, T., Zehetleitner, M., Gramann, K., & Müller, H. J. (2011). Stimulus saliency modulates pre-attentive processing speed in human visual cortex. *PloS One, 6*(1), e16276. https://doi.org/10.1371/journal.pone.0016276

Treisman, M. (1964). The effect of one stimulus on the threshold for another: An application of signal detectability theory. *British Journal of Statistical Psychology, 17*(1), 15–35. https://doi.org/10.1111/j.2044-8317.1964.tb00241.x

Ulrich, R., & Mattes, S. (1996). Does Immediate Arousal Enhance Response Force in Simple Reaction Time? *The Quarterly Journal of Experimental Psychology Section A, 49*(4), 972–990. https://doi.org/10.1080/713755672

Ulrich, R., & Miller, J. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38*(5), 816–827. https://doi.org/10.1111/1469-8986.3850816

Van der Lubbe, R. H. J., Los, S. A., Jaśkowski, P., & Verleger, R. (2004). Being prepared on time: on the importance of the previous foreperiod to current preparation, as reflected in speed, force and preparation-related brain potentials. *Acta Psychologica, 116*(3), 245–262. https://doi.org/10.1016/j.actpsy.2004.03.003

Van der Lubbe, R. H. J., Szumska, I., & Fajkowska, M. (2016). Two sides of the same coin: ERP and wavelet analyses of visual potentials evoked and induced by task-relevant faces. *Advances in Cognitive Psychology, 12*(4), 153–167. https://doi.org/10.5709/acp-0195-3

Vangkilde, S., Coull, J. T., & Bundesen, C. (2012). Great expectations: Temporal expectation modulates perceptual processing speed. *Journal of Experimental Psychology: Human Perception and Performance, 38*(5), 1183–1191. https://doi.org/10.1037/a0026343

Vogel, E. K., & Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology, 37*(2), 190–203. https://doi.org/10.1111/1469-8986.3720190

Wagener, A., & Hoffmann, J. (2010). Temporal cueing of target-identity and target-location. *Experimental Psychology, 57*(6), 436–445. https://doi.org/10.1027/1618-3169/a000054

Weinbach, N., & Henik, A. (2013). The interaction between alerting and executive control: Dissociating phasic arousal and temporal expectancy. *Attention, Perception, & Psychophysics, 75*(7), 1374–1381. https://doi.org/10.3758/s13414-013-0501-6

Weymar, M., Löw, A., Öhman, A., & Hamm, A. O. (2011). The face is more than its parts—Brain dynamics of enhanced spatial attention to schematic threat.

NeuroImage, 58(3), 946–954. https://doi.org/10.1016/j.neuroimage.2011.06.061

Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review, 1*(2), 202–238. https://doi.org/10.3758/BF03200774

Wolfe, J. M. (2010). Visual search. *Current Biology, 20*(8), R346–R349. https://doi.org/10.1016/j.cub.2010.02.016

Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review, 28*(4), 1060–1092. https://doi.org/1010.3758/s13423-020-01859-9

Wolfe, J.M., Butcher, S.J., Lee, C., & Hyle, M. (2003). Changing your mind: On the contributions of top-down and bottom-up guidance in visual search for feature singletons. *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 483–502. https://doi.org/10.1037/0096-1523.29.2.483

Woodrow, H. (1914). The measurement of attention. *Psychological Monographs, 17*(5, Whole No. 76), 1–158. https://doi.org/10.1037/h0093087

Yantis, S. (1993). Stimulus-driven attentional capture. *Current Directions in Psychological Science, 2*(5), 156–161. https://doi.org/10.1111/1467-8721.ep10768973