IT'S ABOUT TIME: CONVERGING METHODS FOR DISTINGUISHING THE INFLUENCE OF ENDOGENOUS AND EXOGENOUS MODES WITHIN THE TEMPORAL DOMAIN OF ATTENTION

by

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Dalhousie University is located in Mi'kma'ki,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

This dissertation is dedicated to my parents, Shawn and Glenda McCormick, for their unconditional love and support.

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ABSTRACT

Endogenous (volitional) and exogenous (reflexive) modes of temporal attention are independent and differently impact performance (Lawrence and Klein, 2013; McCormick, Redden, Lawrence, & Klein, 2018). Despite this, these modes are often conflated within the various sub-domains of temporal attention research (Weinbach and Henik, 2012) and therefore, it is not well understood how the modes differently impact the processing of information. This dissertation aims to better identify the behavioural effects of endogenous and exogenous modes of temporal attention and theorize how these modes distinctly impact information processing via converging evidence from several methodological and analytic techniques. In Chapter 2, a meta-analysis inspired by Posner's theory of alerting (1975) was conducted on 16 studies from the alerting literature to identify the likely effect size for reaction time and accuracy, and to evaluate whether improvements in speed always come at a cost to accuracy across different signal-target intervals. In Chapter 3, participants used a temporal cueing paradigm that manipulated temporal cue validity and the intensity of a warning stimulus, which allowed for the measurement of the endogenous and exogenous modes, respectively. Participants provided a speeded detection response of the briefly presented target and reported the target's colour as accurately as possible on a continuous response colour-wheel. A Bayesian analysis on response fidelity used a von Mises distribution to evaluate the speed at which target-colour information accumulated. Chapter 4 applied a drift-diffusion model to data from a replication of Posner, Klein, Summers, & Buggie (1973), with a novel signaling procedure added to manipulate the contribution of the exogenous mode of temporal attention. The drift-rate and boundary separation parameters generated from this model allowed us to evaluate whether the modes of temporal attention increased the speed at which information accumulated, as well as whether a shift in response criterion occurred. In Chapter 5, converging evidence from the prior chapters is summarized to establish how these modes of temporal attention affect the processing of information, and revisions to past theories of attention are proposed. The dissertation concludes with suggestions for the future study of the temporal domain of attention.

LIST OF ABBREVIATIONS

2-AFC	2-Alternative Forced Choice
AIC	Akaike's Information Criterion
ANOVA	Analysis of Variance
ANT	Attention Network Test
BS	Boundary Separation
CCC	Concordance Correlation Coefficient
CI	Confidence Intervals
CIELUV	Colour Distribution based on Perceptual Uniformity
DDM	Drift Diffusion Modelling
ER	Error Rate
ESS	Effective Sample Size
HDI	Highest Density Interval
LRT	Likelihood Ratio Test
MSEC	Milliseconds
NDT	Non-Decision Time
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REML	Restricted Maximum Likelihood Estimator
RT	Reaction Time
SAT	Speed-Accuracy Trade-Off
SD	Standard Deviation
SE	Standard Error
STOA	Signal-Target Onset Asynchrony
WEIRD	Western, Educated, Industrialized, Rich, and Democratic

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To my parents, Glenda and Shawn McCormick, you have always supported me in every possible way, at every stage of life. Your love and nurturing helped me understand my worth and gave me the confidence to believe I could achieve whatever I put my mind to. I love you both very much. I have also been shaped by my time with other members of my loving family. This includes my brother, Ian McCormick. You share my sense of humor and love of science, and I am incredibly lucky to have you to turn to and be on my side. As I write this, I am also thinking of my grandparents, as well as all my aunts, uncles, and cousins, and the impact they have had on my life. There are too many of you to name and say nice things about, but just know that you have shared a role in getting me to this point. However, I do need to mention Rosie by name, our sweet dog who came into our lives because of a promise made during a tough period. I already mentioned my cat Theo, and Rosie would be jealous if she did not get the same treatment.

My friends have also helped me through this process. Thanks to my bandmates and friends in Sleepy Kicks — Braden Kamermans, Alex Heighton, and Mitch Currie — for providing me with an artistic outlet to do something I love with people I love, and for being understanding of my sometimes-hectic school schedule. Thanks to Mandy Hagen for helping establish consistent writing sessions, where sometimes the most productive thing we could do is commiserate about being a grad student or living through late-stage capitalism. There are many others who come to mind for the meaning they have contributed to my life, but the anxiety of leaving specific names out is too great, so I'll end with this: if you care enough about me to open my dissertation and read through it to this point, you deserve my heartfelt thanks.

CHAPTER 1: INTRODUCTION

1.1 Understanding Attention in Time: An Overview

We have several distinct cognitive mechanisms that allow us to prepare for, and react to, moments in time (Nobre & van Ede, 2018). The ability to increase arousal and predict the temporal structure of events is critical to improve the speed and quality of information processing, along with the preparation and execution of motor movements. This helps us navigate demanding and busy tasks throughout our daily lives. Despite over a century of research on temporal attention (for example, see Woodrow, 1914), there remains inconsistency in the naming of mechanisms, and uncertainty regarding the mental processes they affect. The fields of ‘alerting’ and ‘temporal orienting/cueing’ both use methodology that elicit reflexive (the exogenous mode) and volitional (the endogenous mode) temporal attention. The exogenous mode generates an increase in arousal in response to a salient change in the environment, which include visual cues or auditory signals, while the endogenous mode involves preparation for an upcoming stimulus based on provided, or learned, timing information. This conflation has limited our understanding of how each of these mechanisms distinctly contribute to the processing of information.

The important first step of this dissertation is understanding the development of the taxonomy of temporal attention, while considering past theories on how attention in time impacts mental processes. I will consider the methodological distinctions across the sub-fields of temporal attention, and why seemingly small distinctions can generate divergent results. Then, I will present recent empirical attempts to isolate the two modes of temporal attention. This will set the context for presenting the chapters to follow within this dissertation, that employ various analytical approaches—including meta-analyses, Bayesian analyses, and drift diffusion modeling—to delve deeper into how endogenous and exogenous modes of temporal attention distinctly influence mental processes.

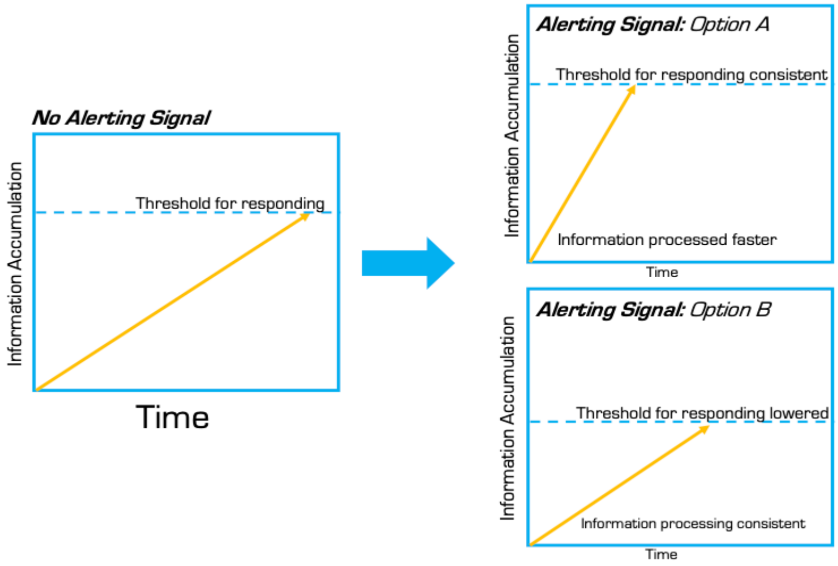
1.2 What is Attention?

Attention is the umbrella term we use to describe the cognitive mechanisms that allow us to interact with both our internal and external worlds. We differentially process information depending on specific qualities, including where that information is located in space, when it occurs in time, or how task-relevant or salient it is. Attention is generated by networks of brain areas that contribute important and isolable functions (Posner & Petersen, 1990). Posner and Petersen proposed a very influential three component model of attention involving three anatomical networks: orienting, executive functioning, and alerting (1990). The orienting network allows us to focus our 'beam' of attention on a source within the spatial domain to improve processing efficiency. In the visual modality, this can either be done with (overt) or without (covert) foveation of the eyes (Posner, Snyder, & Davidson, 1980). The executive functioning network allows for the filtering of unnecessary information so focus can be maintained on the stimulus of interest. This allows us to interpret, and appropriately use, task-relevant information. The alerting network affects an individual's level of arousal to change receptiveness to high-priority stimuli and shorten the time to produce a response (Posner, Klein, Summers, & Buggie, 1973). While these networks are anatomically separate, they can interact with one another depending on the requirements of the associated task (Fan et al., 2002). Since the introduction of the attention network test (ANT), a tool that can measure all three of these networks during a 25-minute session, research on these networks of attention has substantially increased (Klein 2022). We now better understand how different factors uniquely impact each of the attention networks, including lifestyle factors, disorders, as well as behavioural and pharmacological interventions (McCormick, 2022; Klein, 2003; Sinha, Arora, Srivastava & Klein, 2022; Neufang et al., 2019). Alerting resembles ‘attention in time’ within Posner’s taxonomy, as the methodology used to study alerting often provides a non-spatial signal related to *when* a relevant stimulus is likely to occur.

1.3 Posner’s Theory of Alerting

Posner and Boies (1971) used a letter matching task to study how alerting impacted information processing. Their task involved a 2-Alternative Forced Choice (2-AFC) response, in which two letters were displayed and participants were asked whether they were the same or different. Participants experienced either an encoding cue, providing one of the letters earlier than the second letter, an alerting cue, which provided timing information, both an encoding cue and alerting cue at once, or neither pre-target stimulus. In their data, reaction time (RT) effects for encoding cues and warning signals were additive when presented together, indicating that the warning signal, a manipulation of alerting, did not increase the speed at which information about the target accumulated when provided with the encoding cue. However, as noted in a follow-up study, this task did not generate a high enough error rate (ER) to justify an effective evaluation of performance between warning signal conditions, limiting this conclusion (Posner, Klein, Summers, and Buggie, 1973). It is important to evaluate both reaction time and error rate within a task to understand how alerting is impacting performance. Posner et al. proposed two distinct ways shortened response times could be achieved: either response criterion is shifted so participants make decisions in a shorter amount of time without any change in information processing speed, or information accumulates faster, generating improvements to speed without any cost to accuracy. If the error rate stays consistent (or improves) when participants respond faster, in comparison to the ‘no warning signal’ condition, this indicates that alerting increased the speed information accumulated (Figure 1.1, Option A), enabling participants to have the same quality of information with a faster response. If reductions in speed are associated with increases in error, this indicates a shift in response criterion, wherein participants accumulate information at the same rate, but the threshold of information required to trigger a response is lowered[1] (Figure 1.1, Option B; Posner, et al., 1973).

Figure 1.1. The two proposals presented in Posner et al., 1973 for how alerting may decrease reaction time. The figure on the left shows the theoretical accumulation of information after the presentation of the task stimulus as time passes for a no alerting signal trial. The blue horizontal line represents the threshold for when a participant would make a response based on how much information has been processed. The Alerting Signal: Option A shows that it is possible that information processing speed is increased when participants are alerted, generating a steeper accumulation line that reaches the threshold in less time compared to the no alerting signal condition. In contrast, Alerting Signal: Option B shows information accumulation maintaining the same slope, but the threshold of information required to provide a response is lowered, that results in the participant responding in less time. We anticipate that Option B would generate more errors, as there is less information available at the time of the response, so it would generate a speed-accuracy trade off. The quality of information available when responding at Option A should be the same as the no alerting condition.



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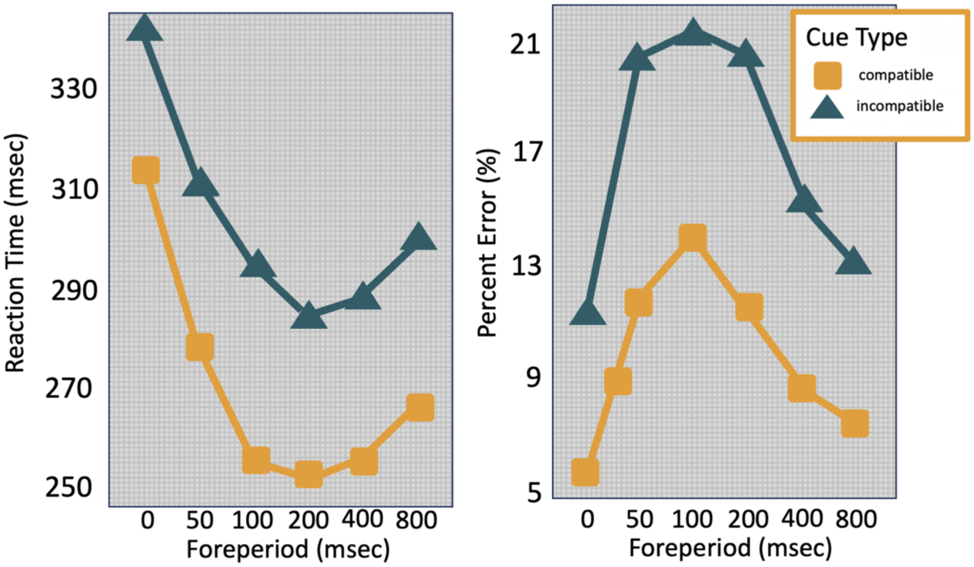
[1] It is worth noting that for Option B, Posner alluded to a shift in *temporal* threshold for decision making, wherein participants respond after a shortened temporal duration which results in less information having been accumulated (imagine a vertical threshold line instead of the horizontal threshold line drawn for Option B). It isn't possible to distinguish which threshold, information accumulation or temporal, better represents the mental process, but Drift Diffusion Modeling involves the accumulation of information in its modelling, so this is what is represented in our figure. We will address this more in the chapter which uses this method of analysis.

To empirically test whether option A or B is more likely, Posner et al had participants complete a spatial 2-AFC in which participants indicated whether the target appeared on the left or the right side of the screen, while providing warning signals that reliably informed the participants about when the target would appear. Posner et al. used several different signal-target onset asynchrony (STOA) conditions and compared them to a ‘no signal’ condition. Importantly, they also implemented a response contingency manipulation: on half the trials, participants provided a spatially compatible response (left side = left button; right side = right button), and on the other half of trials, they provided a spatially incompatible response (left side = right button; right side = left button). This was meant to increase the number of errors within the task, and allow for a proper comparison of accuracy, as a lack of errors was identified as a limitation in Posner and Boies (1971).

This compatibility manipulation successfully increased the overall error rate, and Posner et al. found a clear pattern of results to support a shift in response criterion, leading them to the conclusion that information processing speed is not impacted by alertness (Figure 1; Option B). Reaction times across the different STOA formed a U-shape, with the fastest reaction times occurring within the 200 milliseconds (msec) STOA condition. The ERs revealed an inverted-U-shape that showed a clear speed-accuracy trade-off: participants were less accurate when they responded faster (Figure 1.2). This speed-accuracy trade-off pattern is characteristic of what is now known as Posner’s theory of alerting and has been successfully replicated a number of times (Lawrence and Klein, 2013; McCormick, Redden, Hurst, & Klein, 2019; also see Klein 2023’s reanalysis of Los & Schut, 2008; Han and Proctor, 2022 for a partial replication).

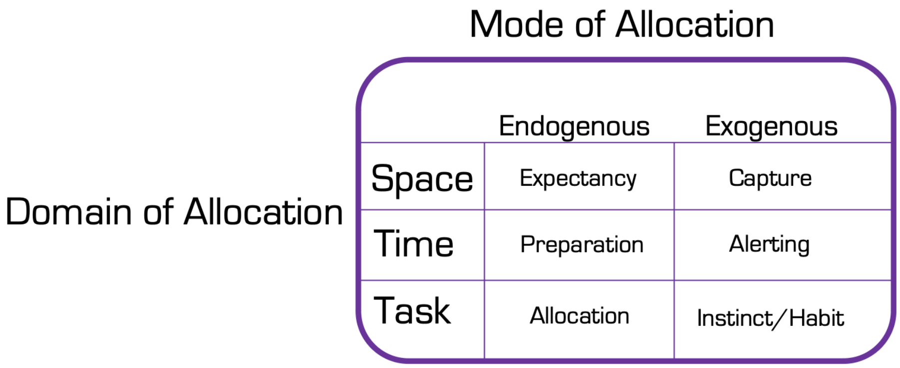
Figure 1.2. A re-drawing of the results from Posner, Klein, Summers, & Buggie, 1973. As participants respond faster within the task, the percent error increases, indicating a shift in response threshold that favors speed over accuracy.



Posner's taxonomy lacks an important distinction: attention can either be volitionally guided or be the result of reflexive processes. This distinction was not missing from his other research, however, as he pioneered research distinguishing 'endogenous' and 'exogenous' modes of spatial attention. Exogenous processes, or modes, are defined as 'bottom-up' mechanisms and represent a reflexive response to salient or task-relevant stimuli. Endogenous elicitation, on the other hand, is considered 'top-down' and typically involves a 'conscious decision' to initiate the mechanism (Figure 1.3). The Posner spatial cueing paradigm is a 2-AFC task that has two locations in space where a target can appear and presents a visual cue to indicate the likely location of the target. These spatial cues were manipulated to initiate different modes of orienting (Posner & Cohen, 1980; Posner, Snyder, and Davidson, 1980). A peripheral spatial cue, involving the illumination of one of the possible target locations, was identified as activating exogenous orienting. Typically, these peripheral cues are made to be uninformative of the likely target location to test the reflexiveness of this mode of attention. Even when participants were informed that they should ignore these cues because they do not provide predictive information, participants are still faster when a target is preceded by a cue, in contrast to when a cue appears at the other location (Jonides & Irwin, 1981). This displays the cue's reflexive quality; in that it automatically captures participant's attention. In contrast, center arrow cues are often used to test endogenous spatial attention by pointing to the side in which a target is likely to appear. Participants voluntarily allocate attention to this side to benefit performance.

Building off the seminal three-component model, Klein and Lawrence proposed a novel taxonomy that accounts for the identification of both endogenous and exogenous modes of allocation across Posner's attention networks (2012; also see Klein, 2022). The '*domain'* of allocation can be considered analogous to the 'orienting, executive functioning, and alerting' titles previously introduced (now called space, task, and time, respectively). The *mode of allocation,* however, adds the distinction of whether attention is elicited *endogenously* or *exogenously*.

Figure 1.3. The new taxonomy structure proposed by Klein and Lawrence (2012), that includes different mechanisms across Modes and Domains of allocation.



Mode of Allocation

Domain of Allocation

	Endogenous	Exogenous
Space	Expectancy	Capture
Time	Preparation	Alerting
Task	Allocation	Instinct/Habit

Because these modes of attention are independent mechanisms with different influences on human behaviour (Briand & Klein, 1987; Briand 1998; Lawrence and Klein, 2013; McCormick, Redden, Lawrence and Klein, 2018; Lawrence, 2018), it is an important distinction for future researchers to consider when studying attention. Without considering the influence of the endogenous and exogenous systems within methodological design, researchers will struggle to replicate findings across different experimental designs that claim to be studying temporal attention, as there will be varying degrees of endogenous and exogenous influence. This limits our understanding of exactly how our attention is being allocated in time. This taxonomy serves as one of the foundational components of this dissertation, as I will be contrasting 'endogenous' and 'exogenous' forms of temporal attention and theorizing on their confounded activation in past paradigms.

1.4 A Method for Studying Endogenous and Exogenous Temporal Attention

In their 'revised taxonomy', Klein and Lawrence (2012) consider endogenous temporal attention to be the volitional allocation of resources to a cued interval. This is typically the result of having a stimulus inform a participant of when an event is likely to happen, which allows a participant to prepare. Exogenous temporal attention, on the other hand, is the reflexive response to a salient and non-informative stimulus, with the result being an increased arousal and receptiveness to stimuli (2012). When 'alerting' is studied in relation to Posner's model, it is typically a conflation of these two properties[2]: a salient stimulus will appear on-screen to inform the participant a target is going to be presented. These warning stimuli generate the exogenous form of temporal attention through their salient presentation at a short interval before the target,

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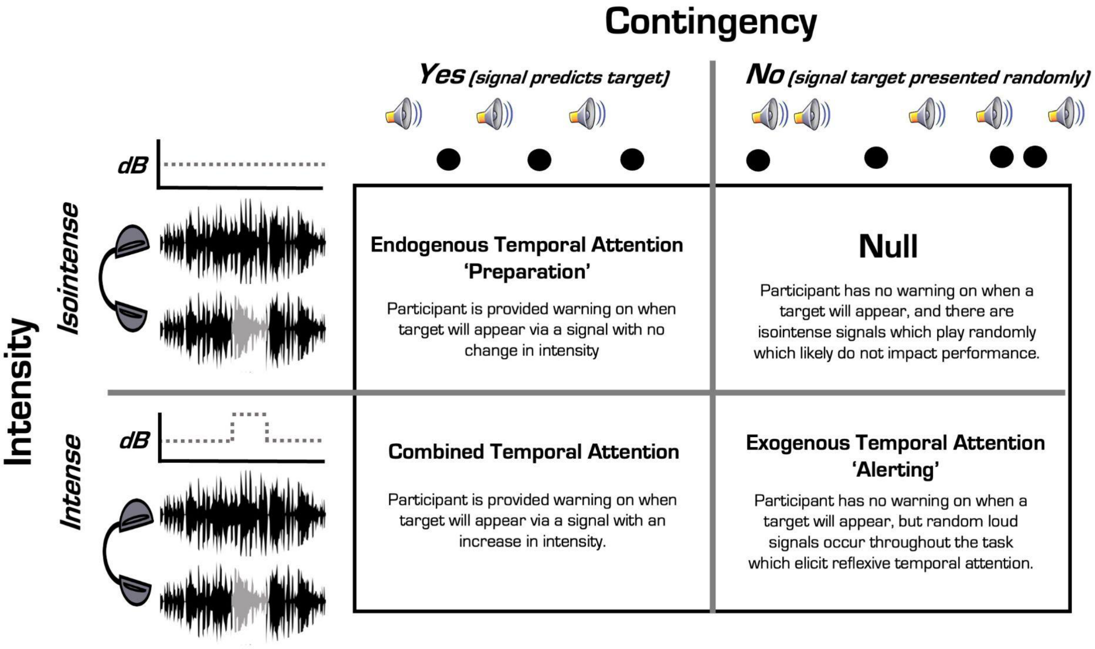
[2] They are also conflated within the 'temporal expectation/cueing' literature, which is covered later in this chapter (see page 15)

while also generating the endogenous form by being presented at a constant duration before the target, allowing a participant to volitionally prepare for presentation. This conflation of these two modes was present within the methodology that informed Posner's theory of alerting (generating a speed-accuracy trade-off; see Posner, Klein, Summers, & Buggie, 1973), as well as in the popular Attention Network Test that is used to study alerting in hundreds of publications each year (Fan et al., 2002).

Lawrence and Klein (2013) sought to better isolate these two modes of temporal attention defined in their taxonomy by developing a methodology that uses both signaling and contingency manipulations (Figure 1.4). In their task, participants were asked to discriminate the colour of a target presented at the center of the screen (2013). This target could be either black or white, making this a 2-AFC task. This allowed researchers to assess both the speed and binary accuracy of each trial. The *contingency* manipulation in this experiment dealt with the predictiveness of the relationship between an auditory warning signal and the target. When signals and targets were 'contingent', there was a consistent relationship in which signals indicated the timing for the presentation of a target. For an entire block of trials (10 practice trials and 40 test trials), the interval between the signal and the target remained consistent. Participants could use these signals to prepare for the target stimulus and generate an appropriate response. In the 'non-contingent' manipulation, targets and signals were randomly presented without any correlation to one another. This meant that the signals have no predictive value to the participants. The *intensity* manipulation dealt with whether the warning signal increased in volume or remained 'isointense'. This controlled for the influence of exogenous temporal attention, which is an involuntary increase in arousal associated with salient changes in the environment. Participants were presented with mono white auditory noise (the same static frequency in each ear) through headphones during the task. This then switched briefly (100ms) to uncorrelated stereo sound (different static frequencies in each ear). This brief shift could be heard without any change in the audio intensity and allows participants to volitionally prepare for an upcoming target. By combining the contingency and intensity manipulations, it is possible to generate pure versions of the endogenous and exogenous modes. If the experimental design was *contingent* and *isointense*, participants could use signals as an indication they should prepare for the targets, they did not experience the reflexive arousal that salient stimuli generate. This represented a purer elicitation of the endogenous mode of temporal attention. If the experiment design was non-contingent and intense, the arousing effect of a salient stimulus without any predictive value was observed. This represents a purer measure of the exogenous mode of temporal attention. For context, most studies that report researching either alerting or temporal cueing use a contingent-intense design to some degree, which means that there are salient signals that are predictive of when the target is likely to appear. This will be referred to as the 'combined' form of temporal attention. In addition, Lawrence and Klein's (2013) intensity and contingency manipulations allow for a 'null' condition, for which the signal-target relationship is non-contingent, and the signal is isointense. Participants do not experience the benefit of the contingency between the signal and target, or the reflexive nature of having an intense signal.

Figure 1.4. A breakdown of the different combinations of contingency and intensity manipulations for Lawrence and Klein, 2013. For intensity, the grey area for the left ear represents the 100 msec 'signal' in which the white noise between each ear of the headphones was uncorrelated. The dB line shows that while this period of uncorrelated noise was increased in the 'intense' condition, it maintains within the 'isointense' condition. In the contingent condition, signals always came at a fixed interval before targets. In the non-contingent condition, signals and targets were presented randomly, and later in the analysis the instances in which signals occurred in the time before target presentation were extracted for comparison.



In Lawrence and Klein's (2013) experiment, these three forms of temporal attention produced different patterns of speed and accuracy performance (see Figure 1.5). The results discussed by Lawrence and Klein included an average of performance for STOAs below 128msec. The endogenous mode of temporal attention enhanced both speed and accuracy of participants' responses, through contrast of the combined isointense-contingent condition in comparison to the null condition. The exogenous mode, generated by intense signals in the noncontingent design, enhanced the speed of participant performance without reducing accuracy in comparison to the null. When comparing the intensity (isointense vs intense) manipulations when signals and targets were contingent, there was a speed-accuracy trade off associated with intense signals, which participants were faster, but less accurate[3]. The results from their 400 msec STOA were also extracted below (Figure 1.5), as much of the temporal cueing literature discussed later uses this foreperiod. Within the temporal cueing literature, faster performance is often observed in the 'combined' intense and contingent manipulation in comparison to the isointense and contingent condition at 400 msec, so we would anticipate that if Lawrence and Klein's results were applicable, the pattern of performance should follow that of the shorter STOAs (top panel of Figure 1.5).

Based on Lawrence and Klein's (2013) results, it was put forth that within temporal attention there are two separable, but potentially interactive, modes, which distinctly impact behaviour. As mentioned before, Posner's theory of alerting (Posner et al., 1973) states that warning signals generates a criterion shift, as they found speed-accuracy trade-offs within his cueing task. Posner et al.'s (1973) methods closely resemble the intense and contingent condition from Lawrence and Klein, which was influenced by both the intensity of the warning stimulus and the contingent nature of the signal and target (which had a consistent STOA across blocks). This indicates that the activation of the exogenous network, in the context of a task that requires a participant to prepare for upcoming intervals, generates a shift in response criterion.

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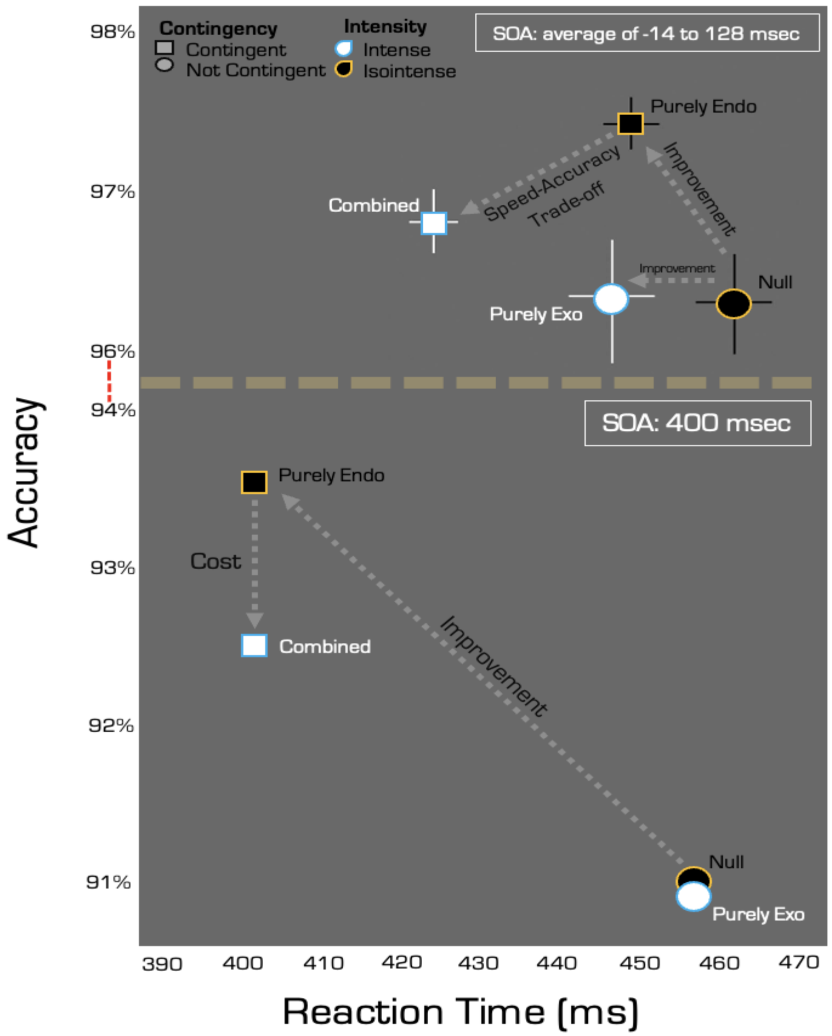
[3] Note that in this figure (Figure 1.5), this pattern is true for the top panel, which includes a presentation of the aggregate short STOAs. At the 400 msec STOA, performance is equally fast in the combined condition in comparison to the endogenous condition, but less accurate, representing a performance cost.

Figure 1.5: Redrawn results of aggregate performance from the shortest STOAs (2013; top half) and a transformation of their results for the 400 msec STOA (bottom half). The ‘purely exo’ (exogenous temporal attention) and ‘purely endo’ (endogenous temporal attention) were compared to the ‘null’ condition, since they add the influence of intensity (former) or contingency (latter). The ‘combined’ condition (both endogenous and exogenous temporal attention) was compared to the ‘purely endo’ condition because they were the same except for the intensity added within the ‘combined’ condition. Performance contrasts are labeled within the figure. Decreases in response time without a cost to accuracy were considered ‘improvements’ in performance (movement left without movement downward), while decreases in response time with cost to accuracy (movement left and down) were considered a trade-off. In the case of the 400 msec STOA, the addition of the exogenous mode generates what could be considered a pure cost (decreases in accuracy without any improvement in speed). When comparing performance between the short STOAs and the 400 msec condition, overall participants were faster at 400 msec (further left), but at a cost to accuracy performance.

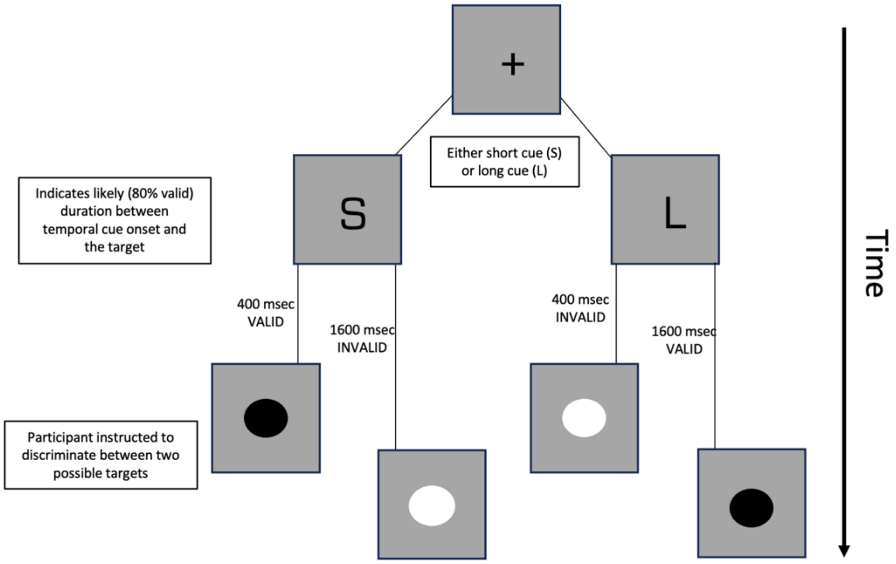


1.5 The Development of a ‘Temporal Cueing’ Paradigm

Kingstone (1992) developed an analogous test to the previously mentioned ‘Posner cueing paradigm’ to measure how we flexibly focus our attention in time, an understudied domain of research. This was done within a series of experiments that manipulated expectation for both form-based (colour, shape) and non-form (space and time) based properties during a task. In Kingstone’s design, participants waited for an alphabetic cue to inform them of when the target was likely to appear. This could either be an ‘S” (short), which indicated that the target would likely appear 400 msec after the cue is presented, or an ‘L’ (long), which indicated the target would likely appear 1600 msec after the cue. These cues were 80% predictive, with the other 20% of targets appearing at the alternate interval. Due to issues with hazard sensitivity, a confounding temporal structure, often only the short interval trials are included for the assessment of temporal cueing effects. This is because if a participant is cued to the short interval with an S, and that interval passes, the target has a 100% chance of being presented at the 1600msec interval and, as a result, allows for the shifting of an individual’s mode of temporal attention. Because of this, valid and invalid cue performance cannot be clearly distinguished when target is presented at the long interval.

In Kingstone’s study, participants were faster when provided with a valid timing cue in comparison to an invalid timing cue. This is what we will refer to as a ‘temporal cueing effect’. Importantly, there were no changes in accuracy associated with this improvement in the speed of responding. This indicates that participants responded faster with no loss of information quality, indicating an improvement to the efficiency of information processing. This deviates from what would be expected based on Posner’s theory of alerting (1975). Following up on these results, Coull and Nobre (1998) compared spatial and temporal orienting using Kingstone’s paradigm with a detection task, while performing brain imaging (PET and fMRI). The task involved cueing both the likely location, likely interval, both location and interval, or nothing. Analogous reaction time advantages were found for both the temporal and spatial conditions, and while there was overlap in some areas of processing, Coull and Nobre found strong hemispheric lateralization, such that spatial orienting was associated with activation in the right parietal areas and temporal orienting was associated with activation in the left parietal areas. Sometimes referred to as 'temporal orienting' because of its similarity to spatial orienting paradigms (Figure 1.6), the cue-directed focusing of attention in time required further study to understand exactly how it impacts perception and decision making.

Figure 1.6: A typical temporal cueing paradigm. Participants are presented with a fixation point, and after some random duration, a temporal cue is presented that indicates the likely interval between the onset of the cue and the onset of the target (typically a 2-AFC or a detection task). Participants are instructed to respond as quickly and as accurately as possible.



With a flagship paradigm established, the temporal orienting or temporal cueing literature has increased substantially since the 1990s. In contrast to the 'alerting' literature, which often describes it as a state of arousal which increases receptivity to external stimuli (which is a bit more agnostic to the contribution of exogenous and endogenous mechanisms), the temporal cueing literature identifies that their paradigms are measuring the endogenous ‘orienting’ of attention in time (although these definitions do vary, see Weinbach & Henik, 2012). However, temporal cueing paradigms, through the onset of temporal cues, were eliciting the exogenous mode, just as the alerting literature was generating the endogenous mode through consistent intervals between warning signals and targets.

Weinbach and Henik (2012) critiqued the lack of distinction made between the arousing and preparatory components of temporal attention, which we define as the exogenous and endogenous modes. These two temporal mechanisms can present quite similarly, as they both impact early (perception and response selection) and late (motor preparation) processing stages depending on task demands and are both biased by the presence of competing or conflicting information (Weinbach & Henik, 2012; McCormick et al., 2018; Posner, 1994; Callejas, Lupiáñez, & Tudela, 2004; Menceloglu, Suzuki & Song, 2021). There is evidence that they are distinctly impacting performance (Lawrence and Klein, 2013; McCormick et al., 2018). Additionally, recent research indicates that the time-course of endogenous and exogenous modes differ substantially, with the more exogenous mode peaking sometime between 80 and 100 msec (Denison et al., 2021; Lawrence and Klein, 2013) after stimulus onset, and the more endogenous mode peaking sometime around 400 msec (Lawrence and Klein, 2013; Denison et al., 2021, McCormick, Redden, and Klein, 2023[4]). Considering the clear distinctions between these two mechanisms, it is important to control for them (or at least acknowledge their contributions to an effect) within research.

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[4] Note that these endogenous modes can benefit performance at a range of intervals, which depend on related task demands. Denison et al. observed a 600msec peak, while McCormick et al. observed cueing as early as 200msec.

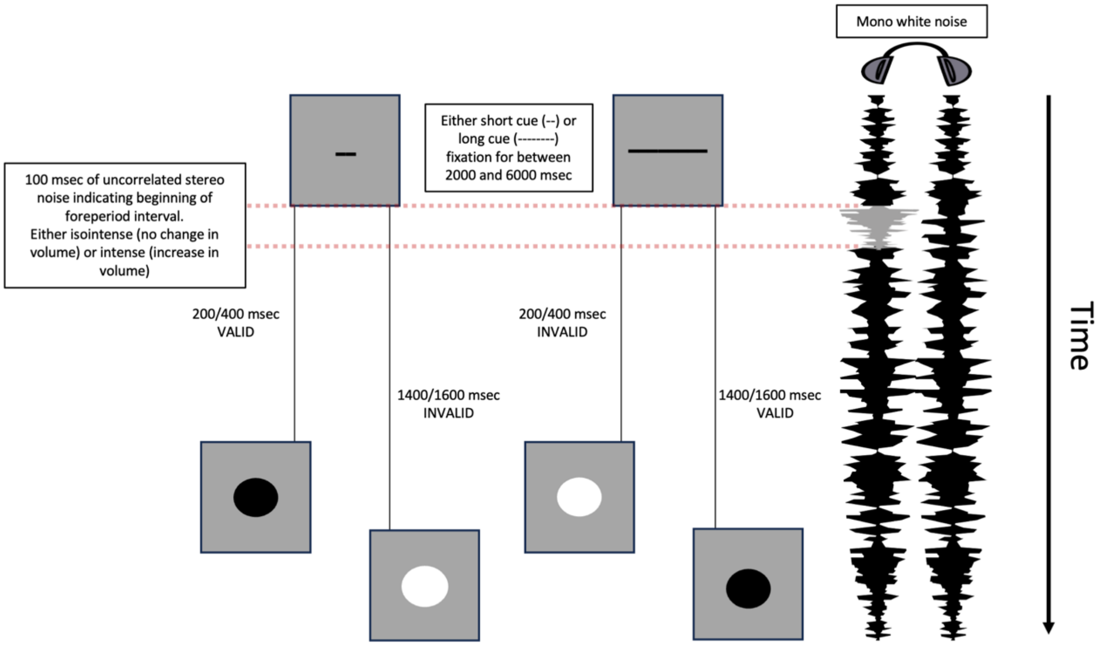
As previously explained, the exogenous mode of temporal attention is elicited when salient stimuli are presented before a target, which includes the sudden onset of visual cues before a target. One argument against a need to consider the influence of an exogenous mode of temporal attention could be that both the valid and invalid trials which are compared to one another include stimuli that elicit the exogenous mode of temporal attention. If this were the case, the exogenous mode would be controlled for and the contribution of the endogenous mode on performance would be isolated. However, this point ignores that, while independent (McCormick et al., 2018), these two modes of temporal attention have distinct impacts on performance and could interact with one another (Lawrence and Klein, 2013; Nobre & van Ede, 2018). Additionally, these two mechanisms have distinct time-courses of activation, with the exogenous mode peaking around 50 to 80 msec after a warning stimulus (Denison, Carrasco, Heeger, 2021), while endogenous alerting does not activate until sometime between 200 and 400msec (Yeshurun and Tkacz-Domb, 2021; McCormick, Redden, & Klein, 2023). The time-course of activation for the endogenous mode may additionally be impacted by the demands of the task, in which more challenging tasks delay when the endogenous mode can peak (McCormick, Redden, & Klein, 2023). With these factors considered, comparisons across the temporal cueing literature may vary between STOA lengths and methodologies if researchers do not choose to better isolate the contribution of exogenous modes of alerting within these more endogenous temporal cueing procedures.

Within the temporal cueing literature, valid temporal cues generate faster responses from participants in comparison to invalid temporal cues without decreasing response accuracy (Correa et al., 2005 & 2006; Davranche et al., 2011; McCormick et al., 2023). In addition to this, other methods of measuring the quality of information, including mixture modeling involving continuous response variables, show improvements in participants' representation of target properties, resulting in higher accuracy performance (Denison et al., 2017, 2021). Many other performance benefits have been observed which are distinct from changes in threshold (see Nobre & van Ede, 2023 for a complete review). As previously emphasized, both the temporal cueing and alerting literature typically involve the conflation of exogenous and endogenous modes of temporal attention. So why does the 'alerting' literature observe evidence of a criterion shift (speed-accuracy trade-off) and the 'temporal cueing' literature observe enhanced information processing speed (improvements to processing of information)? One possibility is that the differences in methodology between these two areas of study may influence the amount of activation from each mode, which is then generating different patterns of performance. To recap, the most common difference in these methodologies is the trial-by-trial variation of STOA and its associated instruction. Temporal cueing studies provide participants with some sort of symbolic cue which represents different possible temporal durations for the following trial (S=short, L=long; different line lengths). Importantly, these temporal cues are 75 to 80% predictive, so that 'valid' cue performance (target appears at expected interval) can be compared to 'invalid' cue performance (when target appears at unexpected interval). In contrast, studies in the 'alerting' literature will use one single alerting cue, either flashing a dot or an audio signal, but maintain the same STOA duration for an extended duration of trials, often a full block (with 100% validity). Repeating STOA durations can generate larger temporal cueing effects, likely due to an increase in hazard rate or task demand (Correa et al., 2004; van Elswijk, Kleine, Overeem, and Stegeman; 2007). Another important consideration previously mentioned is STOA length between the cue and the target and task demand (such as target discrimination difficulty, cue type, dual task).

1.6 Identifying the Contribution of Exogenous Temporal Mechanisms Within the Temporal Cueing Task

McCormick, Redden, and Klein combined the temporal cueing paradigm of Kingstone (1992; also see Coull & Nobre, 1998) with the signaling method of Lawrence and Klein (2013) to isolate the contribution of the exogenous mode of temporal attention within a temporal cueing procedure. This was done to better understand how each of these mechanisms is impacting performance (see Figure 1.7 for visual breakdown). Within this updated paradigm, participants were presented with a line cue indicating the likely temporal interval before a target would appear: a short line represented a likely "short" interval (200 or 400 ms; E1 and E2 respectively), and a long line represented a likely "long" interval (1400 or 1600 ms; E1 and E2 respectively). This cue was presented at the beginning of the trial, instead of at the start of the indicated temporal interval (in contrast to the often-used Kingstone paradigm, see Figure 1.6) and this remained on the screen until the target was presented. Then, after a random interval of fixating on the temporal cue, between two and six seconds, an auditory signal informed participants to prepare for the target to appear at the cued interval following this signal. As in Lawrence and Klein (2013; Figure 1.4), this signal entailed a switch from mono to stereo white noise, which allowed for the comparison of intense and isointense signals. Intense signals, which increased in dB, represented the common (confounded) manipulation within field of temporal cueing in which there was a combination of endogenous and exogenous modes of temporal attention, whereas isointense signals provided a novel opportunity to study a more purely endogenous mode of temporal attention. De-confounding the relationship between endogenous and exogenous temporal attention addressed the issues raised by Weinbach and Henik (2012), while also better controlling for the exogenous influence of hazard rate that may have been present in the purely endogenous condition in Lawrence and Klein (2013), since Lawrence and Klein’s signal-target interval was fixed for a full block.

Figure 1.7. The methodology from McCormick, Redden, & Klein, 2023. Each trial began with a temporal cue presented at the center of the screen and mono white noise playing. The temporal cue remained on screen until the target was presented. After a random interval between 2000 and 6000 msec, the white noise shifted to uncorrelated stereo noise, and the volume either remained consistent (isointense) or increased in intensity (intense). This indicated the beginning of the indicated interval. After either 400 or 1600 msec (or 200 and 1400 msec for E2), a target was presented which required a discrimination response. The cue indicated the valid STOA length 80% of the time.



McCormick, Redden and Klein (2023) found temporal cueing effects, in which participants were faster for cued trials in comparison to uncued trials. This was the case at both the 200 and 400 msec STOA. The rapid allocation of endogenous temporal attention at the 200 msec STOA, which is faster than what is typically observed in cued discrimination studies, can likely be attributed to the separation of the temporal cueing information and the start of the cueing interval using the novel signaling method and more intuitive line cue (Correa et al., 2004; McCormick, Redden, & Klein, 2023). However, the expected speed-accuracy trade-off that was predicted by prior alerting research was not observed (Lawrence and Klein, 2013, see above Figure 1.5; also Posner, et al., 1973). The intense signals in combination with the temporal cues generated faster performance without any cost in accuracy in comparison to the isointense signals. The exogenous mode should have shifted response criterion, but instead this generates evidence that information processing efficiency improved. This outcome, when ignoring the separation of endogenous and exogenous mechanisms, is consistent with most research within the temporal cueing space, which finds evidence of an increase in information processing ability; however, it leads us to question the applicability of Posner's theory on exogenous modes of temporal attention.

One consideration in relation to why we did not observe the expected speed-accuracy trade-off for the exogenous mode is that the temporal cueing effects are much smaller than those within fixed interval alerting studies, in which the cue-target interval remains consistent across blocks of trials (Correa et al, 2004). Detecting a signal within white noise to start one's internal timer is also more cognitively demanding, and this may have reduced the temporal cueing effect size. Comparing how the modes of temporal attention impact response accuracy is something that may be better addressed by moving away from 2-AFC response tasks into continuous response paradigms, allowing for the use of more advanced analysis techniques. Although McCormick, Redden, & Klein (2023) was our third attempt at increasing effect size within this temporal cueing paradigm (McCormick et al., 2018), it is possible to modify methodology further while controlling for the influence of other temporal mechanisms. Outside the temporal cueing literature, the past studies that have informed the theory of alerting either contain small sample sizes (Posner, Klein, Summers, & Buggie, 1973) or unreplicated results that have not yet been shown to carry over to other related paradigms (Lawrence & Klein, 2013). Different approaches should be applied to Posner's theory of alerting (1975) to either provide additional evidence and reinforce the original proposal or challenge the ideas currently in place. The current dissertation will address this specifically by performing a meta-analysis on the applicable literature to observe the aggregate RT and ER alerting effects, as well as introducing a drift diffusion model to look at parameters that are directly related to the information accumulation rates and response criterion shifts.

1.7 An Overview of This Dissertation

This introductory chapter has emphasized the overlap within the fields of alerting and temporal cueing due to the conflation of multiple forms of temporal attention, including those identified in Lawrence and Klein (2013), Weinbach and Henik (2012) and Nobre and van Ede (2018). Because of this conflation, along with various deviations in methodological design, there is a lack of consensus on how exogenous and endogenous modes of temporal attention differently impact performance, specifically in relation to how they may impact response criterion and/or the accumulation of information. This dissertation will address how endogenous and exogenous modes of temporal attention differently impact the processing of information and response behaviour, furthering our understanding of how attention functions in the temporal domain, and emphasizing a need for stricter methodological control. In Chapter 2, I conduct a meta-analysis on the alerting literature to assess the validity of Posner's theory of alerting across multiple STOAs. Using multiple STOAs allows us to observe whether this theory applies differently across time-courses based on the contribution of endogenous and exogenous modes, as we know they peak at different times (Denison et al., 2021). Additionally, the meta-analysis vastly increases the power from the original experiment informing Posner’s theory of alerting (1975; Posner et al., 1973) and its subsequent replications. In Chapter 3, I conduct a series of modified temporal cueing paradigm experiments to better contrast how the two modes of temporal attention impact the quality of perceptual processing. The modifications include using a continuous accuracy measure, which allows us to apply a more advanced Bayesian mixture modeling analysis to accuracy data, and presenting the target for a fixed duration to allow us to control for the duration in which participants can encode target information. These modifications are theorized to lead to more informative, and relatively larger, performance effects. Finally, in Chapter 4, I will conduct a drift diffusion model analysis to assess the speed at which information accumulates and response criteria are shifted under endogenous and exogenous modes of temporal attention. This will use data from a replication of Posner et al.’s (1973) seminal experiment that implemented Lawrence and Klein’s (2013) signaling method (McCormick et al., 2019). Analyzing the diffusion metrics across foreperiods will allow us to appraise Posner’s theory while controlling for the influence of each of the modes of temporal attention. In Chapter 5, I will synthesize these results into an appraisal of the endogenous and exogenous modes of temporal attention, along with an assessment of past theories of alerting.

CHAPTER 2: POSNER'S THEORY OF ALERTING: A META-ANALYSIS OF SPEED-ACCURACY EFFECTS

Colin R. McCormick & John Christie

Co-Authors for this manuscript include Colin R. McCormick and John Christie. Colin R. McCormick wrote each section of this paper, completed the literature review, ran the statistical analysis, and generated the figures. John Christie provided feedback on the content of the writing and advised on the analysis.

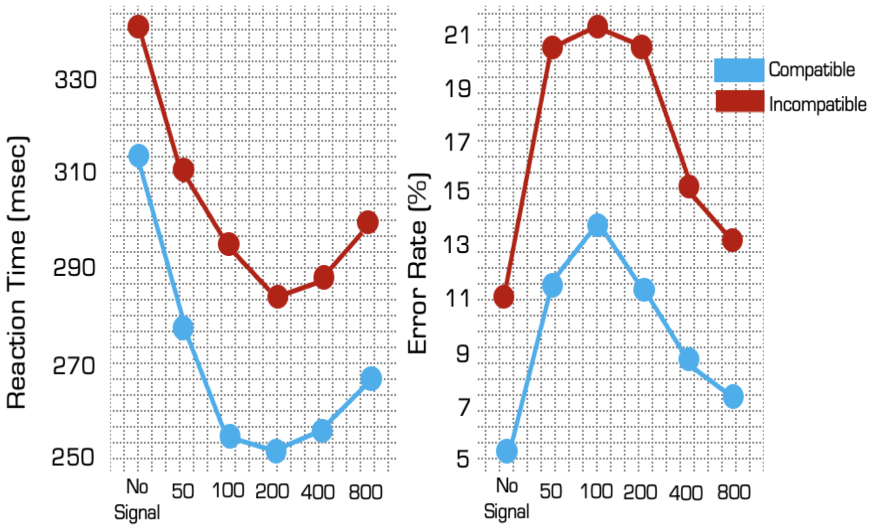
2.1 Introduction

A popularized approach to understanding attention is categorizing it as three isolable networks that influence the processing of information (Petersen & Posner, 2012; Xuan et al., 2016). Alerting is one of these networks, and its activation helps generate a heightened sensitivity to external stimuli (Posner & Petersen, 1990). This allows an individual to be in a state of increased response readiness, providing a behavioural advantage when response speed is required (Posner, 2008). Typically, experiments on alerting will initiate the state through either an auditory or visual stimulus, often called a 'warning signal'. The warning signal can provide a varying degree of temporal certainty as to when this target will be presented, depending on the experimental design. Research studying how warning signals impact performance extends over a century, with questions related to finding the optimal foreperiod (interval of time) between the signal and the target, how the consistency of a foreperiod impacts performance, and how it impacts the speed at which individuals accumulate information about the target (Niemi & Näätänen, 1981).

Almost 50 years ago, Posner published a seminal theory on how alertness impacts information processing (Posner, 1975). This theory was informed through the analysis of speed and accuracy performance within alerting paradigms that presented warning signals before targets. In a task in which participants were asked to provide a speeded response discriminating whether two letter stimuli were the same or different, Posner and Boies manipulated the encoding of information using form cues that provided one of the letter stimuli in advance, as well as alerting via a warning signal which provided timing information (1971). These pre-target stimuli could be presented by themselves, or together. Because the encoding and alerting effects were additive with one another for response speed on this task when presented in tandem, and the alerting signal did not increase the speed at which the encoding cue information could be utilized to inform the response, Posner and Boies reported that the rate of information buildup was unaffected by alerting (1971). In a follow-up study, Posner et al. (1973) identified that error rates (ER) were quite low within Posner and Boies' (1971) data, and the task only covered a limited number of foreperiod durations. Error rates are an important performance metric to determine whether the improvements to response speed associated with alerting are because participants are trading off accuracy for improved speed. Posner et al. (1973) sought to test this outcome with a follow-up experiment that asked for participants to provide a speeded response as to what side of the screen a target was presented and manipulated response compatibility to increase error rate through upping task difficulty (compatible= right target requires a right button response; incompatible= right target requires a left button response). Posner et al. included a range of foreperiods conditions between the warning signal and the target (50 milliseconds (msec), 100msec, 200msec, 400msec, 800msec) along with a no warning signal condition to map out the temporal nature of alerting effects. The results of this experiment showed a clear U-shaped pattern for RT (reaction time), in which the fastest responses were found between the 100 to 400msec foreperiods, along with an inverted U-shape for ER that peaked around 100msec (see Figure 2.1).

In general, lower RTs were associated with higher ERs. Posner et al. used the significant main effect of foreperiod within their Analysis of Variance (ANOVA) for both RT and ER, along with the visualized U- shaped pattern of results, to conclude that alerting does not increase information accumulation speed in participants. Instead, alerting was theorized to shift response criterion, so that responses are generated at a point in time in which less information about the target had been accumulated. This shift in response criterion is referred to as a speed-accuracy trade- off (SAT), wherein one forfeits accuracy performance to improve response speed, or vice versa.

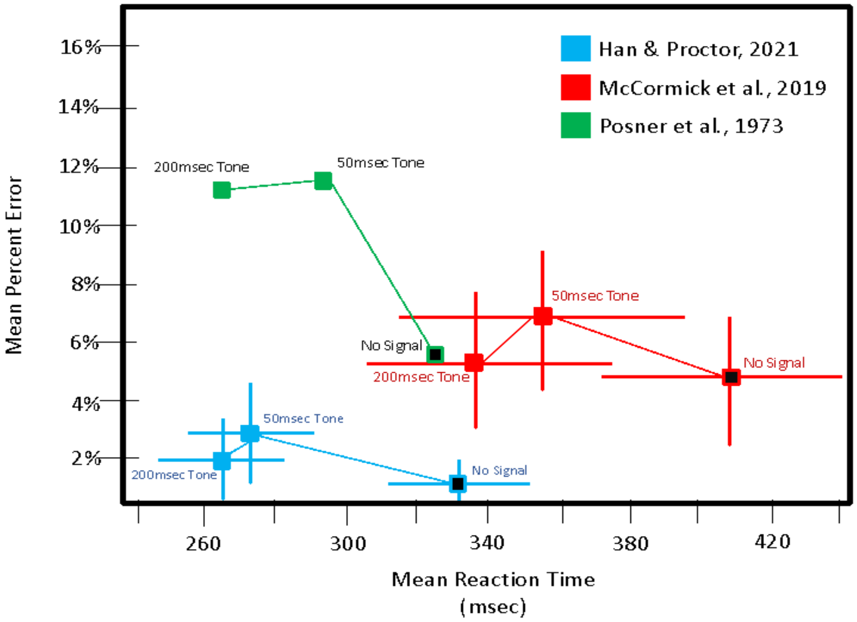
Figure 2.1. Redrawn from the results of Posner, Klein, Summers, and Buggie's 1973 experiment. Their studies '0' foreperiod condition is represented by our 'no warning signal' condition, and the other foreperiod conditions represent the interval between the signal and target onsets.



The theory generated from this research paper long stood as a cornerstone of alerting research. There has recently been a renewed interest in this topic. McCormick, Redden, Hurst, and Klein (2019) replicated Posner et al.'s (1973) experiment with a larger sample size. McCormick et al. declared that the results from the original study were reproduced, as they obtained the same significant effects of foreperiod from their ANOVAs as Posner et al.'s study, along with similar U-Shaped patterns for RT and ER. Han and Proctor (2022) discovered a pattern that had been overlooked by McCormick et al. (2019) when also closely replicating key features of Posner et al.'s methods (1973). When providing RT feedback on each trial, Han and Proctor had comparable RT effects to Posner et al (1973) and McCormick et al's (2019) experiments in both the 50msec and 200msec condition but noted that ER effects were much smaller than the original study. This difference in effect size is also true for McCormick et al.

(2019) but went unnoticed because these authors were fixated on the outcomes of the ANOVA to test the hypothesis. In addition, Han and Proctor's (2022) replication without RT feedback shows RT effects are still present in a similar magnitude to Posner's study, but there is a numeric improvement in the signaled trials compared to the non-signal trials for ER. Based on these outcomes, Han and Proctor make the argument that while a SAT may be present when contrasting the 50 msec signaled foreperiod condition from the no signal condition, such a shift in criterion cannot fully explain what is going on at the 200 msec contrast, as RT is faster with a numerically smaller ER in comparison to the 50 msec foreperiod condition. Therefore, at least some of the speed improvement associated with alerting may be a result of an increase in the rate at which information accumulates. In another set of experiments that conceptually replicated Posner et al., Los and Schut (2008) also showed that faster response times were not as associated with the same increases in error that Posner's theory of alerting would have predicted. However, recently Klein (2023) reanalyzed this data from Los and Schut (2008) in an effort to increase the power of the analysis. To achieve this increased analytic power, Klein collapsed the data across the different experiments and foreperiod conditions and found a similar pattern of results as Posner et al. (1973), in which the fastest-half of conditions, based on mean RTs, generated more errors than the slower half of conditions. Considering that there have been recent studies that both support (McCormick et al., 2019; Klein, 2023) and challenge (Los and Schut, 2008; Han and Proctor, 2022) Posner's theory of alerting (1975), a meta-analysis is warranted to establish consensus within the field and reassess Posner's theory using the aggregate speed and accuracy data.

Figure 2.2. Posner et al. (1973), McCormick et al. (2019), and Han and Proctor (with feedback; 2022). The x-axis is mean reaction time, while the y-axis is mean percent error. The ‘no signal’ conditions are filled in with black, and this represents the reference point to compare the two other tone conditions within each study. This figure helps with understanding SATs, as movements left and up represent a trade-off between speed and accuracy, and movements left and flat or left and down represent pure improvements to performance. Error bars are standard deviation of mean (data unavailable for Posner et al., 1973).



The current meta-analysis looks to address Posner’s disputed theory of alerting by analyzing the relationship between alerting and speed-accuracy performance across a collection of experiments with very similar methodologies. The analysis will involve comparing RT and ER effects between trials in which the participants received an alerting signal, and trials where participants do not receive an alerting signal, across three different foreperiod conditions. This will allow for us to apply the logic used in Posner et al. to see if the warning-signal improvements to RT expected across all three foreperiod conditions are most likely a result of a shift in response criterion (meaning that RT improvements are associated with increased ER effects), or whether there is evidence of improvements to information processing (improvements to RT are not associated with increasing ER effects). The three foreperiods chosen (50, 200, and 400 msec) represent a miniature U-Shaped RT pattern like the one presented in Posner et al.

(1973). Based on the three previously presented studies which motivated the current analysis (Posner et al, 1973; McCormick et al., 2019; Han and Proctor, 2022), there is the strongest evidence of a SAT when the foreperiod between signal and target is 50 msec, but once the foreperiod reaches 200 msec, alerting appears to improve information processing and reduce signaled trial RT without additional cost to ER.

Within this analysis, we will be contrasting the size of RT effects, between signaled and no-signal trials, with their associated ER effects. This analysis will also permit an assessment of the typical RT and ER effect size across the different foreperiods. To correct for differences in the overall accuracy across experiments, additional analyses will be performed using post-hoc log-odds transformations of error rate. This compensates for accuracy changes closer to perfect performance, as these represent larger shifts in the probability of outcomes and should be treated as larger effect sizes (Jaeger, 2008, Dixon, 2008). This will not generate the same values as a true logistic regression but provides a useful approximation to handle the differences in error rate across experiments. It can be seen in Figure 2 that the overall ER values can vary quite a bit, and this impacts the comparisons which can be made. Han and Proctor had a shift in ER performance from .7% in the no signal condition to 3.1% in the 50 msec foreperiod condition, which in log odds translates to a difference of 1.51, whereas Poser saw a shift from 5.2% to 11.6%, which translates to a difference of .87.

The aggregate RT and ER effects across the different foreperiods in this meta-analysis will be contrasted with the effects observed in Posner et al (1973). This is because Posner et al. was the main influence on Posner's theory of alerting (1975) and inspired many of the follow-up studies looking to assess alerting and its impact on response criterion and information processing (Los and Schut, 2008; McCormick et al., 2019; Han and Proctor, 2022; Klein, 2023).

2.2 Methods

2.2.1 Eligibility Criteria

For a study to be included in this meta-analysis, the following conditions had to be met:

- The task had to involve a condition that provided a warning signal, along with a condition in which no warning signal was provided. The 'warning signal' could not provide spatial information. The no-signal condition involves the same trial procedure as a signaled trial, but without the presence of a warning signal. The warning signal could be presented auditorily or visually.
- The design should be a 2-Alternative Forced Choice (2-AFC) task. This means the target can be one of two possible stimuli, or appear at one of two locations in space, and participants must make a speeded response by pressing one of two buttons. This allows for the measurement of Reaction Time (RT) and Error Rate (ER). Reaction time is the amount of time (in msec) required to react after target onset, and accuracy is the binary recording of whether they responded correctly (1) or incorrectly (0). Enough information must be available to extract necessary information for the meta-analysis, such as effect variance.
- The foreperiod between the warning signal and the target had to be 50 msec, 200msec, and/or 400 msec. If a foreperiod condition was within 100msec of these values, it was also included with the closest foreperiod. Deviations in the foreperiod were reported within the data table (Appendix A Table A2).
- The participants within these experiments should be typically developing, and without any reported or induced[5] impairments to cognitive ability.

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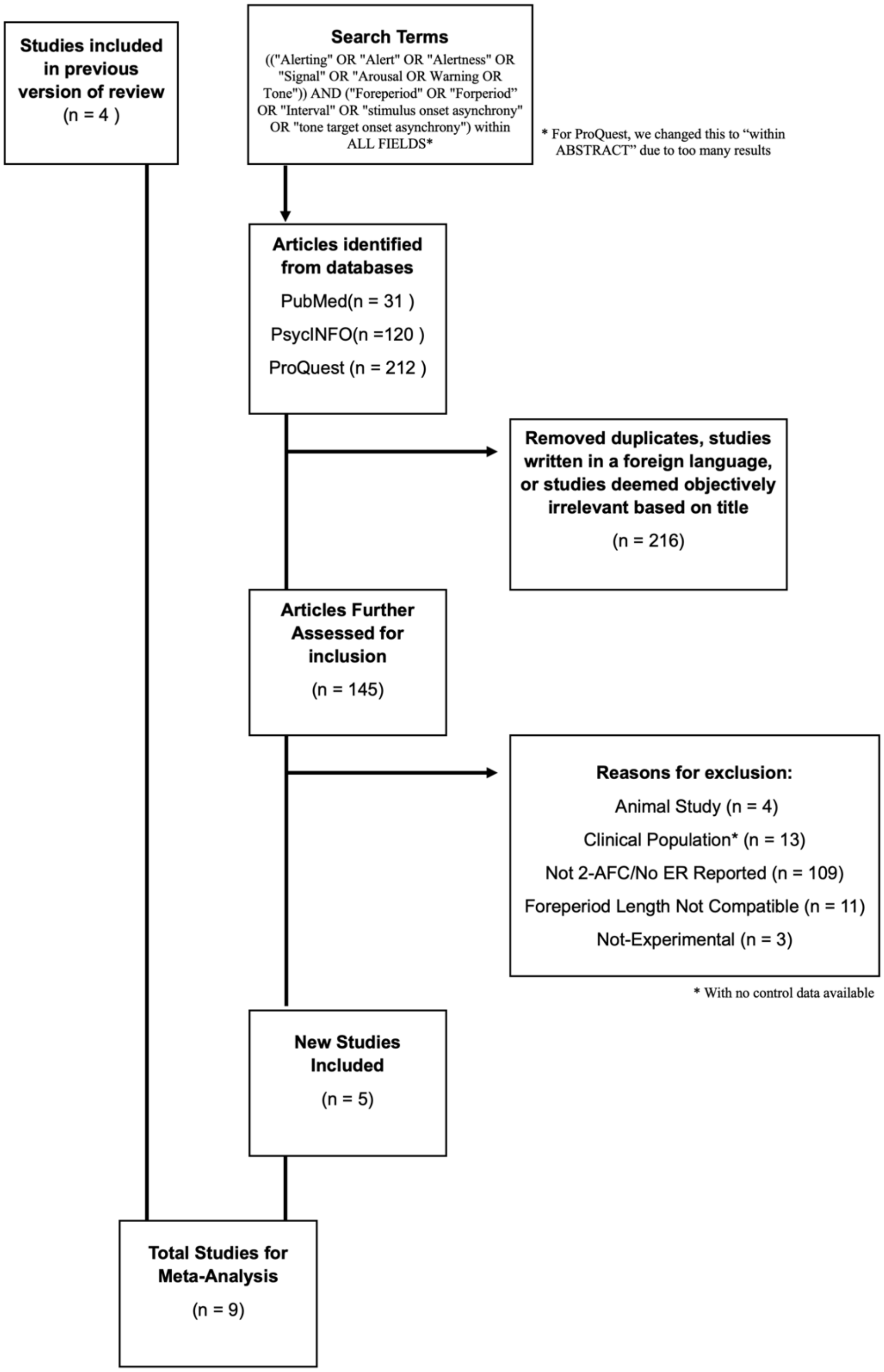
[5] experiments involving the administration of drugs

2.2.2 Information Sources & Search Strategy

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines have been followed in the reporting of how we conducted our review of the literature (see Figure 2.3). One of the authors of this paper (CM) was the sole member conducting the review and did not rely on automation tools. Four experiments were identified prior to the literature review (reported below). The review of the literature took place in October 2023.

The first step of the literature review was setting search terms for the three databases used. This resulted in a combined search-sum of 363. On each of the result pages provided by the database, CM chose to download papers that appeared to plausibly be related to the topic of interest. After removing duplicate results, this left 145 papers to be further inspected for methodological relevance. Of those 145 papers, five were determined to be applicable, in addition to the four previously identified, generating a total of nine experiments. The most common reason for exclusion was that the alerting study only measured RT or ER, but not both. A more detailed reporting of the review of the literature can be found in our flowchart (Figure 2.3). Considering the methodological restraints surrounding inclusion in this experiment, this was a reasonable total and was expected to provide valuable insight into the likely range of effect sizes for reaction time and accuracy, allowing for a re-inspection of Posner's theory of alerting.

Figure 2.3. A flowchart showing the review of the literature that led us to including these nine papers.



2.2.3 Study Selection

The four papers identified prior to the review process were Posner, Klein, Summers, & Buggie (1973), Han & Proctor (2022), McCormick, Hurst, Redden, & Klein (2019), and Dietze & Poth (2022). Posner et al. was the motivating paper for this review, McCormick et al. and Han & Proctor were replications of this experiment, and Dietze & Poth was separately found via use in another research paper. The other five papers included are Han & Proctor (2023), Dietze, Recker, & Poth (2023), Dietze & Poth (2023), Kazen-Saad (an unpublished thesis work; 1983), and He et al. (2020). In total, these nine papers contributed sixteen different experiments.

The temporal distribution of studies is worth noting: two of the papers included are from the 1970s and 1980s, and then seven are from a four-year span from 2019 to 2023. There are a number of studies between this large temporal gap which were interested in the dynamics of alerting, however they often used either just RT or ER, or an alternative methodology (i.e. Simon tasks, Go No-Go, etc.). One of the reasons for this recent spike in research that matches our criteria is a renewed interest in the study of attention within the temporal domain, as it has been identified as a rich and understudied area of research (Nobre & van Ede, 2018; also see Nobre & van Ede, 2023). Additionally, the replication crisis and OpenScience movement inspired the direct replication of Posner's seminal study after 45 years (McCormick et al., 2019).

2.2.4 Data Collection Process

The meta-analysis was performed in R (R Core Team, 2023) using functions from the 'metafor' package (Viechtbauer, 2010). Relevant metrics were extracted from the raw data when possible[6], which included 11 of the 16 total experiments. Data were extracted from figures/supplementary tables otherwise. These metrics included the mean values for RT and ER,

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[6] Either through online repositories or by contacting researchers directly requesting the data: McCormick et al., 2019; Han & Proctor 2022; 2023; Dietze, Recker, & Poth, 2023; Dietze & Poth, 2023; Dietze & Poth, 2022.

standard deviations, the sample size, trials per condition, along with t and F values. If information was not reported within the paper, either within the text or in supplementary materials, relevant equations were used (in the case of calculating effect standard deviation (SD), which was never reported), or estimates were generated based on other experiments (in the case of Kazen-Saad, 1983). If compatibility manipulations were included, as was the case in Posner, Klein, Summers, & Buggie (and the subsequent replications), only the compatible conditions were included.

Additionally, we identified and included four moderating variables: signal modality (was the signal auditory or visual), block structure (was the foreperiod fixed within a block vs intermixed), feedback (was RT feedback provided), and trials per condition (numeric). These moderators were included in the models once it was identified there was very high heterogeneity between the included experiments, despite their generally similar methodology. Signal modality was included as a moderator because the visual and auditory processing systems are distinct from one another and have been shown to differently impact performance (Posner, Nissen, & Klein, 1976; Dietze and Poth, 2023). Block structure was included as it determines whether participants could use the signal to predict when a target was presented or not, which impacts the influence of volitional preparation (endogenous mode) on performance. RT feedback was included as it was one of the features of Han and Proctors' replication of Posner et al. (2022) and was found to impact ER. If participants are provided feedback on performance in cognitive tasks, it will impact the response criterion they put forth, and can lend to faster performance and less accurate performance (Hines, 1979). Trials per condition was used to account for the variance across the included experiments. Other demographic and design notes were recorded and reported in the

Appendix (Appendix A Table A1 and A2), but these four moderators were the only moderators tested on the model.

2.2.5 Data Items

2.2.5.1 Reaction time

Reaction time was the amount of time it took participants to respond to target stimuli within the task. Only the RTs for correct responses were included in the analysis. For experiments in which the data files were not available, RTs and their SDs were provided within tables or supplementary materials. For Posner et al. (1973) and Kazen-Saad (1983), RTs were extracted from tables, and condition SD was unavailable.

2.2.5.2 Error Rate

Error rate is the binary measure of accuracy (1=correct, 0=incorrect) averaged across available trials. For experiments in which the data files were not available, ER and its SDs were provided within tables or supplementary materials. For Posner et al. (1973) and Kazen-Saad (1983), ERs were extracted from tables, and condition SD was unavailable.

2.2.5.3 Log Odds

In addition, a transformation of ER into log odds values was conducted using the qlogis function in R (R Core Team, 2023). The effect SD for the log-odd values were based on the theoretical variance for values and can be found within the included R script. The theoretical variance was generated by running a high number of simulations with the logistic distribution, until the variance of the output stayed consistent to the second decimal place. This was required for the transformation into log odd values as we did not have enough information on individual participant performance in each condition from the included experiments, which is required for generating 95% confidence intervals (CI).

2.2.5.4 Summary Measures

Mean RT and ER effects are included for RT, ER, and Log Odds, which are difference scores between our mentioned comparisons of interest (no signal and signal conditions). Difference scores were compared for each signal-foreperiod condition that a study included. Log-odds were generated by transforming ER values. These are presented in forest plots.

2.2.5.5 Effect Variance

Effect variance was not provided by any of the included papers, so it was calculated via the F-values from the ANOVAs for non-raw data extraction (using *effect variance* = $effect\ size/\sqrt{F} * \sqrt{n}$). This is except for Kazen-Saad (1983), in which no statistical test was reported for ER. In this case, we applied the same effect SD as Posner et al., 1973, as Posner et al.'s effect SD was a conservative estimate and methodologically near identical. In the case of the raw-data analysis, we applied this equation to the data for each foreperiod difference score:

$$\sqrt{(variance(A)\ +\ variance(B)\ -\ 2 * (Covariance(AB))}$$

2.2.6 Risk of Bias in Individual Experiments

All the experiments included in this meta-analysis involve within-group comparisons, so comparisons between our different conditions are not impacted by sampling differences. Abnormalities within any of the experiments, including information on methodological abnormalities, statistical reporting abnormalities, data trimming, and any other possible concerns which could indicate a bias, were reported.

2.2.7 Risk of Bias Across Experiments

Risk of bias was assessed by presenting the included experiments in a funnel plot, which allows for a comparison of precision and effect size that can signal biases in the field. If the experiments are unbiased, they should be distributed symmetrically around the mean effect. Two of the experiments from the same paper use the same participants (Dietze & Poth, 2023; split into visual & auditory signals), but have no repeated data between them. Interpretations of the funnel plot and the possible sources of the biases were presented. Moderating variables were included to observe whether this controls for some of this bias.

Additionally, although there were 16 experiments total, six of these experiments included the authors 'Dietze and Poth', three were conducted by 'Han and Proctor', and Klein was an author on three of the papers. It is worth noting that these experiments likely share subtle design or sampling characteristics which could influence results (speed/accuracy emphasis, geographical location. etc.), so we note any clustering of effects that may occur. We were able to find an unpublished dissertation involving two relevant experiments (Kazen-Saad, 1983) which have very similar methodological designs to Posner et al's experiment (1973). This adds some richness to our experiment sample, as we know academic journals have a bias towards publishing significant research outcomes (Song et al., 2010).

2.2.8 Synthesis of Results

Three meta-analyses were run on RT data, three on ER data, and three on log-odd data, for a total of nine. This involved looking at the RT, ER, and log-odds effect of a warning signal with a 50 msec foreperiod before the target, 200msec before the target, and 400 msec before the target compared to when no signal was used. The effects for each condition involve difference scores of mean RT, ER when subtracting the 'no signal' condition mean from the 'signaled' condition. Each foreperiod condition had its own analyses, as the amount of time between the warning signal and target influences the size of behavioural effects (Posner et al., 1973; Lawrence and Klein, 2013) and involves different amount of influence from endogenous (volitional) and exogenous (reflexive) modes of alerting (Lawrence and Klein, 2013; Klein, 2022). The time-course of endogenous and exogenous influence is discussed at length later when interpreting analysis outcomes. Moderating variables were included for signal modality (was the warning signal auditory or visual), block structure (were the foreperiods fixed or intermixed), and feedback (was RT feedback provided or not). The data from these analyses are presented in forest plots, which include calculated 95% CIs for each effect. A mixed-effects model was run through the rma.uni function (within the metafor package in R; Viechtbauer, 2010) with a restricted maximum likelihood estimator (REML) selected as the method. This is because the effects across experiments are not fixed and running the model as if they are fixed biases the model towards the experiments with very low overall ERs. This model also produces measures of heterogeneity (I^2 and T), which are reported and discussed.

The models reported represent the aggregate effect at the ‘mean’ of each of our dummy coded moderator variables. This accounts for differences generated by our three moderator variances by weighing their influence in proportion to the number of experiments which included the manipulation. This makes it so the reported effect best represents the overall effect for 2-AFC alerting experiments, and controls for more of the heterogeneity across experiments. This ‘Meta-Regression’ or ‘adjusted’ model, will be presented alongside the RE model, which does not include the moderating variables, within the forest plots.

2.3 Results

2.3.1 Study Selection

Sixteen experiments were included in this meta-analysis, pulled from nine different research papers. These experiments provided a methodologically homogeneous sample to allow us to explore how alerting impacts speed and accuracy performance across three foreperiod conditions.

2.3.2 Characteristics of the Experiments

All 16 experiments matched the inclusion criteria outlined in the methods section. They all used a 2-AFC task which compared signaled and no signaled trials across various foreperiods (50msec, 200msec, and 400msec).

Not all the included experiments contributed data to each foreperiod analysis. One-hundred and sixty-five participants were included in the 50 msec analysis (from six experiments), 298 for the 200 msec comparison (from 13 experiments), while four-hundred and four participants were included for the 400 mesc foreperiod comparison (from 11 experiments). Deviations in the exact length of foreperiod conditions is reported in the Appendix table (Appendix A Table A2). The participants were all typically developing, with an average/median age around the mid to low 20s, with one study having an experimental group with an average age of 75. The median number of trials per-condition cell was 60 (min: 15, max: 202, mean = 81).

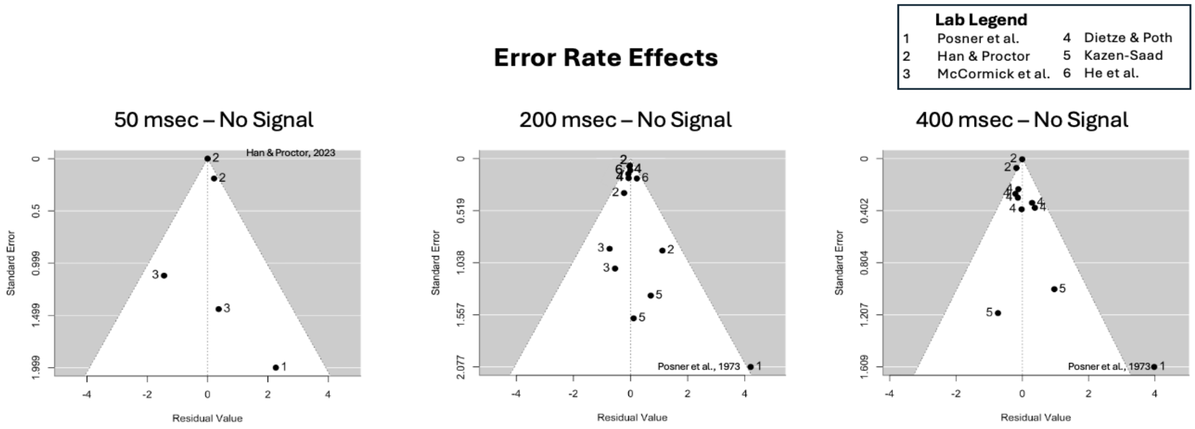
Ten of the included experiments used auditory warning signals and six used a visual signal. For McCormick et al.'s (2019) experiment, there was an isointense manipulation that involved a shift from mono to stereo white noise in the task without a change in intensity (analogous to isoluminance in vision). This did not have any substantial non-additive effects within their study, so we have included it among the other experiments. Twelve of the experiments had consistent foreperiod durations within a block, while four intermixed the presentation of foreperiods throughout the experiment. Five experiments provided RT feedback, while 11 did not. These distinctions can be found in the notes of the Appendix table (Table A1), along with other relevant methodological distinctions.

2.3.3 Risk of Bias Across and Within Experiments

Moderators were included in the models to attempt to control for the unexplained heterogeneity across experiments. This included signal modality (was the signal auditory or visual), block structure (was the foreperiod fixed within a block vs intermixed), trial feedback (was RT feedback provided), and trials per condition (numeric). For the 50 msec foreperiod models, all the experiments use auditory signals, so there is no signal modality moderator. For the 200 msec signal and the 400 msec signal models, we have included all four moderators to observe their impact on heterogeneity. The influence that these moderators had on heterogeneity is evaluated with a likelihood ratio test (LRT), which compares the full model (all moderator levels included) to a restricted model with the moderator of interest dropped (α < .05). The funnel plots, which were used to evaluate bias, used the full model with moderators; funnel plots generated without moderators included can be found in the Appendix (Appendix A Figure A1).

2.3.3.1 Evaluation of Bias for Error Rate Effects

Figure 2.4. Funnel plots for error rate effects across the different foreperiod conditions. The x-axis represents the effect sizes. The line is the mean effect size across all experiments, the white triangle represents the likely values across the various standard error values (y-axis). In non-biased fields, experiments should be arranged symmetrically around the center line. Because many of these papers come from the same researchers, and we want to be able to detect possible 'biases' based on this, points are marked based on which author published the study. Experiments that generated unexpected values are labeled.

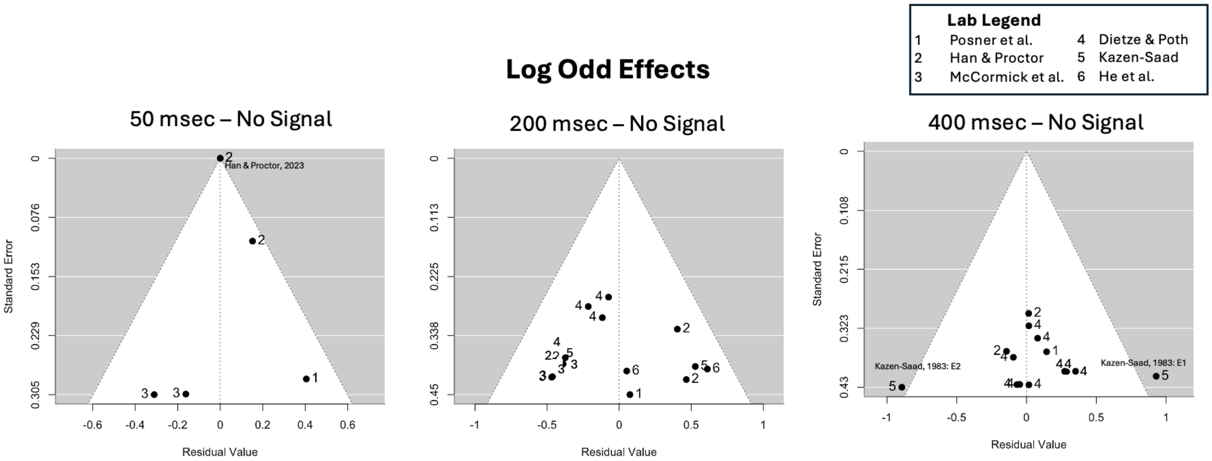


Within the 50msec foreperiod ER model, block structure (LRT = 5.58, p = .02, ΔI^2=39%) and feedback (LRT = 6.59, p = .01, ΔI^2=48%) had an influence in reducing heterogeneity, but trials per condition (LRT = 1.14, p =.29, ΔI^2=-24%) did not. In the full model, the confidence interval for residual heterogeneity included a range of values that provided little insight toward the level of heterogeneity across the included experiments (I^2=24%, CI [0, 98]; *Tau*=.002, CI [0, 7.10]). For the 200msec foreperiod ER model, feedback (LRT = 19.35, p < .01, ΔI^2= 80%) and trials per condition (LRT = 6.24, p =.01, ΔI^2= 34%) reduced the residual heterogeneity, while block structure (LRT = 0, p = .82, ΔI^2=0.00%) and signal modality (LRT = 3.8595, p = .05, ΔI^2=8%) did not. In the full model, the confidence interval included a range of values that provided little insight toward the level of heterogeneity across the included experiments (I^2= .003%, CI [0, 97]; *Tau*=.0021, CI [0, 2.16]). For the 400msec ER model, the trials per condition (LRT = 8.40, p < .01, ΔI^2=54%) reduced the overall heterogeneity. Block structure (LRT = 1.39, p = .24, ΔI^2=0.00%), feedback (LRT = 2.27, p = .13, ΔI^2=8%), and signal modality (LRT = .19, p = .66, ΔI^2=0.00%) did not have a significant influence in reducing heterogeneity. The full model shows that there is little certainty regarding level of heterogeneity, as the confidence interval covers a wide range of values (I^2= 0%, CI [0, 96]; *Tau*=0, CI [0, 2.67]).

Based on the funnel plots generated for ER models with moderators (Figure 2.4), there does not appear to be a bias towards larger or smaller values, as they are relatively equally distributed on the left and right side of the plot. Posner et al.'s ER has the largest effect size at the 200 msec and 400 msec foreperiod comparisons, while also being an outlier in the amount of standard error generated, based on it falling outside of the expected values in the funnel plot (Figure 2.4). Han and Proctor (2023) have next to no standard error. This is because it is the only 'intermixed' block structure in the 50msec modes, so the residual error value is zero (this can be compared to the funnel plot generated by models without moderators in the Appendix A Figure A1).

2.3.3.2 Evaluation of Bias for Log-Odd Effects

Figure 2.5. Funnel plots for log-odd effects across the different foreperiod conditions. The x-axis represents the effect sizes. The line is the mean effect size across all experiments, the white triangle represents the likely values across the various standard error values (y-axis). In non-biased fields, experiments should be arranged symmetrically around the center line. Because many of these papers come from the same researchers, and we want to be able to detect possible 'biases' based on this, points are marked based on which author published the study. Experiments that generated unexpected values are labeled.

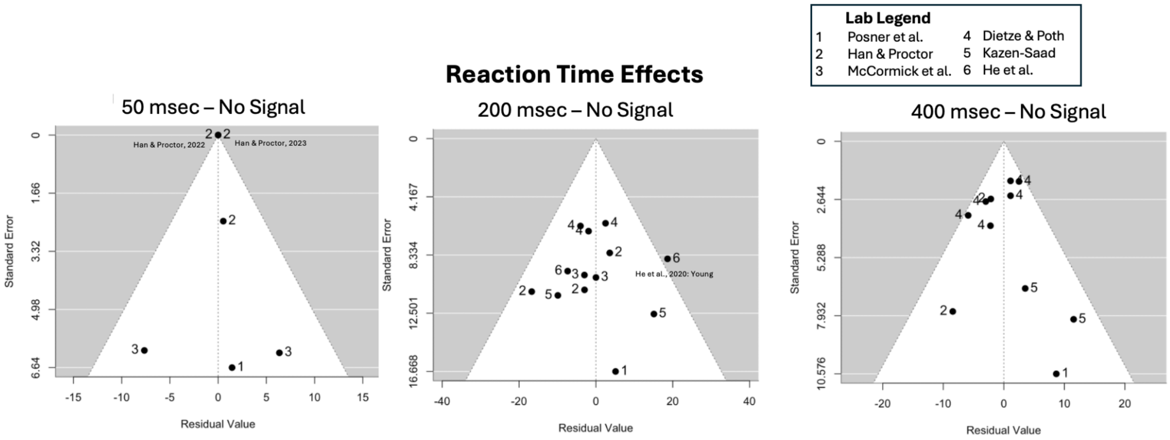


When comparing moderator influence on heterogeneity for the 50msec model, trials per condition (LRT = 7.01, p =.01, ΔI^2=7%) and feedback (LRT = 11.27, p < .01, ΔI^2=12%) had an influence in reducing residual heterogeneity, while block structure (LRT = 1.04, p = .31, ΔI^2=-4%) did not. There was evidence of medium to high heterogeneity across the included experiments, as indicated by a confidence interval range which only includes moderate to larger values (I^2= 84%, CI [34, 99]; *Tau*=.34, CI [.10, 2.45]). Within the 200msec foreperiod log-odds model, feedback (LRT = 7.59, p =.01, ΔI^2=3%) had an influence in reducing heterogeneity, while block structure (LRT =.67, p = .41, ΔI^2=.4%), signal modality (LRT =2.391, p = .12, ΔI^2=1%) and trials per condition (LRT = 1.39, p =.24, ΔI^2=.2%) did not. There was evidence of high heterogeneity across these different experiments (I^2= 93%, CI [85, 98]; *Tau*=.46, CI [.29, .90]). Within the 400msec foreperiod log-odds model, the moderators did not influence the unexplained heterogeneity between experiments (feedback (LRT = 2.91, p = .09, ΔI^2=0%); block structure (LRT =.39, p = .53, ΔI^2=.3%); signal modality (LRT =.13, p = .71, ΔI^2=.4%) and trials per condition (LRT = 3.0139, p =.082, ΔI^2=0%). There are high levels of heterogeneity, as the confidence interval covers only high values (I^2= 99%, CI [97, 99]; *Tau*=.51, CI [.31, 1.17]).

When inspecting the log odd effects within the funnel plot (Figure 2.5, the effects are distributed evenly on either side of the effect distribution (Figure 5). Posner et al.'s effects are now within the expected outcomes. However, in the 400 msec model, Kazen-Saad's two experiments both have very small (E2) and large (E1) effect size relative to the other experiments, with most experiments being clustered to the right. In their E2 experiment, the visual warning signal remained on until the target was presented. This may have helped with time-estimation, improving the participant's ability to accurately prepare for the target. Additionally, for both E1 and E2, this study had very high accuracy rates (conditions means were between 98.9% and 99.9% accuracy), so it makes sense that this effect ends up being distinct when converted to log-odds.

2.3.3.3 Evaluation of Bias for Reaction Time Effects

Figure 2.6. Funnel plots for reaction time effects across the different foreperiod conditions. The x-axis represents the effect sizes. The line is the mean effect size across all experiments, the white triangle represents the likely values across the various standard error values (y-axis). In non-biased fields, experiments should be arranged symmetrically around the center line. Because many of these papers come from the same researchers, and we want to be able to detect possible 'biases' based on this, points are marked based on which author published the study. Experiments that generated unexpected values are labeled.



When comparing moderator influence on heterogeneity within the 50msec RT model, trials per condition (LRT = 9.17, p <.01, ΔI^2=38%) had an influence on reducing residual heterogeneity, while feedback (LRT = 2.79, p = .10, ΔI^2=6%) and block structure (LRT = .13, p = .72, ΔI^2=-19%) did not. For the full model, the confidence interval included a full range of values that provided little insight toward the level of heterogeneity across the included experiments (I^2= 48%, CI [0, 90.3]; *Tau*= 5.38, 95 CI [0, 17.0]). For the 200msec model when comparing moderator influence on heterogeneity, feedback (LRT = 6.42, p =.01, ΔI^2=9%) and trials per condition (LRT = 1.65, p =.20, ΔI^2=8%) had an influence in reducing heterogeneity, while block structure (LRT =.90, p = .34, ΔI^2=-.8%) and signal modality (LRT =.30, p = .58, ΔI^2=1%) did not. The full model indicates moderate to high heterogeneity (I^2= 77%, CI [47, 95]; *Tau*= 10.22, CI [5.29, 21.0]). For the 400msec model when comparing moderator influence on heterogeneity, trials per condition (LRT = 7.7, p =.01, ΔI^2=54%) had an influence in reducing heterogeneity, while block structure (LRT =.90, p = .34, ΔI^2=-9%), signal modality (LRT =.00, p = .98, ΔI^2=-9%), and feedback (LRT = 2.27, p =.13, ΔI^2=11%) did not. The current analysis indicates no certainty on the level of heterogeneity, as the confidence interval covers a wide range of values (I^2= 9%, CI [0, 86]; *Tau*= 1.3, CI [0, 10]).

For RT (Figure 2.6), there is a good balance of effect sizes across the different foreperiods (Figure 6). In the 200 msec foreperiod condition, He et al. (2020) falls outside the expected effect. This could possibly be due to only 30% of the trials in a block containing alerting signals, so they were more impactful in generating a reflexive alerting reaction in comparison to other experiments where alerting signals were more frequent/always provided within a block. Additionally, Han and Proctor had two of their experiments which had abnormally small (2022 [no feedback]; 2023 [intermixed foreperiods]), but this was due to them having a level of moderator which was not present across other experiments.

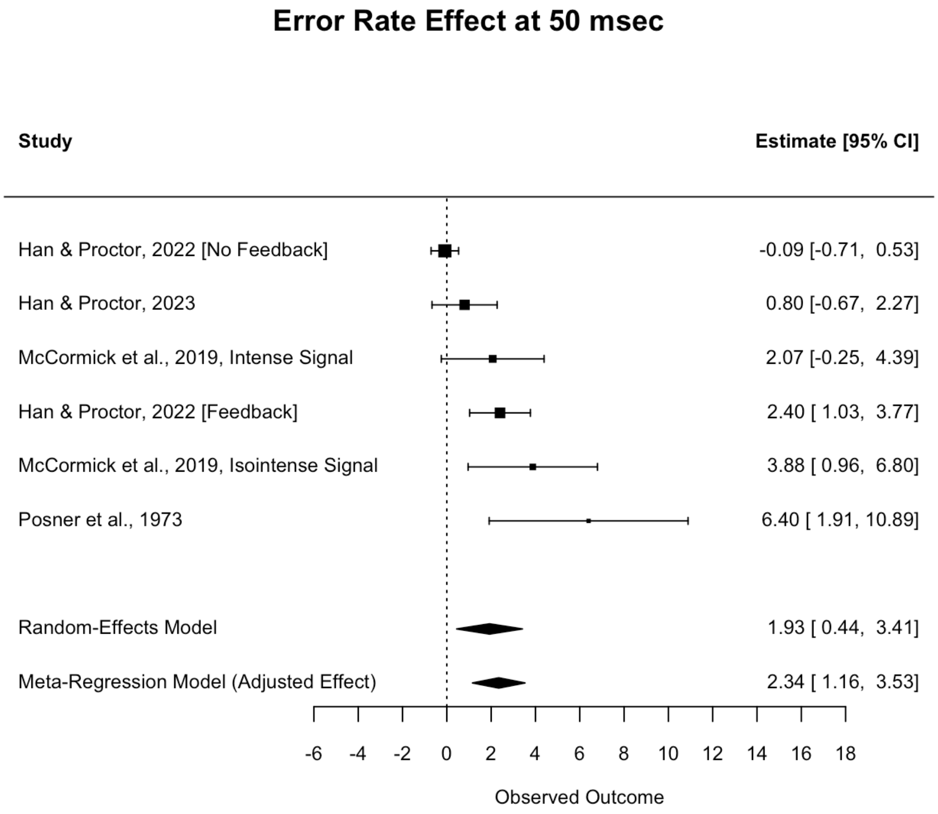
2.3.4 Synthesis of Model Results

Below are the forest plots for ER, RT, and log-odd effects at each foreperiod. Both the Random-Effects model and the Meta-Regression (Adjusted) model are presented. The latter represents a weighted estimate of the effects based on included moderators, while the former is a model that does not involve the influence of moderators. The range of effects for each of these models is often quite similar, but in conditions where the included moderators explained residual heterogeneity, the adjusted model will have a tighter confidence interval. The reported values within text will represent the adjusted model values.

2.3.4.1 Error Rate

2.3.4.1.1 50 msec vs No Signal

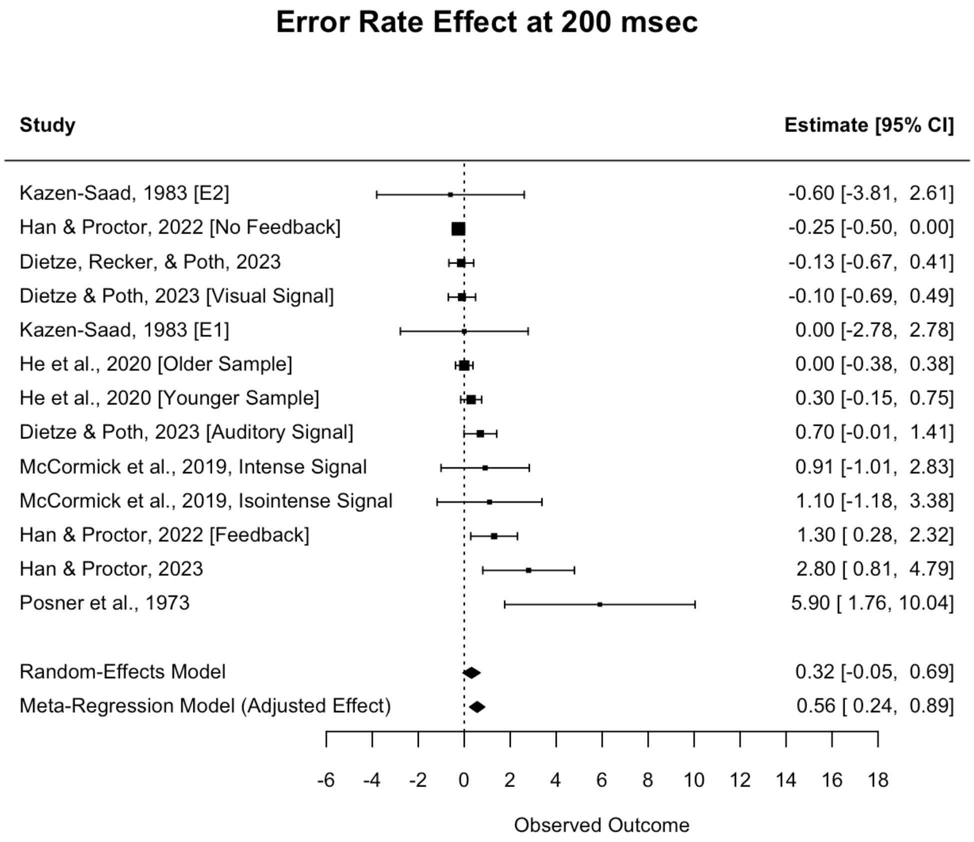
Figure 2.7. Forest plots for the error rate effect (difference in ER % between signaled trials vs no signal trials) at a foreperiod of 50 msecs. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these six experiments, participants made more mistakes on signaled trials compared to non-signaled trials (effect size = 2.34%, Standard Error (SE) = .61, 95% CI [1.16, 3.53]; see Figure 2.7). This is a small effect relative to the possible values originally reported in Posner et al. but was captured within the lower bound of their confidence interval. Experiments with RT feedback had larger ER effects in comparison to experiments without RT feedback (estimate = 2.84%, SE = .63, 95% CI [1.61 4.07]). Additionally, experiments with fixed foreperiod block structure had larger ER effects than experiments with intermixed foreperiod block structure (estimate = 1.95%, SE = .93, 95% CI [.14, 3.77]).

2.3.4.1.2 200 msec vs No Signal

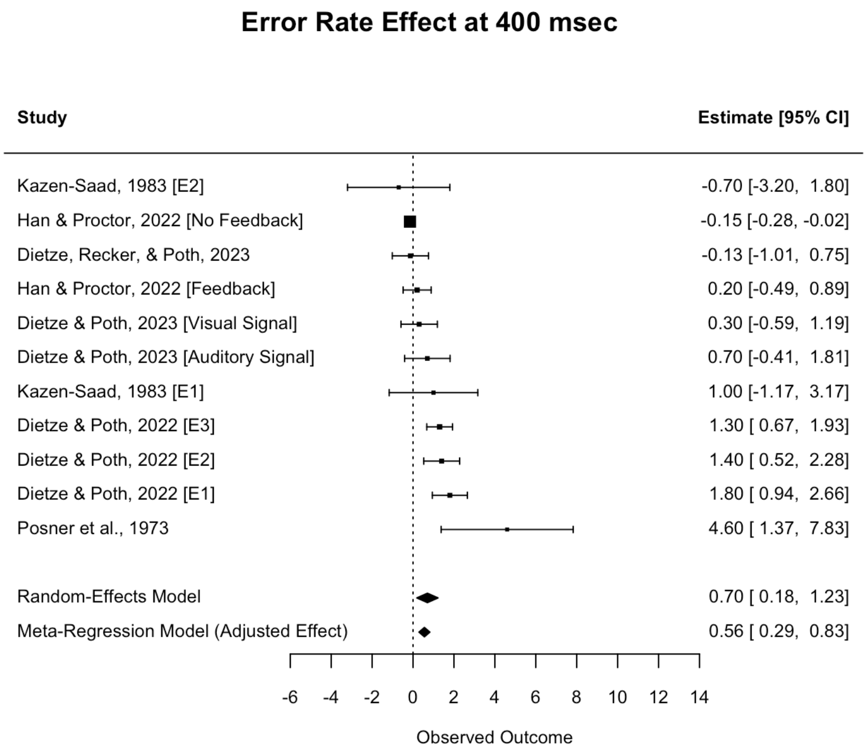
Figure 2.8. Forest plots for the error rate effect (difference in ER % between signaled trials vs no signal trials) at a foreperiod of 200 msecs. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these 13 experiments, participants made more mistakes on signaled trials compared to non-signaled trials (effect size = .56%, SE = .17, 95% CI [.24, .89]; see Figure 2.8). This range of small effect sizes falls outside the confidence interval from Posner et al., 1973. Experiments with RT feedback had larger ER effects in comparison to experiments without RT feedback (estimate = 1.61%, SE = .44, 95% CI [.75, 2.47]), and experiments with more trials per condition had larger effects (estimate = .007, SE = .003, 95% CI [.00, .01]).

2.3.4.1.3 400 msec vs No Signal

Figure 2.9. Forest plots for the error rate effect (difference in ER % between signaled trials vs no signal trials) at a foreperiod of 400 msecs. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these eleven experiments, participants made more mistakes on signaled trials compared to non-signaled trials (estimate = .56%, SE = .14, 95% CI [.29, .83]; see Figure 2.9). This range of small effect sizes falls outside Posner et al.'s original study's range. As the trials per condition increased, so did the effect size (estimate = 01%, SE = 0.003, 95% CI [0.00, 0.02]).

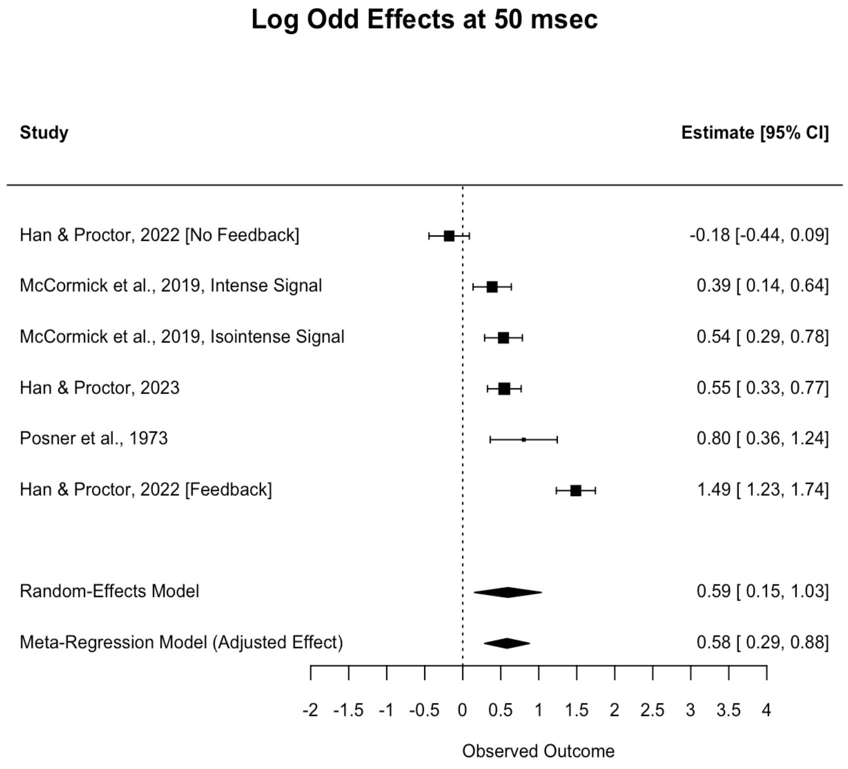
2.3.4.1.4 Comparison of ER Effects Across Foreperiods

When comparing ER effects across the different foreperiod conditions, the confidence interval generated by the 50msec model does not overlap with the range of values produced by the 200msec model or the 400msec model. This means that they likely represent different effect sizes, in which the alerting signal at a foreperiod of 50msec generates more error than when there is a 200 or 400msec foreperiod. The 200 and 400 msec effect sizes are nearly identical to each other. Overall, the ER effects are very small, especially compared to what Posner et al., 1973 found when establishing their theory of alerting.

2.3.4.2 Log Odds Transformation of Error Rate

2.3.4.2.1 50 msec vs No Signal

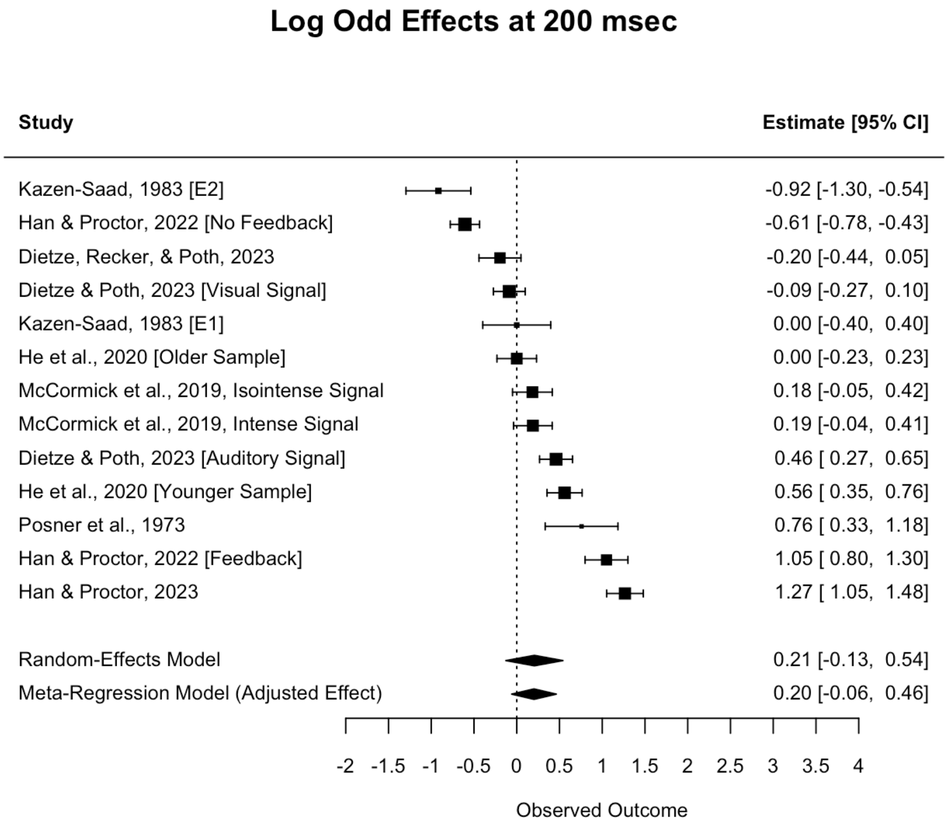
Figure 2.10. Forest plots for the log odd effect (difference in log-odds between signaled trials vs no signal trial) at a foreperiod of 50 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within the included six experiments, participants made more mistakes on signaled trials compared to non-signaled trials (effect size = .6, SE = .2, 95% CI [.2, 1.00]; see Figure 2.10). The range of effect sizes is quite small. Experiments with RT feedback had larger log-odd effects in comparison to experiments without RT feedback (estimate = 1.51, SE = .50, 95% CI [.53, 2.50]).

2.3.4.2.2 200 msec vs No Signal

Figure 2.11. Forest plots for the log odd effect (difference in log-odds between signaled trials vs no signal trial) at a foreperiod of 200 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.

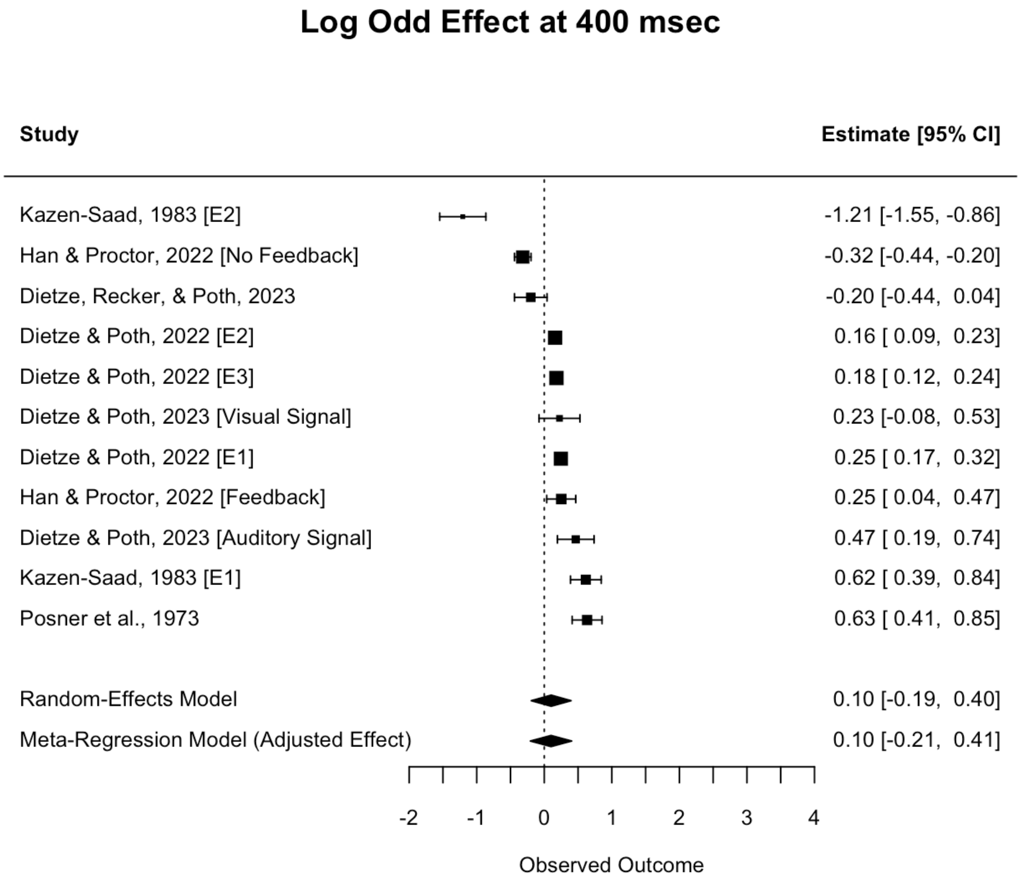


Within these 13 experiments, a range of both positive and negative values were captured within the effect of signal on error performance (effect size = .2, SE = .13, 95% CI [-.06, .46];

see Figure 2.11). A majority of the effects captured by the 95% confidence interval are positive values, however, they are small effects. If there is an effect of alerting on accuracy, it is challenging to declare that they are meaningful. Participants had higher log odd effects when provided with RT feedback than when not (0.82, SE = .32, 95% CI [.18, 1.45].

2.3.4.2.3 400 msec vs No Signal

Figure 2.12. Forest plots for the log odd effect (difference in log-odds between signaled trials vs no signal trial) at a foreperiod of 400 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these eleven experiments, both positive and negative values were captured within the effect of signal on error performance (effect size = .1, SE = .17, 95% CI [-.22, .43]; see Figure 2.12). This indicates uncertainty regarding the presence of an effect of alerting on accuracy.

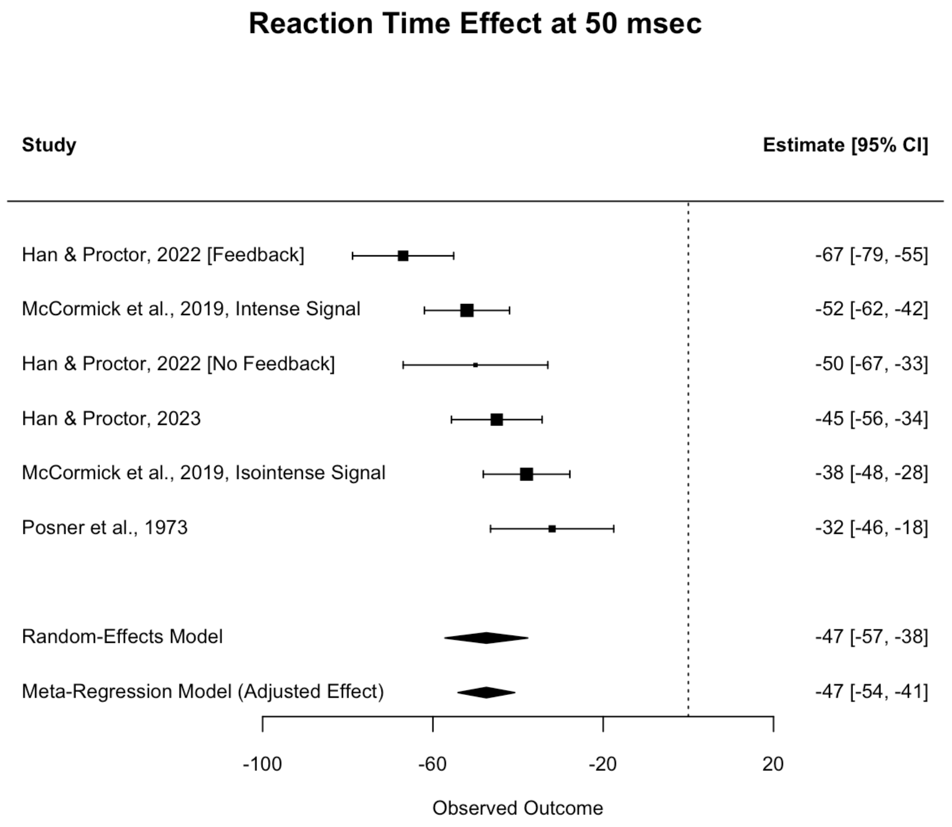
2.3.4.2.4 Comparison of Log-Odd Effects Across Foreperiods

When comparing log-odd effects across the different foreperiod conditions, the CI ranges from the adjusted random effect models all overlap with one another. This means that there is a possibility that the effect sizes could be the exact same value, so we cannot distinctly claim that there are differences in accuracy effects between foreperiods. This is distinct from the ER analysis, in which the 200 and 400 msec foreperiod models generated effects that were smaller than the 50msec condition. However, the 50 msec foreperiod condition is the only condition in which the confidence interval contains exclusively positive values. Even so, there is still a possibility of the effect being negligibly small. The transformation did change the magnitude of effects within some of the individual experiments, specifically those with very high (or lower) overall accuracy. However, there is still generally high heterogeneity across these experiments, signaling that there is inconsistency between experiments. The random effects model represents values that are either outside what was presented in Posner et al., 1973, or toward the lowest possible effect sizes.

2.3.4.3 Reaction Time

2.3.4.3.1 50 msec vs No Signal

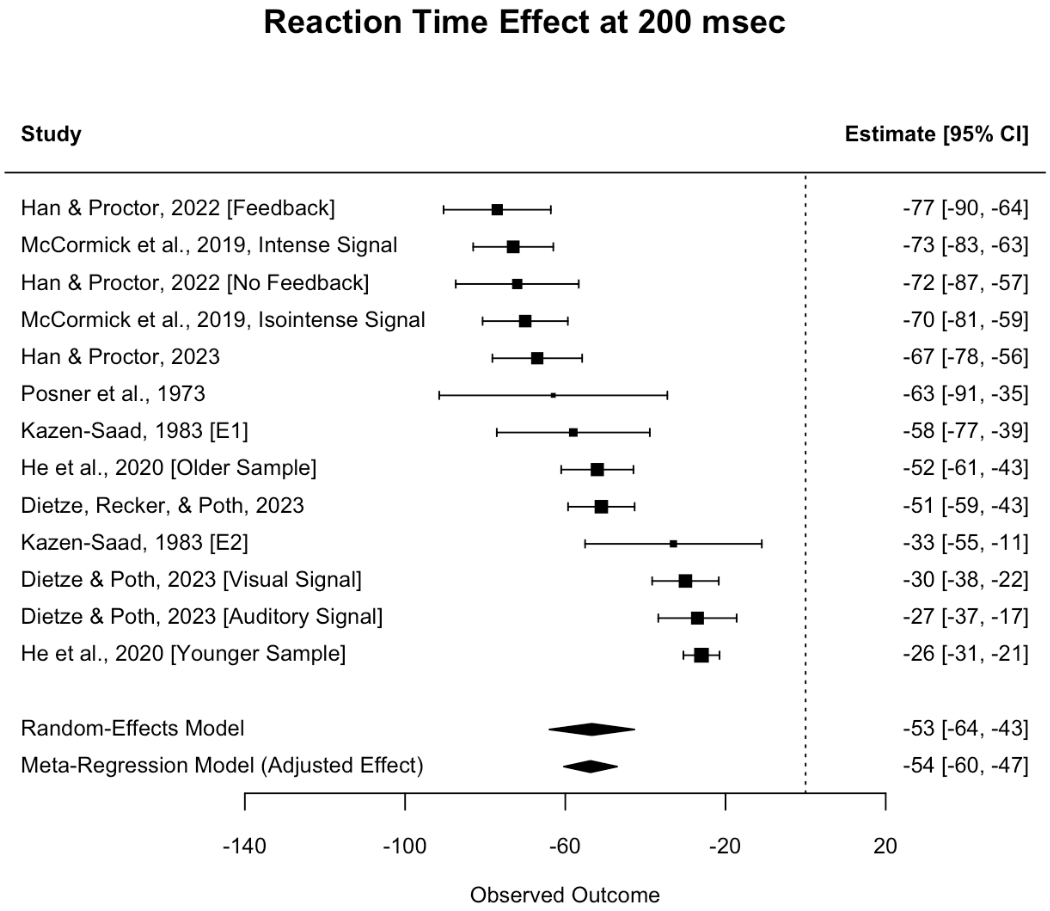
Figure 2.13. Forest plots for the RT effect (difference in RT between signaled trials vs no signal trial) at a foreperiod of 50 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these six experiments, participants were faster on signaled trials compared to non-signaled trials (effect size = -47 msec, SE = 6.32, 95% CI [-60, -35]; see Figure 2.13). This is a fairly consistent effect across alerting experiments, and comparable to what was reported in Posner et al. 1973. As the number of trials per condition increased, so did the RT effect size (estimate = 1.36, SE = .46, 95% CI [.46, 2.26]).

2.3.4.3.2 200 msec vs No Signal

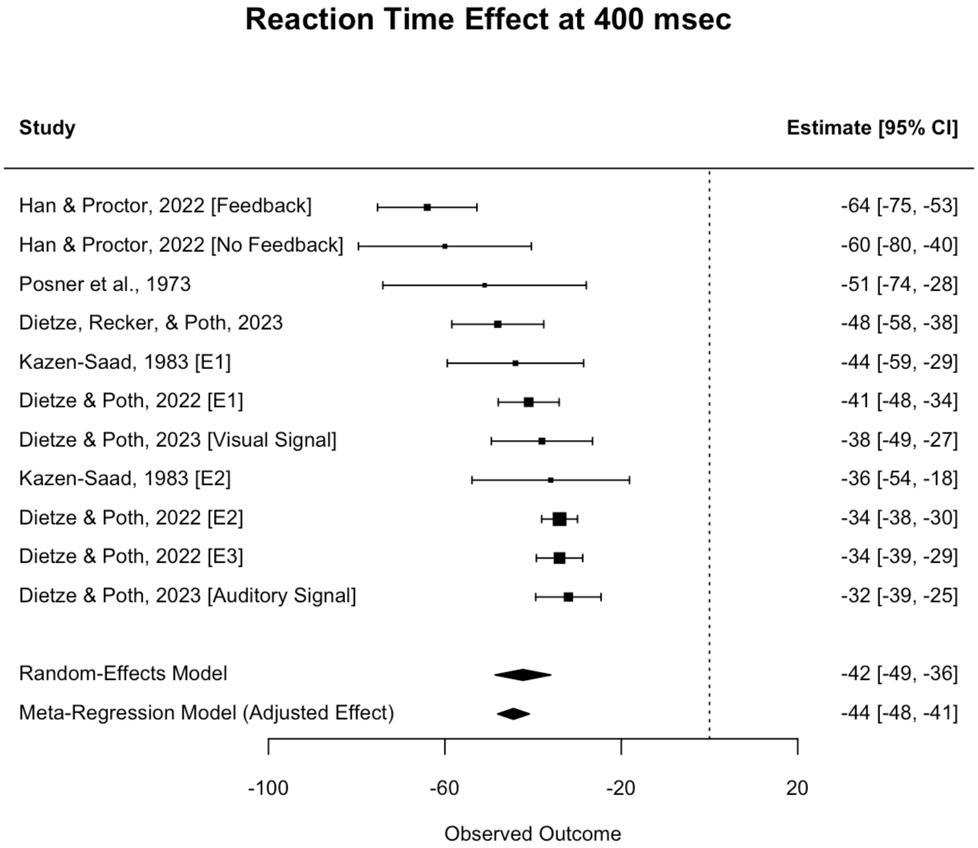
Figure 2.14. Forest plots for the RT effect (difference in RT between signaled trials vs no signal trial) at a foreperiod of 200 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



Within these 13 experiments, participants were faster on signaled trials compared to non-signaled trials (effect size = -54 msec, SE = 4.1, 95% CI [-62, -46]; see Figure 2.14). This is a comparable effect size to Posner et al. 1973. Providing RT feedback made RT effects larger (estimate =19, SE = 8, 95% CI [3, 35]). The number of trials per condition increased effect size (estimate =.24, SE = .10, 95% CI [.03, .44]).

2.3.4.3.3 400 msec vs No Signal

Figure 2.15. Forest plots for the RT effect (difference in RT between signaled trials vs no signal trial) at a foreperiod of 400 msec. Error bars are 95% CIs, while the size of the mean dot represents the study's sample size. The mean and CI generated by a random effects model, and the adjusted effect accounting for moderating variables, are presented at the bottom of the figure.



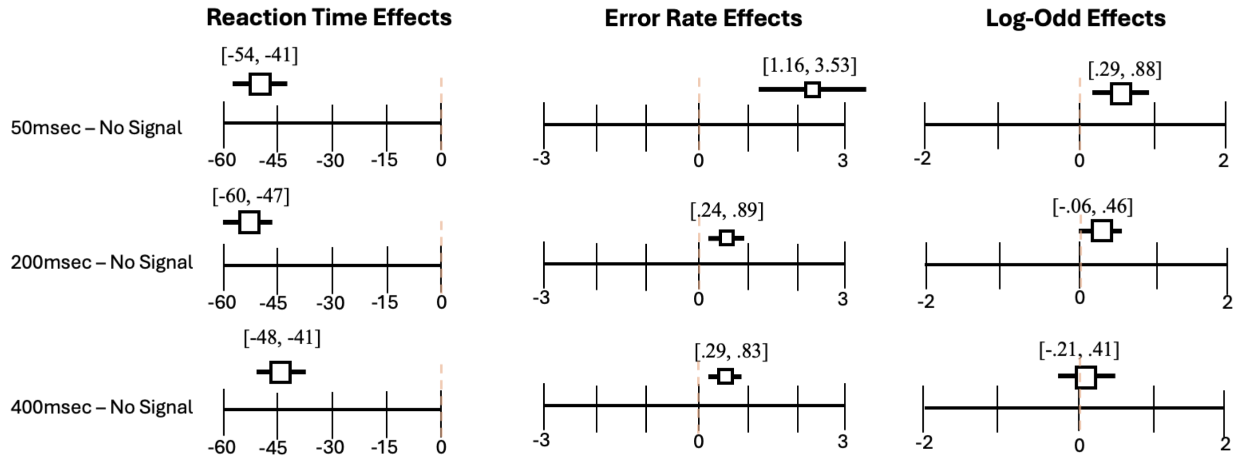
Within these eleven experiments, participants were faster on signaled trials compared to non-signaled trials (effect size = -43 msec, SE = 2.4, 95% CI [-48, -38]; see Figure 2.15). This is a tight range of possible effect sizes, and comparable to Posner et al., 1973. As the trials per condition increased, so did the RT effect size (estimate =.09, SE = .03, 95% CI [.03, .15]).

2.3.4.3.4 Comparison of RT Effects Across Foreperiods

When contrasting the different RT effects for the foreperiod conditions, they all overlap with one another, so one cannot claim there are differences. This runs counter to the ‘U-Shaped’ function found in Posner et al. (1973) and, to a lesser degree, the subsequent replications (McCormick et al., 2019; Han & Proctor, 2022), in which 200 msec produced the fastest RTs, with 50 and 400 msec being relatively slower. The confidence intervals for 50 and 200 msec are comparable in width, and the confidence interval around the random effects model for 400 msec is tighter around a slightly smaller effect. The 200 msec foreperiod seems to have the most varying effect size across the 13 experiments.

2.3.5 Summary of Results

Figure 2.16. A summary of the adjusted effect forest plots for reaction time, error rate, and log-odd across the three foreperiod conditions. Values represent the likely effect sizes for reaction time, error rate, and the log-odd transformation, Error bars are 95% CIs.



RT alerting effects were generally quite large, and all comparable to Posner et al.’s original alerting experiment. When looking at alerting’s impact on error rate, all three foreperiod conditions have quite small effect sizes. Additionally, the 200msec and 400msec conditions have a smaller, and equal, ER effect size compared to the 50 msec condition, indicating that participants maintained their speed-advantage for alerted trials while also slightly reducing the overall error rate. When converted to log-odds, which allows us to partially adjust for overall accuracy differences, we can see that the effect sizes are still small, and in the case of the 200 and 400 msec foreperiod, now contain negative values (see Figure 2.16). This means that alerting generated faster responses on these 2-AFC tasks, while having very little, if any, impact on accuracy.

2.4 Discussion

The current meta-analysis aimed to reassess the relationship between speed and accuracy across three foreperiods, using the logic from Posner et al. (1973). Posner's theory (1975), which was drawn from their results, states that alerting shifts an individual's response criterion, so participants are faster at the cost of accuracy[7] without improving the speed at which information is processed. The evidence generated by this meta-analysis will be interpreted in the context of Posner's theory, with consideration to how variations in methodology may have impacted performance outcomes. Specific emphasis is put on contrasting Posner et al's (1973) effects with the confidence intervals generated by the models.

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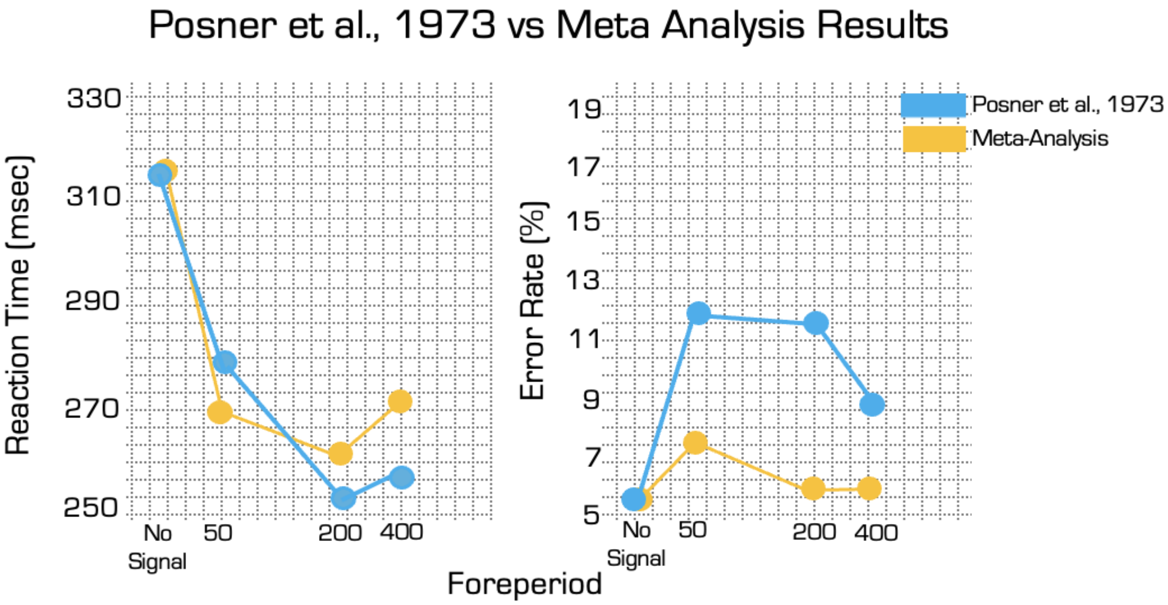
[7] Or vice versa. However, all experiments included found the former to be true.

2.4.1 Magnitude of Reaction Time and Error Rate effects in Comparison to Posner et al.

Figure 2.17. Condition means from Posner et al. compared to the results of this meta-analysis. For the meta-analysis, the effect size for each foreperiod condition was subtracted/added to the RT/ER of Posner et al.'s 'no signal' condition. Only compatible response mapped trials were included.



Although the RT effects were generally large and comparable to Posner et al., it appears that the ER effects in each foreperiod condition had much smaller estimates (see Figure 2.17). This is especially true for the 200 and 400 msec foreperiod conditions, where the confidence interval for the ER model is completely below the smallest possible values reported in Posner's wide confidence interval (see Figures 2.8 & 2.9). This suggests that the ER effects of alerting at each foreperiod are small, even in the context of large reaction time effects. When considering the log-odds transformation of the error data, which accounts for the overall differences in accuracy between the experiments, there is limited evidence for the presence of an effect of alerting on accuracy. In addition, the confidence interval for 200 and 400 msec conditions contain possible negative effects. The addition of log-odd transformations is helpful in the interpretation of accuracy effects across experiments. Consider the two direct replications recently conducted of Posner et al., and how it changes the interpretation: Posner et al. compared values of 11.6% (warning signal trials) and 5.2% (no warning signal trials), whereas Han and Proctor compared 3.1% and .7%, and McCormick et al. compared 6.5% to 4.4%, respectively. McCormick et al. declared a successful replication within their paper because their ANOVA foreperiod effect on ER was significant, although the relative log-odd effect size we calculated here was half the size of Posner's at 50 msec (.4 vs .9). Meanwhile Han and Proctor declared a lack of a speed-accuracy trade off because their ANOVA foreperiod effect on ER was non-significant, even though the log-odds effect size was much larger than the original study (1.5 vs .9).

Posner et al.'s (1973) ER effect sizes are anomalously large in comparison to the other alerting experiments, which can be observed in the funnel plots (Figure 2.4). It is not surprising that Posner concluded substantial criterion shifts across the different foreperiod conditions based on this outcome (1973; 1975). One important factor that may have influenced the increased magnitude of errors in Posner et al.'s task was the compatible and incompatible response mappings implemented across blocks. This feature of the task was used to increase the overall error rate within the alerting task, because a prior alerting task failed to observe a significant effect on ER due to high overall accuracy (Posner & Boies, 1971). However, we now know there is an interaction between alerting and response compatibility, in which alerting can activate the direct path between matching stimulus and response features (De Jong et al., 1994). This likely puts additional cognitive load on signaled trials in comparison to non-signaled trials, which means this task manipulation did not evenly apply this increase in difficulty among all the conditions. With this said, the included experiments from McCormick et al. (2019) and Han and

Proctor (2022; 2023) also had response mapping manipulations, and we did not observe anomalous effect sizes. In addition, we only included the ‘compatible mapping’ trials from these experiments, although one could imagine carry-over cognitive load and task-switching effects within these trials.

In summary, RT effects are consistently large across the three different foreperiods, while the effect of alerting on accuracy, evaluated through log-odd transformations, shows very small, if present at all, accuracy effects. This outcome is a significant deviation from the results of Posner et al., 1973, in which the faster a participant is, the more errors they generate. This novel pattern of results needs to be contrasted using the same logic previously used by Posner (1973; 1975).

2.4.2 Relationship Between Speed and Accuracy: Evidence for a Criterion Shift or Improved Information Processing?

Under Posner’s theory of alerting (1975), alerting generates faster responses without any increase in processing speed, resulting in less information being available to the participant at the time of response. This means that when RTs are reduced via a warning signal, ERs should increase. However, across the three foreperiod conditions in which substantial reaction time effects were observed, the effect on accuracy was either quite small, or non-existent, as indicated by both ERs and the transformed log-odd values. Additionally, when we specifically contrasted RTs and ERs between our three foreperiod conditions, we observed a consistent RT effect, but that ER effect at the 200 or 400msec foreperiods is smaller than the 50 msec condition. The maintenance of the RT benefit with an improving ER supports the premise that alerting has some enhancement to the efficiency of information processing, and these effects are not just exclusively shifting the response criterion to trade-off speed for accuracy.

However, it is possible that alerting generates a criterion shift in which participants trade-off accuracy at the betterment of speed, in addition to increasing the efficiency of information processing. In our meta-analysis, the highest error rates appear to be at a foreperiod of 50 msec. Han and Proctor (2022), in their replication of Posner et al. (1973), indicate that a shift in criterion may only occur at the shortest foreperiod durations due to the increased influence of automatic alerting mechanisms. Lawrence and Klein (2013) isolated the influence of voluntary (endogenous) and automatic (exogenous) modes of temporal attention (a more general term for alerting). Endogenous temporal attention involves voluntary preparation for an upcoming stimulus based on learned (or cued) temporal distributions, whereas exogenous temporal attention is an automatic response to salient stimuli, like a warning signal. The two modes of temporal attention have distinct time-courses, and therefore have varying levels of influence on performance depending on foreperiod condition. Peak exogenous alerting occurs around 50 to 80 msec after a warning stimulus (Denison, Carrasco, and Heeger, 2021), while peak endogenous alerting occurs some time around 400msec (McCormick, Redden, and Klein, 2023). Lawrence and Klein propose that the combination of endogenous and exogenous temporal attention, around very short foreperiod durations between 50 and 100 msec, generates SATs (2013; page 568). Together, this evidence suggests that the peak of the exogenous mode of temporal attention is driving a criterion shift, and the endogenous mode is driving a criterion shift of speed for more accuracy. More research is required to better separate the dynamic influence of endogenous and exogenous modes at various foreperiod durations.

The consideration of how endogenous and exogenous modes of temporal attention differently impact performance is salient in relation to Klein's recent replication (2023) of Posner's et al.'s pattern through a reanalysis of Los and Schut (2008). In this reanalysis, the four foreperiods (50, 100, 350, and 400 msec) with the slowest RTs, and the four foreperiods (150, 200, 250, and 300 msec) with the fastest RTs were combined to compare the combined mean ERs. Klein found that the average ER of the fastest SOAs was larger than the average ER of the slowest, replicating the SAT outcome of the seminal study by Posner et al. (1973). However, based on what we know about the two modes of alerting, the errors occurring at the 50 msec foreperiod have a distinct source in contrast with errors occurring at the 400 msec foreperiod. With this said, Klein indicates that the outcome of the reanalysis mirrors the overall pattern of performance from Posner et al. (1973), but this does not necessarily mean that these changes in performance are being generated exclusively by a shift in response criterion.

2.4.3 Moderating Factors

This meta-analysis included either direct replications of Posner et al. (in the case of McCormick et al, 2019; Han & Proctor, 2022) or near-direct replications, so it was surprising to obtain such high heterogeneity measures across our various effects. There are a relatively small number of experiments within some of our meta-analyses, so an outlier study can have a stronger bias on the amount of heterogeneity calculated (the I^2 value). Papers that contributed multiple experiments also impacted the heterogeneity, as the size of effects from experiments in the same study tended to cluster together even when using different sets of participants, likely due to minor experimenter-specific distinctions in methodology or sampling. Three of our moderators — trials per condition, RT feedback, and block structure — did account for some of the heterogeneity. Trials per condition affects the amount of variance between experiments, since studies that have more trials for each participant will have a more accurate representation of their average performance, so this is a rather straightforward moderating factor. The other moderators, along with other considerations, are discussed below.

2.4.3.1 RT Feedback

In the 50 msec condition, RT feedback impacted ER effect size, but did not impact RT. However, only one out of the six experiments did not provide feedback, so we exercise caution in generalizing this comparison. However, at 200 msecs, where there is a more balanced representation of experiments providing RT feedback or not, there was a moderating effect of feedback on RT, ER, and Log-Odd effects in the expected direction: larger ER and RT effects (Hines, 1979). This indicates that RT feedback shifts the response criterion at a cost to accuracy. However, in the 400 msec condition, there was no difference in speed or accuracy performance based on RT feedback. It is possible that sufficient volitional preparation after a signal can help control for errors when increasing speed. This is the duration that is most commonly used in temporal cueing experiments, as a measure of endogenous temporal attention, and these experiments often display overall improvements in performance (as opposed to a trade-off between speed and accuracy; Nobre & van Ede, 2018). Han and Proctor (2022) explicitly manipulated RT feedback across their two included experiments, and showed that the warning signal condition improved both speed and accuracy in comparison to the no signal condition when no RT feedback was provided (in contrast with the speed-accuracy trade-off observed when it was). These two experiments both produced relatively larger, and comparable RT effects. It is still puzzling why participants were still able to maintain similar RT effects when they did not have feedback, while also reducing ER. Experiments from Dietze and Poth (2022; 2023; also Dietze, Recker, and Poth, 2023), which did not provide RT feedback, had overall smaller RT effects than other experiments included in this analysis.

2.4.3.2 Block Structure

The only model that detected a difference in ER performance for block structure levels was the 50 msec foreperiod analysis. It is unwise to generalize this significant difference, since there was only one study with an ‘intermixed’ condition, so this difference could have been influenced by other methodological factors from that one study. There was otherwise no impact of having predictable foreperiod durations vs intermixed foreperiods within a block. This is surprising, as we would anticipate that experiments using a fixed foreperiod design would generally have lower ER effects (and possibly faster RTs), considering that the consistent duration allows participants to volitionally prepare for upcoming targets. In the case of Han and Proctor, which intermixed foreperiods within a block, it is not surprising that varying the foreperiod did not impact this component of preparation, considering the range of the foreperiods was less than 200msec. These foreperiods are similar enough that participants could maintain an increased state of vigilance once hearing a warning signal. Additionally, 200 msec is the shortest duration that participants can volitionally prepare for in a 2-AFC task (McCormick, Redden, & Klein, 2023). However, in the case of Dietze and Poth (2023), in which a non-aging distribution of foreperiods was used (ranging from 100 to 1500 msec foreperiods), this represents a purer version of the reflexive alerting mode. This is because there is much more uncertainty on the timing between a signal and a target, so participants cannot rely on volitional preparation, resulting in performance differences coming from a participants reflexive reaction to the salient warning stimulus. Based on Lawrence and Klein’s findings (2013), we would expect to observe performance contrasts between this study by Dietze and Poth (2023) and the other experiments that involved components of volitional preparation.

2.4.3.3 Signal Modality

Although past research has indicated distinctions in the time-course of alerting via auditory and visual warning signals (Bertelson, & Tisseyre, 1969; see introduction of Dietze & Poth, 2023 for a review), we did not observe any influence of signal modality across any of our models. One of the experiments included in the analysis, Dietze and Poth, 2023, did make an explicit comparison of visual and auditory alerting signals across a variety of foreperiods, and concluded that in general, both stimulus types are relatively equal in generating an alerting response.

2.4.3.4 Other Considerations

There are other possible distinctions in methodology that could impact performance across experiments. While we did control for the difference in overall ER by transforming values to log-odd, which did impact interpretations, this was not controlled for within RT analysis. It is worth considering that the overall speed could impact the size of these effects across the different foreperiod conditions. However, for our current meta-analysis, involving RT transformations would have added additional complexity and affected the overall power available. Instead, this is something that may be explored empirically in future experimental paradigms. Additionally, we saw some clustering of performance effects based on the lab in which a study was conducted. While this clustering could be related to deviations in methods — such as how experimenters emphasize speed or accuracy within the task — it is possible this is also due to sampling differences. A focus for future alerting research should be to expand beyond WEIRD[8] samples to obtain a more representative picture of how alerting impacts information processing in the average human (Henrich, Heine, & Norenzayan, 2010). However, any slight clustering of effects

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[8] Western, Educated, Industrialized, Rich, and Democratic

based on which author was involved was never overly concerning, as the magnitude of influence over the effect was within reason.

2.4.4 Limitations

While the homogeneity of methodological procedures was an asset for this meta-analysis in generating meaningful estimates of effects, as it ensured our comparisons of mean values were more directly comparable, such homogeneity could also be considered a limitation for generalizability. Based on the outcome of this analysis, we now better understand how alerting operates under these very stringent conditions, and we can update past theories on how alerting impacts information processing. However, we are limited in understanding how the alerting process is impacted by many other mediating mechanisms which are often involved when we elicit alerting to interact within dynamic and noisy tasks in our daily lives. Research indicates that there are a number of reflexive and volitional mechanisms that distinctly impact performance outcomes depending on task demands, and that often operate in tandem (Nobre & van Ede, 2023). Future meta-analyses should consider analyzing the effect of alerting on information processing across distinct methodologies.

2.5 Conclusion

Based on the outcome of the current meta-analysis, it appears that alerting increases the efficiency of information processing to some degree, contrary to Posner's theory (1975) that it solely impacts the response criterion. Large RT effects were generated by alerting signals, but there was limited evidence of a meaningful impact on ER, especially in the longer 200 and 400msec foreperiod conditions. The behavioural effects occurring at the 50 msec foreperiod are likely more influenced by exogenous alerting mechanisms than the later 200 and 400 msec foreperiods, which rely more on endogenous alerting mechanisms. To our knowledge, this is the first meta-analysis to be conducted on this topic in the 50 years since the publication of Posner et al. (1973), and our divergent result emphasizes the importance of revising theories as new evidence is generated. Future research should explore how endogenous and exogenous modes of alerting differently impact performance at different foreperiods, determine the degree to which there may be changes in response criteria, and ascertain how this is influenced.

CHAPTER 3: EVALUATING THE EFFECT OF THE EXOGENOUS MODE OF TEMPORAL ATTENTION ON RESPONSE FIDELITY WITHIN A TEMPORAL CUEING TASK

Colin R. McCormick & Raymond M. Klein

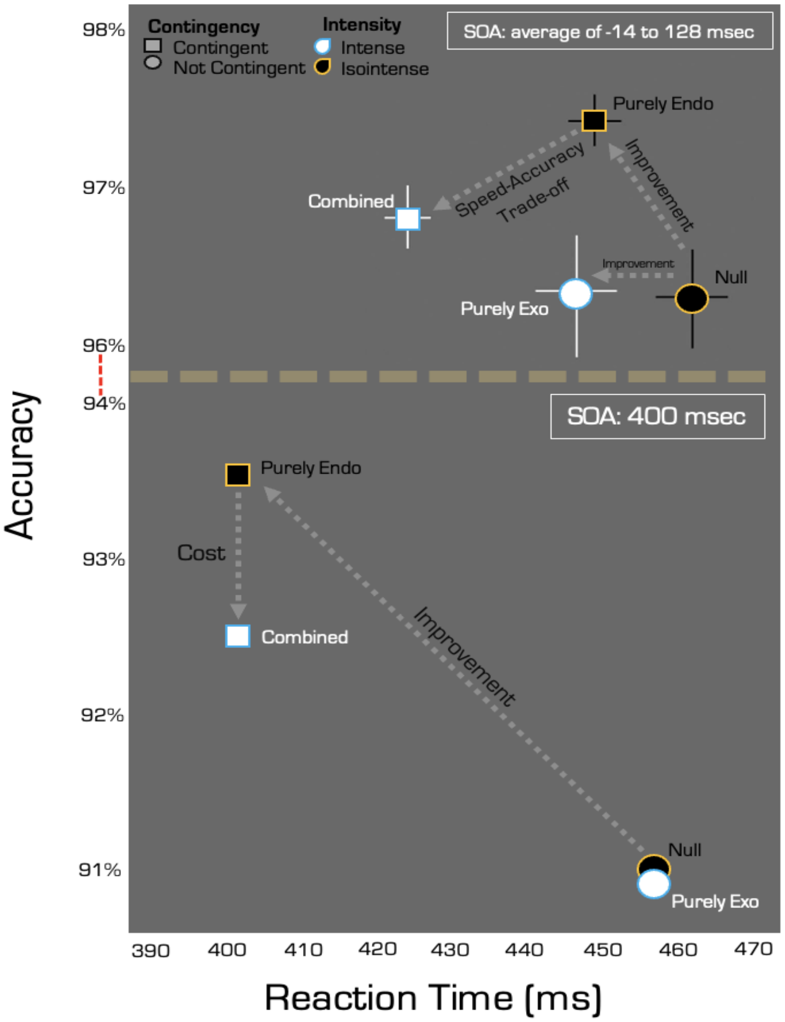
Co-Authors for this manuscript include Colin R. McCormick and Raymond M. Klein. Colin R. McCormick wrote each section of this paper, ran the participants, conducted the statistical analysis, and generated the figures. Raymond Klein provided feedback on the content of the writing and advised on methodology.

3.1 Introduction

One issue within the alerting and temporal cueing literature is the lack of experimental control for the influence of endogenous (volitional) and exogenous (reflexive) modes of temporal attention. These distinct modes of temporal attention are defined under Klein's revised taxonomy (2022). The exogenous mode involves a general increase in ones' receptiveness to stimuli, automatically elicited by a salient signal that does not predict target qualities. The endogenous mode involves the volitional preparation of ones' attentional resources to the time when an event of interest is likely to appear, without an associated salient change in the environment. Behavioral evidence indicates that these two mechanisms are independent from one another (McCormick, Redden, Lawrence, and Klein, 2018). The lack of experimental control of these modes is argued by Weinbach and Henik (2012), by highlighting how temporal preparation and alerting are used interchangeably depending on the background of the researcher. Those interested in studying 'alerting', described within Posner & Petersen's three-component taxonomy of attention as a phasic change in receptiveness to stimuli (2012), often do not consider that having a reoccurring foreperiod allows participants to volitionally prepare on top of the arousing effect of the stimulus. Meanwhile, those within the field of temporal cueing, who use informative cues to indicate when a target is likely to appear, often use salient stimuli to communicate relevant target-timing information. These cues elicit a reflexive alerting response on top of motivating volitional preparation through the cues informativeness. While the intensity of these stimuli may be consistent across conditions, targets are not always presented at the same interval in comparison to the cue (both within and between studies), which means the salient stimulus will have differing levels of influence on performance. This is problematic, as we know the combination of exogenous and endogenous modes within a task produces a unique pattern of speed/accuracy performance in comparison to when only the endogenous mode is elicited (Lawrence and Klein, 2013).

Lawrence and Klein developed a novel methodology to differentially measure these modes of temporal attention (2013). Participants were asked to discriminate the identity of a target stimulus by pressing one of two possible buttons. There were four main conditions dictated by two properties of the auditory signal: its intensity and contingency in relation to the target. The intensity of the signal was used as a manipulation of exogenous temporal attention, while signal-target contingency (were the signals predictive of target presentation or uncorrelated) was used as a manipulation of the endogenous ‘expectancy’ component of temporal attention. The intensity manipulation relied on mono white noise being played throughout a trial, and then briefly shifting to stereo uncorrelated white noise for 100 msec. During this stereo shift, the volume could either increase or remain the same. When the white noise volume increased during this shift, it represented the ‘intense’ signal condition, and it was meant to exogenously arouse the participant. When an ‘isointense’ signal was used, the volume remained unchanged, and the signal was detectable through the noticeable change in the correlation of noise between each ear. The intensity and contingency manipulations allowed for the isolation of endogenous and exogenous temporal mechanisms within Lawrence and Klein’s experiment, and identified unique response behaviours across STOAs (Signal-Target-Onset-Asynchrony; time between signal and target onsets) for each combination of the manipulations (Figure 3.1).

Figure 3.1: Comparing the different modes of temporal attention at the short STOA presented in Lawrence and Klein to the 400 msec STOA data. The ‘purely exo’ (exogenous temporal attention) and ‘purely endo’ (endogenous temporal attention) are compared to the ‘null’ condition, since it allows for the contrast of intensity and contingency conditions. The ‘combined’ condition (both endogenous and exogenous temporal attention) was compared to the ‘purely endo’ condition because the manipulations were the same except for the intensity added within the ‘combined’ condition. Performance contrasts are labeled within the figure. Decreases in response time without a cost to accuracy are considered ‘improvements’ in performance (movement left without movement downward), while decreases in response time with cost to accuracy (movement left and down) are considered a trade-off. In the case of the 400 msec STOA, the addition of the exogenous mode generated what could be considered a pure cost (decreases in accuracy without any improvement in speed). When comparing performance between the short STOAs and the 400 msec condition, overall participants were faster at 400 msec (further left), but at a cost to accuracy performance.



When provided with isointense signals that allowed participants to predict the time of target presentation (a constant interval between signal and target), both speed and accuracy performance was improved in comparison to a control condition for which there are no arousing/predictable trial stimuli. When adding intense signals to this contingent manipulation to generate the ‘combined mode’ condition, which elicits both endogenous and exogenous modes, Lawrence and Klein (2013) observed that for short intervals (shorter than 128 msec), participants responded faster, but accuracy decreased. However, at the 400 msec foreperiod —the foreperiod used most often in temporal cueing studies— reaction time performance was equivalent between the combined and purely endogenous conditions, but accuracy decreased in the combined mode condition.[9] This indicates that there are distinctions in speed and accuracy performance between the different combinations of these modes, and the dynamics of these distinctions shift across different time-points (Figure 3.1).

The relationship between speed and accuracy can be used to understand how the modes of temporal attention differently impact the processing of information. Improvement to speed that is associated with a decrease in accuracy, commonly referred to as a speed-accuracy trade-off, indicates a shift in response criterion is taking place. This is said to reflect a person responding in a shorter amount of time, at a point in which less information has accumulated, resulting in more errors. This is the pattern of performance that informed Posner’s theory of alerting (1975), when alerting (a combination of endogenous and exogenous modes of temporal attention) is said to shift an individual’s response criterion without impacting the rate at which information accumulates (Posner, Klein, Summers, & Buggie, 1973). A speed-accuracy trade-off

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[9] In prior studies, a reaction time difference between signal intensity has been observed in the temporal cueing task at an interval of 400 msec (McCormick et al., 2018; McCormick, Redden, Klein, 2023), so we anticipate our results will more closely represent the pattern of results at the shorter intervals of this study.

was observed in Lawrence and Klein's (2013) 'combined modes' condition (intense signals presented at a fixed interval before target), the condition that most closely resembles Posner et al.'s task. In contrast to this result, when RT decreases without a cost to accuracy, as was the case in the purely endogenous (isointense signal at fixed interval from target) and purely exogenous (intense signal with no contingency to the target) conditions in Lawrence and Klein (2013), this is evidence of an enhancement in the efficiency of processing information. If the accuracy of the response is maintained between comparison conditions, but the speed has improved, that means that the amount of information informing the response is equal, but has accumulated in a shorter duration of time.

McCormick, Redden, Lawrence, and Klein (2018) applied Lawrence and Klein's (2013) signal intensity paradigm within a temporal cueing paradigm, in which temporal probabilities shifted on a trial-by-trial basis using temporal cues. This is akin to Kingstone's temporal analog of the Posner spatial cueing paradigm (1992; but also, see Coull & Nobre, 1998). Within McCormick et al.'s (2018) temporal cueing paradigm, white noise played throughout, which allowed for signals to be intense (a stereo shift in noise that increased in volume) or isointense (a stereo shift in noise that maintained volume). Participants were first shown a letter cue, either an S or an L. An 'S', which stood for 'Short', indicated that there was an 80% chance that the interval between the upcoming signal and target will be 400 msec (and 20% chance it will appear after 1600 msec). An 'L' stood for 'long' and communicated the inverse of the S cue. Manipulating validity allowed for the comparison of when attention was appropriately allocated in time (for valid temporal cues) and when it was not correctly allocated in time (invalid temporal cues). Participants fixated on this cue, and after some random interval between 2 and 10 msec, the signal was presented to indicate that the STOA had begun. The signal informed participants to start their mental timer to whatever interval was communicated by the letter, and sometime later the target was presented.

It is important to highlight how this temporal cueing task distinctly manipulates temporal attention in relation to Lawrence and Klein's (2013) manipulation, in which the duration between a signal and a target is fixed across a block of trials. When the interval between the signal and target is fixed across longer durations, it elicits the additional influence of other temporal mechanisms on performance, such as hazard sensitivity and sequence effects (Nobre & van Ede, 2018). Hazard sensitivity is an independent mechanism of temporal attention that generates a probabilistic expectation about when stimuli are likely to appear, resulting in effects that improve performance on attention tasks. This can occur without conscious awareness (Janssen & Shadlen, 2005; Ghose & Maunsell, 2002). Sequence effects involve an influence on performance based on matching features of prior trial: participants respond faster if the current trials STOA matches the prior trials STOA (Correa et al., 2004). In McCormick et al's (2018) design, participants must focus their temporal attention to the likely interval on each trial to benefit from the cue information. McCormick et al.'s paradigm generated smaller cueing effects compared to Lawrence and Klein (2013)[10], but this is likely because it is less influenced by non-endogenous temporal mechanisms such as hazard sensitivity and sequence effects, and therefore, better represents a measure of how volitional preparation impacts performance.

McCormick et al. (2018) were interested in further understanding how the two modes of temporal attention distinctly impact performance in this modified cueing paradigm, extending the results of Lawrence and Klein (2013). McCormick et al.'s experiment involved measuring

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[10] However, our paradigm quite possibly adds a "dual task" component of difficulty in detecting an isointense signal from within noise, which may be another important component to consider in designing methodology; see Experiment Two below.

detection responses, which involved a single-button speeded-response when target stimuli were presented. In McCormick et al.'s task, participants were faster when presented with an intense signal compared to an isointense signal, indicating benefits from the exogenous mode. Participants were also faster when provided with a valid temporal cue, in which the participant was informed of the correct STOA, in comparison to an invalid temporal cue, indicating performance benefits of the endogenous mode. Most notably, McCormick et al. (2018) found additivity between the exogenous and endogenous modes of preparation through Sternberg's additive factors method (1969), by assessing the additivity of both reaction times and reaction time variance. This implied that these two mechanisms operate at different stages of processing and are independent mechanisms.

A follow-up to McCormick et al.'s cueing experiment was carried out using a 2-alternative forced choice decision making response instead of a detection response (McCormick, Redden, & Klein, 2023). Within this task, which maintained an identical cueing and signaling procedure as McCormick et al. (2018), participants were still faster in the intense condition in comparison to the isointense condition, and there was a comparable magnitude of the speeded temporal cueing effect (validly cued trials in comparison to invalidly cued trials). This indicates the same reduction in reaction time for both the exogenous (via comparing intense and isointense signals) and endogenous (via comparing valid and invalid temporal cues) modes as McCormick et al. (2018), respectively. However, there were no differences in error rates across any of these conditions, and most notably a near-identical error rate performance in the intense and isointense conditions. Based on the results of Lawrence and Klein (2013) and Posner's theory of alerting (1975), McCormick, Redden, and Klein (2023) should have observed a speed-accuracy trade-off (SAT) in the intense-signal manipulation: activation of the exogenous temporal mode via an intense signal within this temporal cueing task should shift the response criterion so participants are responding faster with less available information in comparison to when an isointense signal played, and as a result, increase the intense signal conditions error rate. Instead, McCormick, Redden, and Klein (2023) observed that the exogenous mode is generating speed improvements without a cost to accuracy, implying an improvement to information processing efficiency. This outcome is incompatible with Posner's theory of alerting (1975), and other related research (Posner, Klein, Summers, and Buggie, 1973; McCormick, Redden, Hurst, & Klein, 2019; Klein, 2023).

There have been other experiments investigating the time-course of temporal attention that also indicate that Posner's theory of a criterion shift (1975) may not universally apply across all methodological conditions. Los and Schut (2008) presented warning signals at various STOAs and had participants discriminate whether a stimulus appeared on the left or right of a display. Their results replicated Posner et al.'s (1973) reaction time effects across STOAs, but Lost and Schut did not observe the accompanying error rate increases that would be anticipated (although see Klein, 2023 for a reanalysis of Los and Schut's data, in which the faster half of conditions, based on mean RTs, had a higher mean ER than the slower half of conditions). Several other experiments either directly or conceptually replicated Posner et al.'s methods (1973) in the following decade, with the concensus of behavioural evidence showing that while an SAT may occur at foreperiods of 50 msec, it is less evident from 200 msec onward (Han and Proctor, 2022; 2023). This aligns with research from the temporal cueing literature that have used 2-alternative forced choice (2-AFC) paradigms (Griffin, Miniussi, & Nobre, 2001; Correa, Lupiãnéz, Milliken, and Tudela, 2004) that mostly have use STOAs around 400msec. These temporal cueing experiments show response speed improvements without any cost to accuracy when attention is allocated at the correct point in time, in contrast to when attention is not focused on the correct interval. In addition, a recent meta-analysis of the alerting literature[11](McCormick & Christie, Chapter 2) showed alerting ER effects are much smaller than anticipated at 200 and 400 msec STOAs, possibly even absent, even in the presence of large RT effects. It was proposed within the meta-analysis that the improvement of information processing observed at the longer STOAs is likely due to the activation of the endogenous mode of temporal attention, while the criterion shift at the shortest STOA is due to the additional influence of the exogenous mode, since this mode peaks in activation around this time-point (Denison et al., 2021). However, we still observe benefits from signal intensity, the task manipulation that elicits the exogenous mode, at 400msec when it is manipulated separately from preparation (McCormick et al., 2023). Based on this, it is a possibility that the exogenous mode is differently impacting behavioural effects based on its time-course of activation.

In review, McCormick et al.'s temporal cueing study with intense and isointense signals (2023) represents a failure to replicate the pattern of behavioural effects expected for each of the modes of temporal attention that would have been predicted by Lawrence and Klein (2013), when replicating their novel signaling method. Lawrence and Klein's results were in line with Posner's theory of alerting, since manipulating intensity made participants faster but less accurate. Considering the number of studies that have conflicting evidence in the context of Posner's theory of alerting (1975), it is worth exploring alternative methodologies and analytic techniques that may be better suited for addressing whether criterion shifts or enhancements to information processing efficiency are generating behavioural effects in temporal attention. Most of the experiments exploring how temporal attention impacts mental processes that have been

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[11] Experiments included in the meta-analysis used a 'no warning signal' condition, as well as warning signals at intervals of 50, 200, and/or 400msec before a target.

cited so far used 2-AFC designs that measure both response speed and accuracy (Posner et al., 1973; Lawrence and Klein, 2013; McCormick et al., 2019; Han and Proctor, 2022; 2023; McCormick et al., 2023; Griffin, Miniussi, & Nobre, 2001; Correa, Lupiãnéz, Milliken, and Tudela, 2004; also, Coull & Nobre, 1998; McCormick et al., 2018 for speed-only tasks). According to Posner et al., (1973) one can determine whether a criterion shift or an increase in information processing speed occurs by observing whether accuracy decreases as responses become faster. However, this approach overlooks the possibility that both a criterion shift and improvements in processing speed could occur simultaneously when alerted. It is ambiguous at what point the entire speed improvement can be attributed to a trade-off with accuracy: if there is a 60 msec speed effect when comparing a warning signal present and absent condition, and only a .9% accuracy difference, how can we be sure that there were not improvements to the speed at which the information accumulated along with this criterion shift? While measuring the speed of binary response options to targets is a popular method within many domains of cognition, it is not the only method that can be used to observe differences in information processing. Other research in the temporal attention domain that has focused on measures of accuracy tend to suggest that temporal attention impacts performance through the enhancement of perceptual processes, either through increasing information processing speed or improving the onset of encoding (Correa, Lupiáñez, and Tudela, 2005; Davranche et al., 2011; Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019; see also Klein and Kerr, 1974).

In temporal attention studies that have focused mainly on accuracy measures, targets are only briefly presented on the display for participants. This is distinct from the 2-AFC experimental designs described above. When target stimuli remain on screen in 2-AFC speeded-response paradigms, task-relevant information continues to accumulate up until a response is made. This means that slower responses are typically more accurate, and faster responses are less accurate, under Posner's (1975) assumption that information accumulation is consistent when a participant experiences a warning signal. Alternatively, when a target stimulus is presented briefly, there is a fixed period in which target information can accumulate to inform a response. This is a controlled interval of target processing time that allows us to test whether there are differences in the speed at which target information accumulates between conditions. Under Posner's theory of alerting, accuracy on a task where the target is presented briefly should be equal when comparing trials where the exogenous mode of alerting is elicited vs when it is not, since the rate of information accumulation should be equal and only the response criterion should be affected[12]. Temporal cueing research using briefly presented targets in a letter discrimination task identified that when the targets appeared at an expected interval, participants were more accurate than when the target was presented at a low-expectation interval (Vangkilde, Coull, and Bundesen, 2012). Vangkilde and colleagues additionally performed an analysis on this data that separated visual perceptual threshold and speed of encoding and found that the speed at which the target information accumulated was the likely influence on these improved accuracy scores. Increased processing speed was also theorized as the mechanism that improved temporal order judgements in another temporal cueing study, in which participants had to identify which briefly presented stimulus appeared first (Bausenhart, Rolke, & Ulrich, 2008), as well as when participants were cued to the likely target presentation interval within a rapid serial visual presentation task (in which target stimuli were embedded in an array of briefly presented stimuli

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[12] Klein and Kerr (1974), who found improved accuracy when manipulating warning signal presentation (warning signals at various foreperiods vs no warning signal) with briefly presented targets, were testing Posner's (1975) theory that an exclusive criterion shift is compatible improvements in accuracy since a warning signal would generate earlier consultation of the accumulated target information, and there would be less information decay on the briefly presented target stimulus. Based on the other temporal studies presented in this section, this interpretation of this outcome is less plausible than the increasing of information processing efficiency, but plausible nonetheless, and is considered later in this chapter in the context of task results.

that appear one by one; Davranche, Nazarian, Vidal, & Coull, 2011). Denison and colleagues, in studying the influences of cued temporal attention on performance, used a briefly presented circular patch with straight line-gratings as a target stimulus within a temporal cueing task (Denison, Heeger, and Carrasco, 2017; Denison, Yuval-Greenberg, and Carrasco, 2019). This is referred to as a continuous response metric, and participants responded with the orientation of the target patch gratings, with 360 degrees of possible response options. By using a continuous response metric, there is more insight as to how the different task conditions impact the quality of information obtained regarding the target's form, as there are degrees of accuracy instead of a binary correct-incorrect rating. Within Denison and colleagues' studies, they found that participants had their highest accuracy ratings on validly cued trials (correct timing information provided; temporal attention appropriately allocated) followed by a neutral no-cue condition, and finally the invalidly cued condition. This indicated that temporal attention improved information processing efficiency, and there were performance trade-offs associated with focusing on an incorrect time-point. It is worth noting that within this task, the possible intervals in which targets could be presented were close in temporal proximity (within 300 msec of one another).

The prior section highlights that experiments focused on the measure of accuracy performance while studying temporal attention support the concept of information processing efficiency being improved when temporal attention is focused at the correct interval. However, these studies are focused on studying the endogenous mode of temporal attention while not controlling for the influence of the exogenous mode (as identified by Weinbach and Henik, 2012; Lawrence and Klein, 2013). The experiments within this chapter contribute to the field of temporal attention by implementing a continuous response variable into a paradigm that isolates the endogenous and exogenous modes of temporal attention. This will allow us to observe whether the endogenous and exogenous modes differently impact the rate at which information accumulates about a briefly present target stimulus through comparing differences in response accuracy.

3.2 Experiment One

Experiment One follows up on prior attempts to compare the distinct modes of temporal attention within a temporal cueing task (McCormick et al., 2023) using the Lawrence and Klein (2013) signaling method. The main methodological modification involves implementing a continuous response metric that asks participants to report a briefly presented target's colour. The target being presented for a fixed period allows us to compare the quality of information available when participants have their endogenous and exogenous modes of temporal attention activated by temporal cues and intense signals, respectively. If responses are more accurate, this indicates that there was increased efficiency in information processing, since the participant had more target-information in the same duration of time.

Within the current task, the methods largely follow the procedure described in McCormick et al., (2023): participants were provided with a temporal cue at the beginning of a trial, which indicates the likely (75% accuracy) STOA. This allows us to compare how the endogenous mode of temporal attention impacts performance, contrasting validly cued trial performance (cue matched STOA) to invalidly cued trials (cue did not match STOA). We refer to this as a cue validity effect. Then, either an intense or isointense signal played (as described in Section 3.1 re: Lawrence and Klein, 2013), indicating that participants should start their internal timer to the cued interval. The isointense signal does not increase in intensity and allows for a measurement of the purely endogenous mode generated by temporal cues, while the intense signal allows us to observe how the exogenous mode of temporal attention modifies performance through reflexive arousal. The target is then presented very briefly, with its colour is pulled from a continuous distribution of possible colours (see Figure 3.3 for an example). This continuous variable allows for a richer measure of accuracy outside of binary correct-incorrect judgements and has been executed in recent temporal cueing experiments (Denison, Heeger, and Carrasco, 2017; Denison, Yuval-Greenberg, and Carrasco, 2019).

Colour as a continuous response measure has been successfully implemented in attention paradigms in other domains (Redden, d'Entremont, and Klein, 2017; Hurst, Lawrence, and Klein, 2019; see also Zhang and Luck, 2008 for the method's original implementation in a memory task). Participants were asked to select the colour on a colour response wheel that best represents the hue of the target. The colour wheel, a continuous distribution of the possible target colours, allows for accuracy to be measured on a scale of 0 to 180 degrees (zero represents perfect colour recall; 180 represents picking the colour on the exact opposite side as the correct colour). Using a continuous response task allows us to compare the fidelity of responses across conditions. Fidelity is a measure of the stimulus encoding accuracy by the participant. A higher fidelity response suggests more efficient information accumulation within a condition, since the participant was able to encode a more accurate representation of the target in the fixed target-presentation duration (Hurst, Lawrence, and Klein, 2019). In addition, half the participants in this task were asked to provide a speeded detection response when they first observed the target before providing their colour judgement, generating a conceptual replication of past temporal cueing research that measured response speed (McCormick et al., 2018) to see if temporal cues are being utilized by participants to guide temporal attention.

3.2.1 Predictions

The current study explores how the endogenous and exogenous modes differently influence accuracy performance using fidelity measures in a temporal cueing task. Based on the past research on temporal cueing effects, specifically those which have implemented a continuous response measure (Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019), fidelity should be higher when participants are validly cued on target presentation time, in comparison to when they are invalidly cued. This temporal cueing effect is representative of the endogenous mode of temporal attention. For our novel implementation of intensity in a continuous accuracy measure task, it is less clear what will happen to fidelity. It is possible that fidelity will be equal between intensity conditions if the exogenous mode purely impacts response criteria and does not impact information accumulation, as is predicted by Posner's theory of alerting (1975). However, prior detection experiments with brief target presentation in the field of alerting do suggest that the shifting of response criterion (without increases to information processing efficiency) generated by warning signals could generate higher fidelity (Klein and Kerr, 1974): if a participant consults their accumulated target information faster due to a shift in response criterion, elicited by the intense signals activation of the exogenous mode of temporal attention, response information will experience less decay, resulting in an accuracy advantage for alerting under Posner's theory (1975). We believe for this to be less likely in this context, given that accuracy is the emphasized aspect of performance to participants, and speed-accuracy trade-offs potentially only appear in alerting tasks that emphasize response speed (Han and Proctor, 2022). However, in the case that the intensity manipulation impacts response fidelity, the response speed of colour discrimination between signal intensity conditions will be compared as a conceptual check of the applicability of this theory. If we believe that the fidelity improvement associated with signal intensity is generated by an earlier consultation of response accumulation via a criterion shift, the associated reporting of the target colour would also have to be faster, otherwise the encoded target colour would decay more between its consultation and when the response is provided.

Additionally, planned contrasts will involve the comparison of temporal cue validity effects (valid in comparison to invalid cues) for each of the intensity conditions to check for any distinctions in effect size. Based on past research, validity effects should be equal between intensity conditions, given that these two modes have been identified as independent from one another (McCormick et al., 2018). However, occasionally there are differences observed between signal conditions if the temporal cueing task is not intuitive to follow or contains more cognitively demanding design features. Task-demand sometimes interferes with the isointense signaling condition more, given that additional effort is required to detect an isointense signal from white noise in comparison to an intense signal (McCormick et al., 2018; 2023).

For the speeded detection responses, it is anticipated that participants will detect targets faster on trials when they are validly cued to the correct STOA in comparison to when they are invalidly cued. Additionally, participants should be faster on trials where an intense signal is presented in comparison to trials for which an isointense signal is presented. This is based on past temporal cueing research using this signal intensity manipulation (McCormick et al., 2018; McCormick, Redden, & Klein, 2023). Cue validity and intensity should not interact based on the previously mentioned independence of these mechanisms (McCormick et al., 2018), and planned contrasts of these two factors will be conducted to observe whether there is evidence of interactions.

Often in the temporal cueing literature, only the short STOA is analyzable for the effects of temporal attention. This is because there are two possible STOAs. If participants are cued to the ‘short STOA’, and this interval passes, participants know for sure that the target will appear at the longer STOA and there is sufficient time for them to reallocate their attention. This is an example of the hazard rate mechanism that allows participants to respond to the most probable interval of stimulus presentation (Nobre & van Ede, 2018). We are investigating whether the addition of catch trials and an ‘uncued STOA’ in this task will reduce hazard sensitivity enough to make the 1600 msec STOA analyzable. This makes it so there is less certainty on when, or whether, a target will appear after the short STOA passes on trial where the short STOA is cued. If our manipulation is successful, we would observe a relatively equal magnitude of temporal cueing effects at both the short and long STOAs. This is not a novel manipulation and has been found to be effective in past versions of temporal cueing experiments (Correa et al., 2004).

3.3 Method

3.3.1 Preregistration

The current study's desired sample size, measured variables, hypotheses, and planned analyses were preregistered on Open Science Framework (https://osf.io/8ytuv/) prior to any data being viewed. Any changes to methods or analyses are reported.

3.3.2 Sample Size & Data Collection

Recruitment was mainly conducted through Dalhousie's student participant recruitment tool. Other recruitment was conducted through word-of-mouth within the University community. Participants had to be able to provide motor responses and have normal, or corrected to normal, vision and hearing. Additionally, they could not be colour blind. Participants were reimbursed for their time with credit points for their classes, or cash payment equivalent to $6 per half-hour.

3.3.3 Apparatus

Participants were run in testing rooms with MacBook air 11" computers. Headphones (Sony MDR- 101LP) were used to present auditory stimuli. Between 1 and 6 participants were tested at a time. The acceptable volume setting was level five on the Mac interface for volume. This was the default volume when the computers were presented to participants, and participants were instructed to inform the experimenter if it was too loud or quiet. If the experimenter was informed that the volume was not appropriate, they adjusted accordingly and made note of the change. Participants sat at a maximum distance of 102 cm from the screen (the length of the headphone cord). Participants used the space bar to provide their speeded detection responses, while target selection for colour involved moving the on-screen cursor around the colour wheel using the laptop trackpad (see Figure 3.2).

3.3.4 Stimuli & Procedure

Participants were instructed that the temporal cues would help optimize performance, as the cues indicated the interval between the warning signal and the target presentation with high probability. Mono white noise was presented to both ears continuously during the task. Trials began with a line present at the center of the screen. As the temporal information cue, the line could either be short (i.e.: ----) or long (i.e.: ----------). Short line cues informed participants of the correct STOA on 75% of trials with targets, with the other 25% of trials presenting the target at the alternate possible cued STOA, or a never-cued STOA of 1000 msec (Example: for the short line cue, 75% of trials had the target appear 400 msec after the warning signal, 12.5% at 1600 msec, and 12.5% at 1000 msec). The temporal cue remained presented at the center of the screen until the target was presented. The auditory warning signal was presented after a random interval within the range of 2 to 6 seconds (mean = 4 sec) to indicate the target was imminent.

The auditory warning signal involved either an intense or isointense change from mono to stereo noise. An intense change meant that the volume of the stereo signal increased, while an isointense change meant that the volume remained the same. The shift to stereo noise occurred for a duration of 100 ms, then switched back to mono noise. This signal indicated that the participant should start their internal timer for the cued interval, so they were ready when the target appeared. The target was a coloured square that appeared at the center of the screen for a very brief interval of time (see Figure 3.3; explained in section 3.3.4). The participants were informed that if they did not use the temporal cue to prepare for the target, there was a chance they would not be able to report what the target colour was. The colour of the target was sampled from a continuous colour distribution based on perceptual uniformity (CIELUV). A mask was presented immediately after the target, made up of a 4 x 4 square of randomly selected colours. Targets appeared on 75% of the trials, with the other 25% being 'catch trials', in which the participant received a cue and signal, but the fixation point appeared instead of a target, indicating the trial was over. This was to help combat the hazard sensitivity by making it so participants did not expect a target on each trial: if a short STOA was cued to participants, and the target was not presented at the 400msec STOA, there was not a 100% guarantee that it would appear at the other later STOA (as was the case in McCormick, Redden, and Klein, 2023, along with many other temporal cueing tasks). Catch trials may allow for cuing effects to be generated at the usually unanalyzed longer STOA. After the presentation of the target, participants moved their cursor over the colour wheel to select the colour they believed best represented the colour of the target square. The participants were instructed that if they did not see the target, they should still provide a response by randomly selecting on the colour wheel. The experiment had

480 trials total, 360 trials once the catch trials were removed. Participants had a rest break every 40 trials.

3.3.5 Dual vs Single Task and Target Presentation Duration

The first half of the participants run in this experiment were asked to provide a speeded-detection response to indicate when they saw the target, on top of providing their colour discrimination. This is referred to as the 'dual-task' group, although it should be noted that both tasks were related to the same stimulus, so we do not believe this task involved the same level of interference as a typical dual-task manipulation. Speeded responses were made using the space bar on the keyboard. As described, the measurement of speeded responses was implemented to measure the typical reaction time effect that occurs under temporal preparation and ensure that we were replicating prior results. The second half of participants in this task only experienced the colour discrimination component and did not provide a speeded detection response. This is the 'single-task' group. This was to observe whether the addition of detection responses interfered with the size of the colour judgement fidelity effect through introducing additional task demands. Detection responses more heavily rely on motor preparation, which is distinct from the perceptual discrimination required in colour-judgement (Correa et al., 2004). We merged the data for all these participants in the colour discrimination fidelity analysis to increase our overall power in detecting fidelity effects related to signal intensity and temporal cue validity, but included 'task demand' (single or dual task) as a predictive factor in our model to measure whether requiring a detection response influenced the participant's accuracy.

The target presentation duration was brief to encourage the use of the temporal cues within this task. If a participant is not motivated to follow task instructions, completion of the typical temporal cueing task, in which a target remains on display until a response is made, is possible and does not require the additional effort of following the cue information. When presenting the targets briefly, we can inform participants that they are unlikely to be able to accurately report the target without using the temporal cue information. All dual-task participants had target presentation durations of 34 msec. It was recognized when inspecting the mean performance of this data that a number of participants were either randomly guessing when providing colour judgement responses, or relatively close to random guessing performance. To ensure that participants were being challenged appropriately, we added a brief titration procedure to participants experiencing the single task (the second half of participants) to determine an 'optimal' duration of target presentation for each participant completing the colour discrimination task. This titration procedure ensured participants were being challenged, but not so much that they were guessing what the target colour was on average. Participants experienced 15 trials at different target duration intervals, and the target duration scaled up or down until they did not meet the performance standard (Figure 3.3).

Figure 3.2. Procedure for the 400-trial experiment. Half the participants additionally provided a speeded detection response at detection of target onset on top of the colour discrimination task.

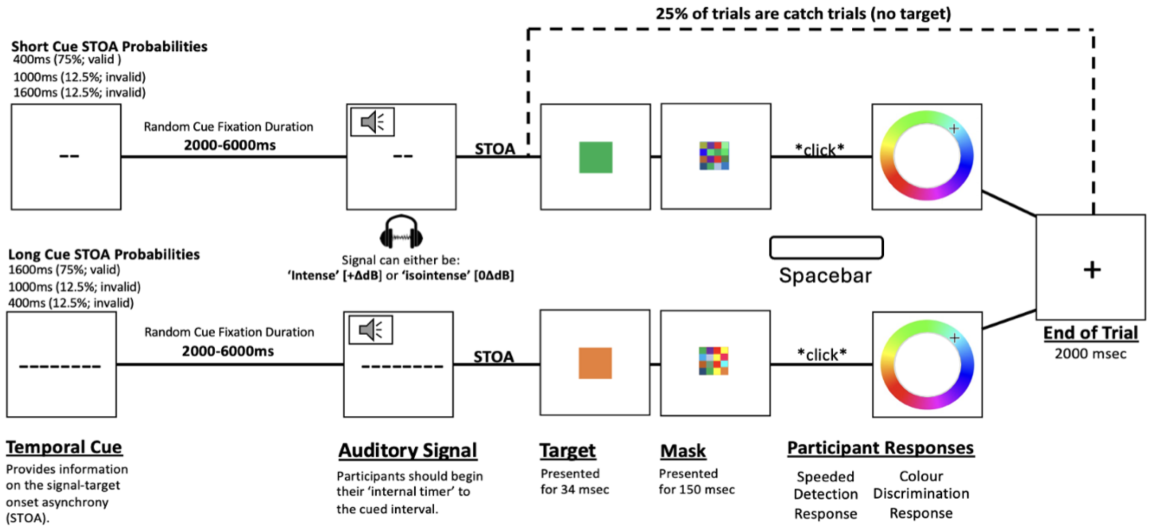
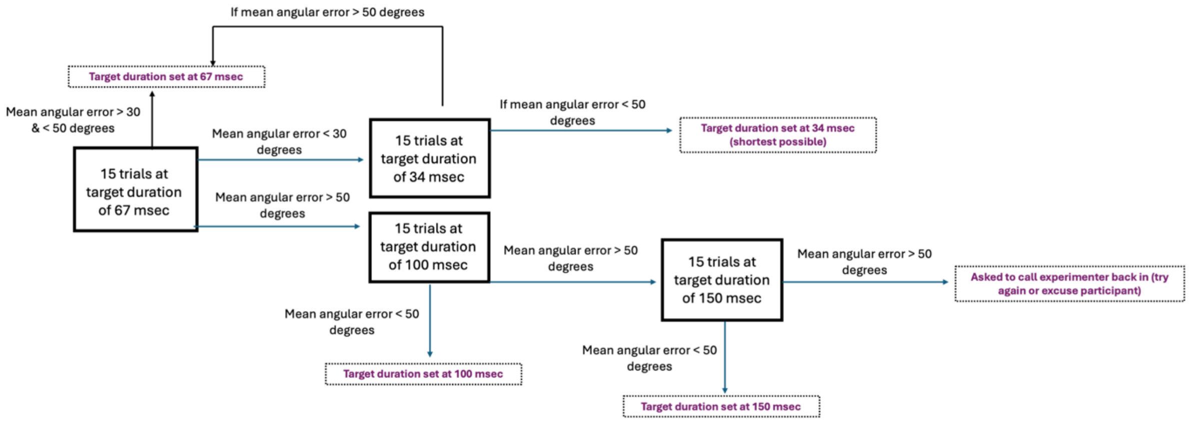


Figure 3.3. The titration procedure to try to adjust target duration to the ability of each participant. Participants started with a target duration of 67 msec. If participants had accuracy rates within the range we dubbed as adequately challenging (between 30 and 50 degrees of angular error), they stayed at this target duration for the experiment. If they performed better than this, the target duration was reduced to see if they could perform the task at 34 msec. If they failed this, they were set at the prior target duration they succeeded at. If they performed worse than 50 degrees angular error at 67 msec, the target duration slowed down until they met the minimum standard of performance.

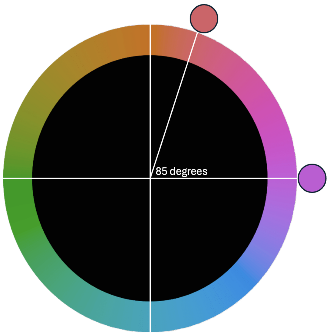


3.4 Results

3.4.1 Participants

In total, 95 participants were run in this experiment. Forty-nine participants were run with the speeded detection component of the task (dual-task) while 46 only provided colour discrimination responses (single-task). Four participants from the dual-task group were removed because their average degree of angular error was greater than 85 degrees in the colour discrimination task (see Figure 3.4). This left 45 participants for the analysis of reaction time (average age of 21.9 [min = 17, max = 39]; gender: 17 men, 26 women, 2 non-binary; handedness: 39 right-handed, 5 left-handed, 1 ambidextrous).

Figure 3.4. An example of what 85 degrees of angular error looks like on the colour wheel. Participants who had an average performance worse than this were removed from analysis.



When checking the average angular error response of the 46 participants who only provided colour discrimination responses (the 'single task' group), none of these participants exceeded the average maximum degree of angular error (85) to be excluded from the analysis.

When accounting for participants from both the single and dual task groups, 75 participants were set at a target duration of 34 msec, 15 had a target duration of 67 msec, one had a target duration of 100 msec, and one had a target duration of 150 msec. Because there were only two participants who fell into the slower bins of 100 and 150, they were excluded from analysis as outliers, and just the 34 and 67 msec duration participants were included. Eighty-nine participants total (mean age of 21.3 (min = 17, max = 41; gender = 31 men, 55 women, 3 non-binary; 76 right-handed, 11 left-handed & 2 ambidextrous) were included in the analysis on fidelity data.

While we predicted that catch trials and a never-cued STOA would increase the temporal cueing effects at the 1600msec STOA, which are typically absent, by reducing certainty on when/whether the target would be presented after the (invalidity) cued interval of 400msec passes, participants may still have increased sensitivity to stimuli at this later time-point, influenced by other mechanisms informed by temporal structures (sequence effects or hazard sensitivity) or strategy (Nobre & van Ede, 2018). Because cue validity effects at the 1600msec STOA have a higher probability of being influenced by unwanted mechanisms, since participants are already aware that the 400msec interval has passed, we perform two sets of analyses: one on the 400msec STOA, and one on the 1600msec STOA. This will allow us to clearly address our main questions of interest, while also comparing effect sizes between these STOAs to observe whether we have removed the influence of unwanted re-attending effects via catch trials and uncued intervals.

3.4.2 Detection Reaction Time Analysis

Linear mixed-effect models were used to analyze the response times from the 45 participants who were asked to press the spacebar as soon as they detected the target. The analysis used the lme4 package in R (Bates et al., 2015; R Core Team, 2021). Reaction times were log-transformed to normalize the distribution. We used the participant identification number to generate a random intercept to control for overall differences in participant performance. Comparisons between an unrestricted model, which included the effect of interest and all lower order effects, and a restricted model, which included the lower order effects, generated evidence in support of “the effect” or “the null.” This was evaluated using likelihood ratios, with Akaike’s information criterion (AIC) corrections to account for the discrepancy of complexity between models (Akaike, 1974). The constructed comparisons looked like this:

$$(AIC(Restricted\ Model) - AIC(Unrestricted\ Model)) * log2(exp(1)).$$

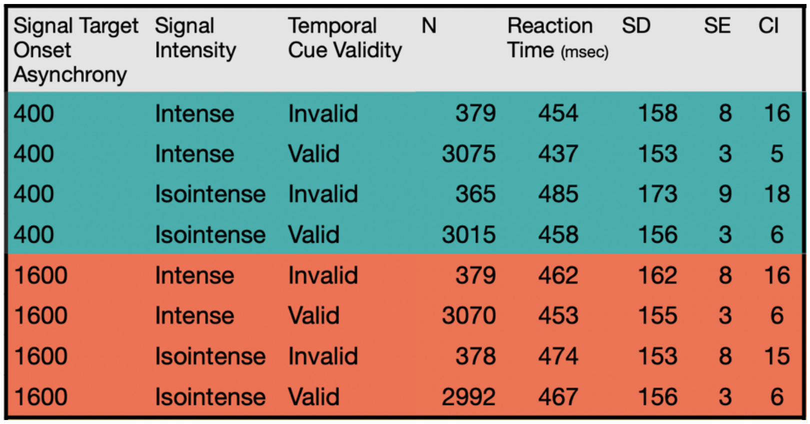
Ratios are presented in log-base-2, so that positive values can be interpreted as evidence for the effect, and negative values as evidence for the null. The absolute values are meant to be interpreted as a continuous metric of evidence for an effect, with 8 being considered pretty strong evidence, and 32 strong evidence (Royall, 1997)

There was evidence for an effect of cue validity on reaction time at the shorter (400msec) STOA. Participants were faster when presented with valid temporal information (447msec) in comparison to invalid temporal information (469msec; effect size: 21 msec, 95% Confidence Interval (CI) [9, 33]; see Figure 3.5). This indicates the presence of temporal cueing effects. There was very strong evidence of an effect of signal intensity, in which intense signals (439 msec) generated faster participant responses in comparison to isointense signals (461msec; effect size: 25 msec, 95% CI [16, 34]; see Figure 3.5). There was no evidence of an interaction between validity and intensity (see Tables 3.1 & 3.2) at the 400msec STOA, however, the isointense condition was more variable and included larger possible effect sizes.

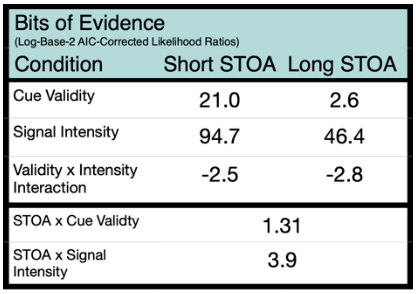
There was no evidence of an effect of cue validity on reaction time (valid cue = 460 msec; invalid cue = 468 msec; effect size: 9 msec; 95% CI [-2, 20] see Figure 3.5) at the longer (1600msec) STOA. There was, however, strong evidence of an effect of signal intensity, in which intense signals (454msec) generated faster participant responses in comparison to isointense signals (468msec; effect size: 16 msec, 95% CI [7, 25]; see Figure 3.5). There was no evidence of an interaction between validity and intensity (see Tables 3.1 & 3.2).

Interactions between STOA and both validity and signal intensity effects were tested, by contrasting a model with an interaction effect and a model with only main effects. While there is not enough evidence to indicate an interaction between STOA and validity effects (bits of evidence=1.31; Figure 3.6), there was some evidence of an interaction between STOA and intensity (bits of evidence= 3.39), with larger intensity effects at the 400 msec STOA in contrast with the later STOAs (see Tables 3.1 & 3.2).

Tables 3.1 and 3.2. Mean RTs for detection responses across the different conditions (left) and the likelihood ratios from our linear mixed-effects models (right). The values are a continuous metric of evidence for an effect, with 8 being considered pretty strong evidence, and 32 strong evidence (Royall, 1997).



Signal Target Onset Asynchrony	Signal Intensity	Temporal Cue Validity	N	Reaction Time (msec)	SD	SE	CI
400	Intense	Invalid	379	454	158	8	16
400	Intense	Valid	3075	437	153	3	5
400	Isointense	Invalid	365	485	173	9	18
400	Isointense	Valid	3015	458	156	3	6
1600	Intense	Invalid	379	462	162	8	16
1600	Intense	Valid	3070	453	155	3	6
1600	Isointense	Invalid	378	474	153	8	15
1600	Isointense	Valid	2992	467	156	3	6



Bits of Evidence
(Log-Base-2 AIC-Corrected Likelihood Ratios)

Condition	Short STOA	Long STOA
Cue Validity	21.0	2.6
Signal Intensity	94.7	46.4
Validity x Intensity Interaction	-2.5	-2.8
STOA x Cue Validty	1.31	
STOA x Signal Intensity	3.9	

Figure 3.5. Temporal cue validity effects (left) and signal intensity effects (right) for RT between STOA conditions. Error bars are 95% CIs. Note the two figures have different y-axis scaling.

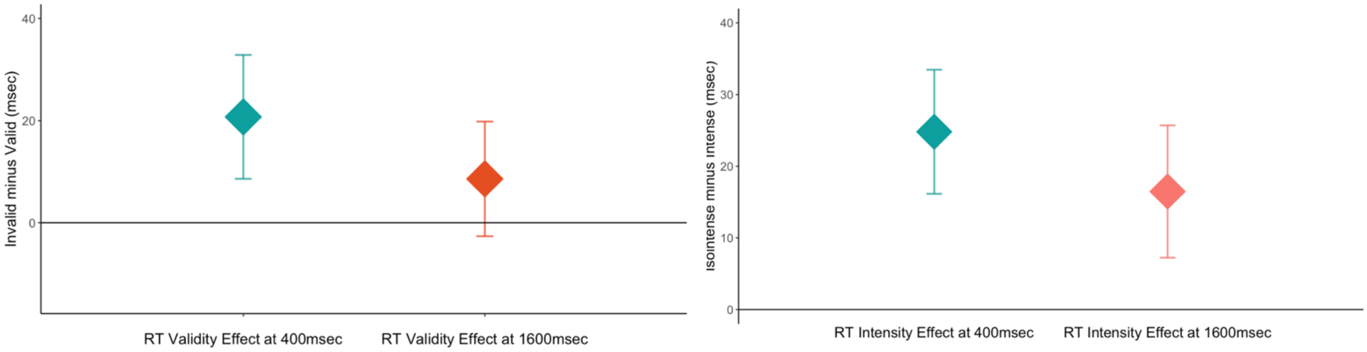
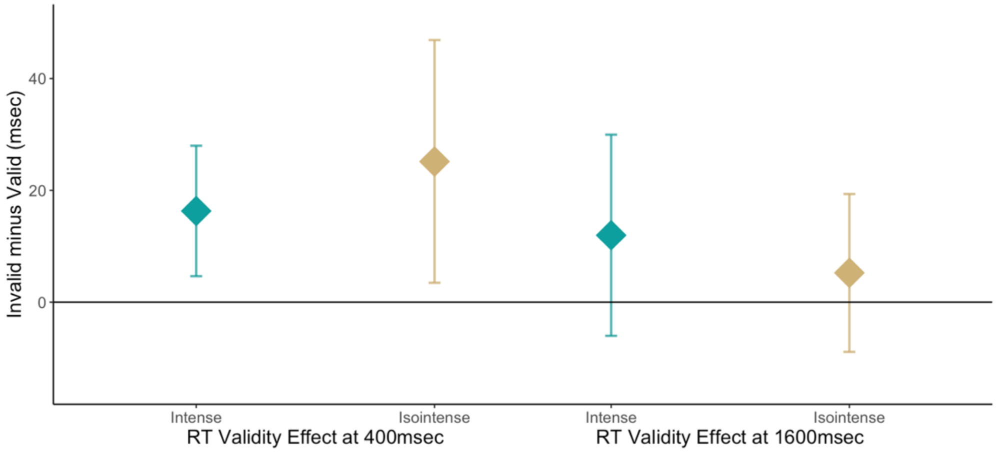


Figure 3.6. Validity effects on RT across the signal intensity and STOA conditions. Error bars are 95% CIs.



3.4.3 Summary of RT analyses

When running the linear mixed model to detect the presence of cue validity effects for each of the STOAs, there was an effect detected at the 400msec STOA, but not at the 1600msec STOA. While the temporal cue effect sizes at the 400msec STOA included larger possible values than the 1600msec STOA (Figure 3.5, left), we cannot confidently state that these two effect sizes are different. However, the smaller effect size and lack of evidence for an effect at the 1600msec condition aligns with prior experiments and is likely due to the reallocation of temporal attention mechanisms at the interval during invalidly cued trials. The addition of catch trials and a never-cued interval did not sufficiently prevent the reallocation of attentional mechanisms to an acceptable degree. At the very least, it was not a worthy trade-off for all the unanalytic trials that were added to the task (catch-trials and the 1000msec STOA).

Participants responded faster when presented with intense signals in comparison to isointense signals at both the 400 and 1600msec STOAs, but the likelihood ratios calculated indicate that the effect of signals was likely larger at 400msec. This is expected, as there would be more decay of the exogenous temporal mode 1600msec after the warning signal was played (Denison, Carasco, and Heeger, 2021). There was no interaction between the validity and intensity manipulations (Table 3.2). These outcomes generally replicate what we have found in our past experiments comparing conditions that manipulate endogenous (isointense signal) and exogenous (intense signal) modes of temporal attention (McCormick et al., 2018; McCormick et al., 2019; McCormick, Redden, & Klein, 2023), and indicate that participants were using the temporal cues to prepare for the earlier time-points.

3.4.4 Fidelity Analysis

A Bayesian generalized multivariate model was fit to both the ‘short’ (400 msec) and ‘long’ (1600 msec) STOA data using a von mises distribution via the brm function from the brms package in R (Bürkner, 2017). The model, with the notation of:

*log(kappa) ~ validity + signal intensity + validity*signal intensity + taskdemand + taskdemand*validity + (1+validity|participant)*

included validity (validly cued or invalidly cued), signal intensity (intense or isointense), and whether participants were in the single or dual task version (taskdemand) as population level effects. There was also an interaction effect included for validity and signal intensity, as well as validity and task demand. The former checks whether validity effects change across the two signaling conditions, while the latter checks whether participants ability to follow cue instructions changed based on whether they were required to provide a speeded detection response. The validity effect and the intercept varied based on each participant's performance. Priors were set for the intercept, the population effects, and the standard deviation[13]. Kappa was log-transformed for this analysis. Four model chains were run with 4000 iterations (1500 warm-

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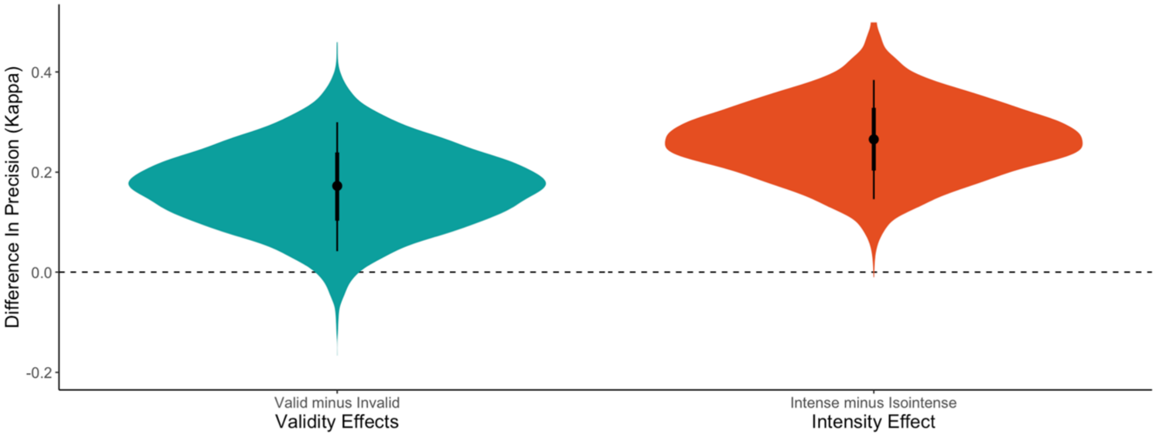
[13] Log-kappa scale: Intercept = normal (1, 1.5) intensity, validity, task demand = normal (0, 2); SD = exponential (1)

up). values are reported as a measure of model convergence (convergence of a model is represented by a value of 1.00; values less than 1.05 are considered ‘acceptable’).

The posterior distribution was generated for each parameter, and the certainty of validity, intensity, and task demand effects were interpreted using the highest density intervals (HDI) around the median difference values. The posterior distributions represent the probability of a parameter being within a given range of values, which allows us to present the varying credibility of an effect along with the effect size. We were interested in the difference between the fidelity distributions for valid and invalid temporal cues, between intense and isointense signals, and between single and dual task demands. If the 89% HDI for the difference of condition values does not contain zero, this was considered a highly credible effect. If the 60% HDI for the difference between conditions does not contain zero, this was considered a weakly credible effect. If the 60% HDI captures zero, there was reported to be no credible effect. For interactions, effect sizes were contrasted between the conditions of interest. For a more in-depth explanation of the logic behind this method of analysis, see Hurst, Lawrence, and Klein (2019), who analyzed fidelity for a continuous response task within the spatial domain.

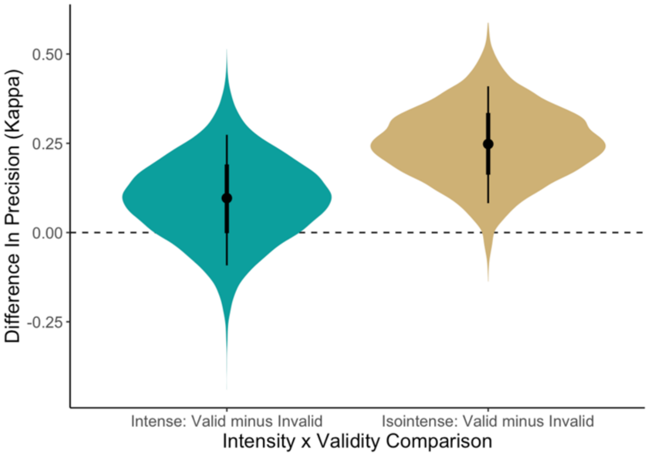
There was a small but highly credible effect of temporal cue validity (valid - invalid) on fidelity within the short STOA (400msec) condition, with a median difference score of .17 (*HDI89%* = [.04, .30], R-hat = 1.00; Figure 3.7). For signal intensity, there was also a small, but highly credible effect, with participants generating higher fidelity responses when presented with an intense signal in comparison to the isointense signal (median difference = .27, *HDI 89%* = [.15, .39], R-hat= 1.00; see Figure 3.7).

Figure 3.7. The effect of cue validity (left) and intensity (right) on fidelity within the short STOA analysis. The posterior distribution of effect is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI



When comparing temporal cue validity effects for each of the intensity conditions (Figure 3.8), the isointense condition has a larger range of positive effect values in comparison with the intense condition. However, when accounting for the overlap in HDIs, there is not much confidence in a real difference of effects (intense validity effect: median difference = .10, *HDI89%* = [-.9, .27], isointense validity effect: median difference = .25, *HDI89%* = [.08, .41]). The mean fidelity values for each condition can be found in Table 3.3.

Figure 3.8. A comparison of cue validity effects on fidelity between the intense (left) and isointense (right) conditions in the short STOA analysis. The posterior distribution of effects is mapped onto the violin plot, while the median and HDIs are plotted in the center of the figure. The thick black line is a 60% HDIs, and the line black line is an 89% HDI.



We additionally compared the presence of the detection task on performance. There was no overall difference in fidelity based on whether participants performed the detection task or not (median difference = -.07, *HDI89%* = [.-45, .30]; Figure 3.9 left) and no interaction with the temporal cue validity effect (single-task: median difference = .17, *HDI89%* = [-.02, .35]; dual-task: median difference = .18, *HDI89%* = [.00, .35]; Figure 3.9 right). Contrasting the time to report the colour of the target indicated no differences between intense and isointense trials (RT difference: 15 msec, 95% CI [-3, 32]).

Figure 3.9. A comparison of task demand between single-task and dual-task participants in the short STOA analysis (left) as well as how this influenced validity effects (right). The posterior distribution of effects is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI. Note the y-axis scaling is different between plots.

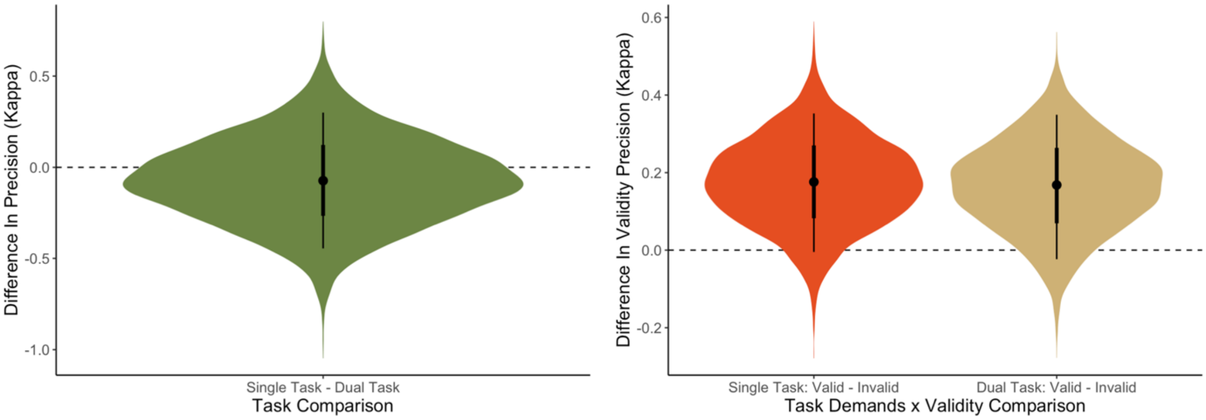
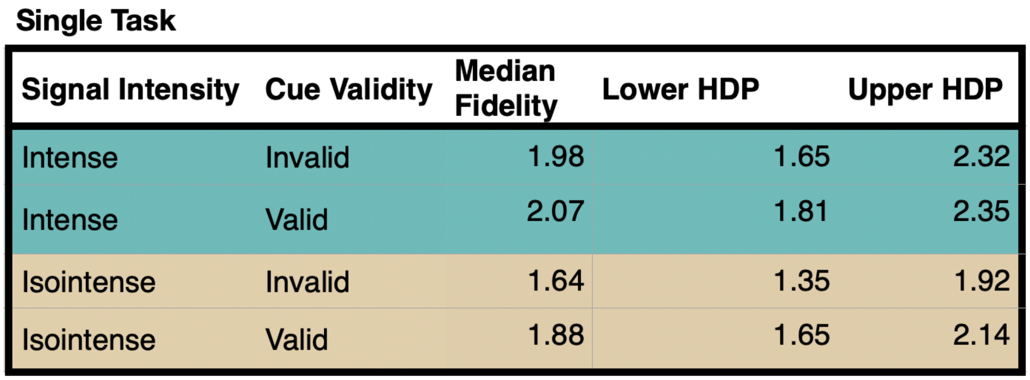
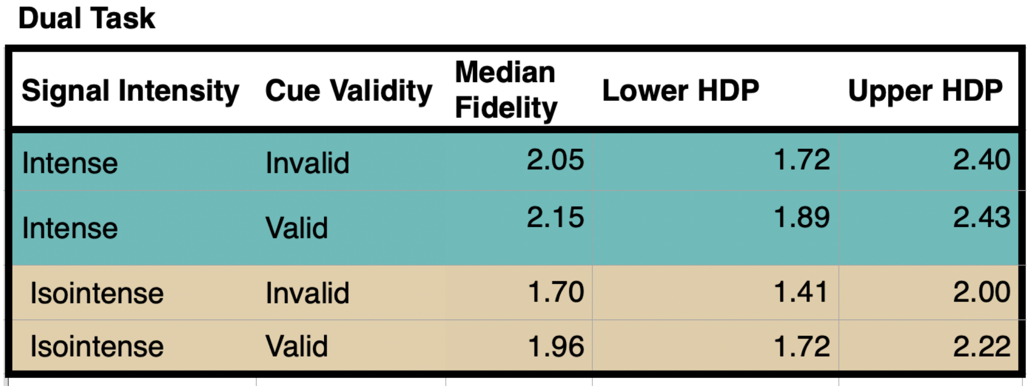


Table 3.3. Median fidelity and 89% highest posterior density (HPD) values for each condition in the short STOA analysis



Single Task

Signal Intensity	Cue Validity	Median Fidelity	Lower HDP	Upper HDP
Intense	Invalid	1.98	1.65	2.32
Intense	Valid	2.07	1.81	2.35
Isointense	Invalid	1.64	1.35	1.92
Isointense	Valid	1.88	1.65	2.14



Dual Task

Signal Intensity	Cue Validity	Median Fidelity	Lower HDP	Upper HDP
Intense	Invalid	2.05	1.72	2.40
Intense	Valid	2.15	1.89	2.43
Isointense	Invalid	1.70	1.41	2.00
Isointense	Valid	1.96	1.72	2.22

There was a small and credible effect of temporal cue validity (Valid - Invalid) at the longer (1600msec) STOA, in which validly cued trials had lower fidelity scores than invalidly cued trials, with a median difference score of -.17 (*HDI89%* = [-.30, -.04], R-hat = 1.00; Figure 3.10). This effect is in the opposite direction as the cue validity effect in the shorter (400msec) STOA analysis. For signal intensity, there was a small and credible effect with the intense signal generating a higher fidelity of responses in comparison to the isointense signal (median difference = .18, *HDI 89%* = [.05, .31], R-hat= 1.00; Figure 3.10). Contrasting the time to report the colour of the target indicated no differences between intense and isointense trials (RT difference: 20 msec, 95% CI [-1, 40]), although the majority of values were positive.

The temporal cue validity effects for the two intensity conditions were similar (Intense Validity effect: Median difference = -.09, *HDI89%* = [-.29, 0.09], Isointense Validity effect: Median difference = -.24, *HDI89%* = [-.43, -.06]; Figure 3.11). The mean fidelity values for each condition can be found in Table 3.4.

Figure 3.10. The effect of cue validity (left) and intensity (right) on fidelity within the long STOA analysis. The posterior distribution of effect is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI.

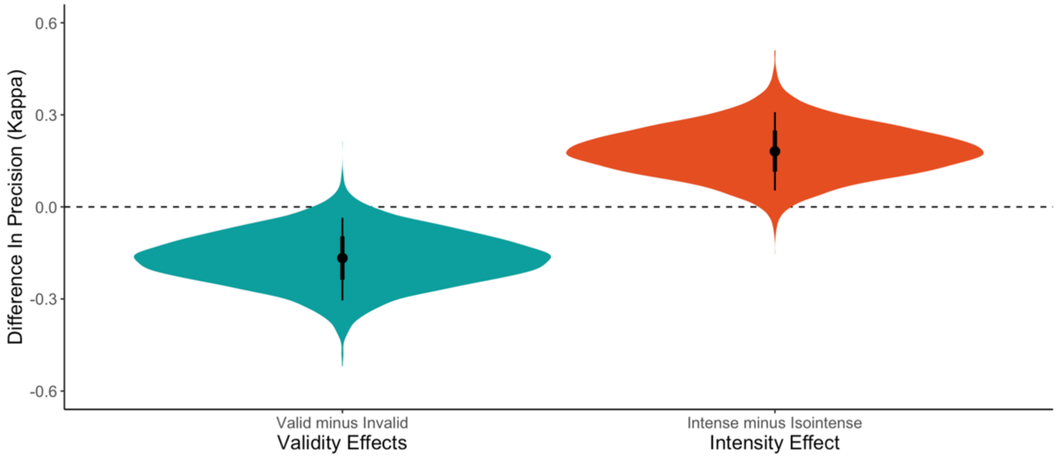
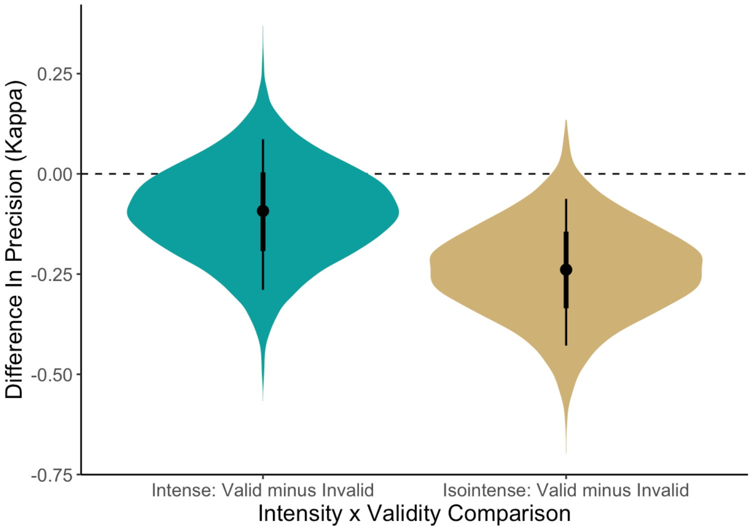


Figure 3.11. A comparison of cue validity effects on fidelity between the intense (left) and isointense (right) conditions for the long STOA analysis. The posterior distribution of effects is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI.



We additionally compared the presence of the detection task on performance. There was no overall difference in fidelity based on whether participants performed the detection task or not (median difference = .07, *HDI89%* = [-.30, .46], R-hat= 1.01 ; Figure 3.12 left) and no influence on the validity effect (single-task: median difference = -.06, *HDI89%* = [- .18, .06]; dual-task: median difference = -.16, *HDI89%* = [-.36, .03]; Figure 3.12 right).

Figure 3.12. A comparison of task demand between single-task and dual-task participants in the long STOA analysis (left) as well as how this influenced validity effects (right). The posterior distribution of effects is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the thin black line is an 89% HDI.

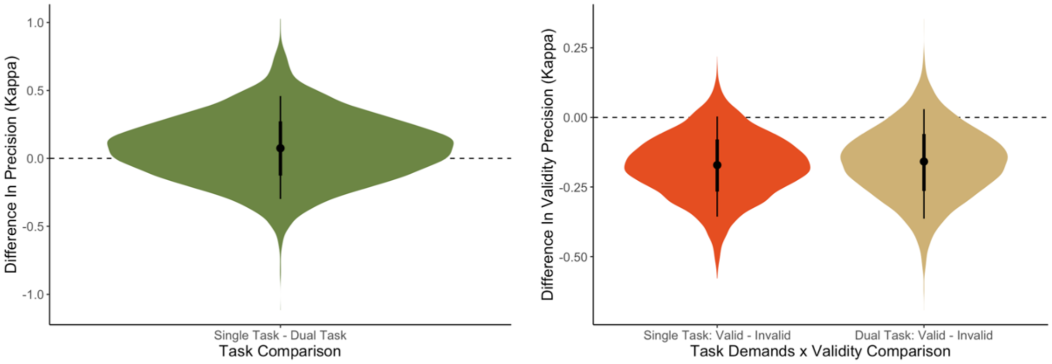
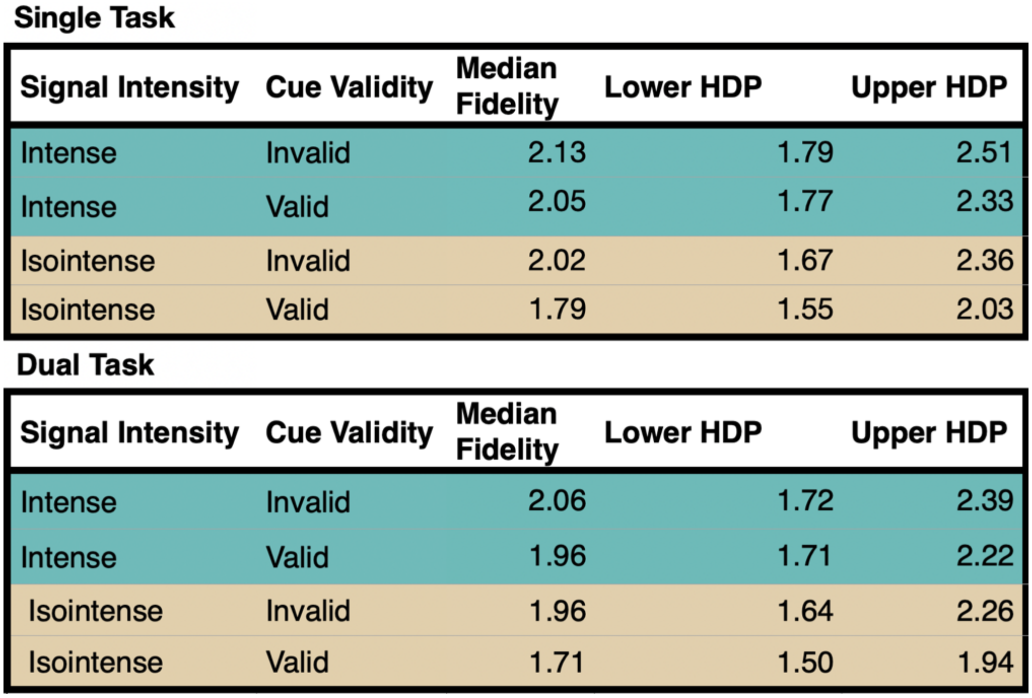


Table 3.4. Median fidelity and 89% highest posterior density (HPD) values for each condition in the long STOA analysis



Single Task

Signal Intensity	Cue Validity	Median Fidelity	Lower HDP	Upper HDP
Intense	Invalid	2.13	1.79	2.51
Intense	Valid	2.05	1.77	2.33
Isointense	Invalid	2.02	1.67	2.36
Isointense	Valid	1.79	1.55	2.03

Dual Task

Signal Intensity	Cue Validity	Median Fidelity	Lower HDP	Upper HDP
Intense	Invalid	2.06	1.72	2.39
Intense	Valid	1.96	1.71	2.22
Isointense	Invalid	1.96	1.64	2.26
Isointense	Valid	1.71	1.50	1.94

3.4.5 Summary & Interpretation of the Fidelity Analysis

We observed a difference in the quality of information available when participants were presented with an intense vs an isointense signal, as indicated by the effect of signal intensity on fidelity. According to past theories of alerting, the exogenous mode shortens reaction time by reducing the time in which participants generate a response, without impacting the speed at which information is processed, which presents as a speed-accuracy trade-off (Posner, Klein, Summers, and Buggie, 1973; Lawrence and Klein, 2013). In this case, we have observed that the exogenous mode of alerting improved the accuracy of participants' reporting of target colour, a novel outcome in the field. In the context of Klein and Kerr's (1974) interpreting similar results within the field of alerting (a manipulation confounding exogenous and endogenous modes), informed by Posner's theory of alerting (1975), one must consider that improved accuracy in the intense signal condition could be the result of participants consulting accumulated target information sooner than when in the isointense signal condition, because of a shift in response criteria via the exogenous mode, resulting in less decay of the target information. To this point, we observed evidence that there was no difference in colour discrimination RTs between signal intensity conditions, which casts some doubt on Klein and Kerr's (1974) proposal. However, this effect was trending towards the direction of participants responding faster in the intense condition in comparison to the isointense condition, as the 95% CI for the effect mostly contained values in the direction of this effect. Under these circumstances, we must entertain the possibility that a shift in response criterion could account for a difference in intense and isointense response fidelity. However, the effect of intensity on response fidelity is similar to the behavioural effect that has been observed for the endogenous mode using temporal cues, both in this dataset, via the analysis of temporal cue validity, and in past research (Vangkilde, Coull, and

Bundesen, 2012; Denison, Heeger, and Carrasco, 2017). This effect of the endogenous mode has been attributed to the enhancement of information processing efficiency, and we expect that it is possible that the exogenous mode also impacts this component of information processing. This novel outcome for the exogenous mode adds to the accumulating evidence that must be considered when appraising Posner's theory of alerting (1975).

For cue validity — our manipulation of the endogenous mode — we would have anticipated more of an effect on fidelity, as we observed small differences between validly vs invalidly cued trials. By making target presentation very brief to encourage participants to utilize the temporal cues within the task, we ended up with generally low overall fidelity scores, somewhere between one and three on average (in contrast, Hurst et al.'s 2019 spatial colour-wheel task had mean fidelity performance around a value of nine). The reduced overall fidelity of responses could possibly be impacting the size of the validity effect. However, the effect of temporal cueing on fidelity, in reality, may just be small. In a spatial-attention measure of fidelity, Hurst, Lawrence, and Klein (2019) observed weakly credible fidelity effects of .45. It would make sense if the fidelity effects generated by temporal cues were smaller than spatial cues, considering RT effects are often smaller in the spatial vs temporal domain (21 msec spatial cueing effect for Hurst, Lawrence, and Klein, 2019; 8 msec temporal cueing effect for McCormick, Redden, and Klein, 2023; also, see the literature on the attention network test (ANT), which measures spatial and temporal cues during its battery of conditions: Fan et al., 2002). The isointense signal condition trending toward having a larger temporal cueing effect in comparison to the intense condition was an unexpected outcome, given that in past manipulations the intense signal condition typically generates larger effects. This may be due to detection of the isointense signal requiring more mental effort (McCormick et al., 2018;

McCormick et al., 2023), resulting in more of an investment in their use by participants. However, because there was so much overlap in likely effect sizes, it is not worth putting too much consideration into this difference, as it could represent natural variation in equal sized effects. Importantly, we also learned the addition of a detection task did not interfere with participant's quality of fidelity responses and the ability to use the temporal cues, based on the contrast of single and dual task performance (Figure 3.12, left).

Considering that implementing catch trials and a never-cued STOA has been successful in past literature (Correa et al., 2004), it is a bit surprising that our attempts to observe cueing effects involving the 1600msec STOA were unsuccessful. As mentioned before, detection RTs comparing valid and invalid temporal cues for this STOA trended toward being smaller. In addition to this behavioural effect, there was, in fact, credible evidence of a reverse temporal cue validity effect at the 1600msec STOA in which participants were more accurate at invalid cues in comparison to valid cues (Figure 3.11), emphasizing that participants were re-allocating attention, and using the probability distributions to strategize preparation. Based on this outcome of invalidly cued trials at the 1600msec STOA generating higher fidelity scores than validly cued trials, it appears that participants were using the probability distribution strategy of preparation more than following temporal cues. Future experiments could explore other methods for enhancing temporal cueing paradigms so that the later STOA better represents a contrast of when temporal attention is properly allocated, in comparison to when it is not allocated to this time-point.

3.5 Experiment Two

Considering the novel effect of intense signals generating improvements to fidelity over isointense signals found in Experiment One, a second fidelity-focused experiment is warranted to replicate and expand upon this result. For this follow-up, three STOAs were included to compare how the time-course of the exogenous mode impacts fidelity. Novel design features were also implemented in an attempt to increase the credibility, and possibly effect size, of our cue validity effect. The key changes to Experiment Two were:

1) To improve upon the manipulation of the endogenous mode of temporal attention, participants self-initiated the pre-target foreperiod within the task. This means that instead of waiting for an intense/isointense signal to indicate they should start their 'internal timer' to the cued foreperiod, participants initiated this interval by pressing the spacebar.
2) To replicate and further explore our findings related to the exogenous mode of temporal attention, and to accommodate the volitional initiation of intervals described in point one, we modified when the signals occurred. On a third of trials, no auditory signal played, representing our purely endogenous condition. On another third of trials, the signal played when the interval was initiated by participants, matching the STOA in signaling condition from Experiment One. On the remaining third of trials, the auditory signal was played 50 msec before the onset of the target. This was close enough to the target that it did not allow for volitional preparation but allowed us to observe and contrast a key STOA, right around where the exogenous mode peaks (Denison et al., 2021), and where a shift in response criterion is most likely (Lawrence and Klein, 2013; Han and Proctor, 2022; Posner et al., 1973, also see Chapter 2).
3) In addition, there were some smaller modifications: target durations were intermixed between 67 msec and 84 msec to increase the overall fidelity of responses. Participants were also provided feedback on accuracy to allow for the self-monitoring of effort and

performance. Catch-trials and never-cued STOAs were dropped, since they did not prove to be as useful as anticipated. Relatedly, our analysis only used trials where the target was presented 400msec after trial initiation, to avoid trials where attention was reallocated.

3.5.1 Predictions

Experiment One had higher fidelity scores in the intense signal condition relative to the isointense condition, indicating that the exogenous mode improved information processing efficiency. The current experiment introduced two different STOA conditions within our analyzable trials to compare to the time-course of the exogenous mode to a no warning signal condition. This allowed us to observe whether fidelity scores change as a result of the time-course of exogenous alerting. Findings from various signaling studies (Han and Proctor, 2022; Posner et al., 1973; McCormick & Christie, Chapter 2; Lawrence and Klein, 2013) indicate that reaction time and error rate effects of a warning signal may be different at very short STOAs (such as 50msec) in comparison to longer ones (400msec), with the shorter STOA generating stronger shifts in response criterion. This is around the exogenous modes peak activation (Denison et al., 2021). Klein and Kerr (1974) also observed improved detectability scores closer to our later STOA (400msec), relative to the 50msec STOA. It will be informative to observe whether fidelity performance is enhanced at the 50msec STOA in a similar manner to what was observed at the 400msec STOA, given that the 50msec time-point is when the speed-accuracy trade-off described by Posner's (1975) theory is most prominent, and Posner's theory emphasizes that these speed-accuracy trade-offs are generated through criterion shifts and not information processing enhancement.

It is anticipated that we will observe temporal cue validity effects for fidelity, in which participants will have higher fidelity responses on validly cued trials in contrast with invalidly cued trials. In our prior Bayesian analysis for Experiment One, there were small and weakly credible temporal cue validity effects. We anticipate that validity effects should be larger and/or more credible because the current experiment involved a self-initiated foreperiod, in contrast with detecting a signal to initiate a mental timer, as well as longer target presentation durations than the prior experiment and increased emphasis on accuracy performance by providing feedback. These modifications make the task easier and emphasize the importance of providing accurate colour responses.

3.6 Method

3.6.1 Preregistration

The current study's desired sample size, measured variables, hypotheses, and planned analyses were preregistered on Open Science Framework (https://osf.io/8ytuv/) prior to any data being viewed. Any changes to methods or analyses are reported.

3.6.2 Sample Size & Data Collection

Recruitment was conducted through Dalhousie's student participant recruitment tool. Other recruitment was conducted through word-of-mouth within the University community. Participants had to be able to execute motor responses and have normal, or corrected-to-normal, vision and hearing. Additionally, they could not be colour blind. Participants were reimbursed for their time with credit points for their classes, or cash payment equivalent to $6 per half-hour.

3.6.3 Apparatus

Participants were run in testing rooms with MacBook air 11" computers. Headphones (Sony MDR- 101LP) were used to present auditory stimuli. One to two participants were tested at a time. The acceptable volume setting for the auditory signal was level five on the Mac volume interface. This volume was pre-set for participants, and they were instructed to inform the experimenter if it was too loud or quiet. If the experimenter was alerted that the volume was not appropriate, they adjusted accordingly and made note of the change. Participants sat at a maximum distance of 102 cm from the screen (i.e., the length of the headphone cord). Participants pressed the space bar to initiate the foreperiod during the trial, while target selection for colour involved moving the on-screen cursor around a multi-colored wheel using the laptop trackpad (see Figure 10).

3.6.4 Stimuli & Trial Procedure

Participants were instructed that the temporal cues would help optimize performance, and that they may miss the presentation of the target if they did not utilize them. Trials began with a word presented at the center of the screen. This word was the temporal cue. The word SHORT informed participants that the target would likely appear (75% chance) 400 msec after the space bar was pressed. If the target did not appear at this interval, it was presented at the alternate foreperiod of 1600 msec. The inverse of this was true for the LONG cue. In contrast to Experiment One, we decided to go with a word cue to be as clear as possible with participants on what length of time to expect. Because each pre-target foreperiod was volitionally initiated, participants could spend as long as needed reading and interpreting this cue. Additionally, we removed the never-cued foreperiod, in addition to the catch trials, as these were not as successful in eliminating hazard sensitivity at the late foreperiod durations. Removing catch trials meant more of the trials had performance data to analyze.

There were three different auditory signal conditions: no signal, tone at foreperiod initiation (STOA 400 msec/1600 msec), and a tone 50 msec before target presentation (STOA 50msec). Because the signal occurred when the trial was initiated, the STOA for ‘tone at foreperiod initiation’ could either be 400 msec or 1600 msec. However, because we are only analyzing trials where the target appeared at the short interval after trial initiation, for the reasons outlined in Experiment One, this will generally be referred to as the 400msec STOA. The signal was a 600Hz sine wave which played for 50 msec. This meant we could look at the exogenous modes influence on performance at two different intervals by contrasting the 50 and 400msec STOA conditions with the no signal condition. The 400 msec STOA signal condition represented a replication of our intense signal condition in Experiment One. The 50 msec STOA condition was novel to this experiment and allowed us to compare how performance was impacted by activation of the exogenous mode when the target was presented in close temporal proximity to the peak of the exogenous mode of temporal attention (Denison et al., 2021). This 50 msec STOA is within the range of when Lawerence and Klein (2013) and Han and Proctor (2022) found a SAT, so it potentially will contribute distinct results in relation to testing how the exogenous mode impacts information processing efficiency or response criterion shifts. It was also, importantly, too close to the target to be used to endogenously prepare for the target presentation, so it represents a purely exogenous manipulation.

The target was a coloured square that appeared at the center of the screen for a very brief interval of time (either 67 or 84 msec). The colour of the target was sampled from a continuous isoluminant, consistent saturation colour distribution. The target was replaced by a mask for 200 msec, which was a 7x7 square made up of a random assortment of colours. The colour response wheel[14] then appeared on the screen, and participants moved their cursor over the colour on the colour wheel they believed best represented the target square. Participants had 5000 msec to provide a response. The participants were instructed that if they missed the presentation of the

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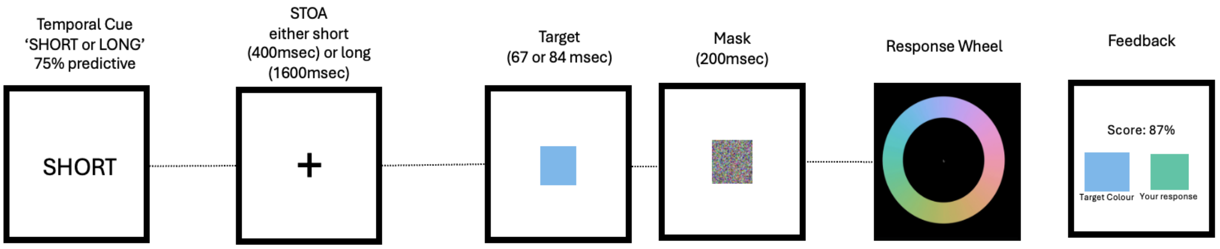
[14] This colour wheel (CIELUV with 75% luminance, 59% chroma [saturation] and a d65 illuminant) was slightly modified from E1 so that the colours on the wheel were more consistently represented, and no particular hue took up more of the distribution.

target, or were unclear of what the colour was, they should still provide a response by randomly selecting a colour on the colour wheel. After providing a response, the target's actual colour and the participant's reported target colour appeared beside one another on the screen for 1500 msec, along with an accuracy percentage score[15]. There was total emphasis on response accuracy in the task instructions, with participants encouraged to try to keep their accuracy feedback in the 90% range. The experiment had 488 trials total, split between ten blocks of 48 experimental trials, and one practice block of eight trials. Blocks took roughly five minutes to complete. See Figure 3.13 for a visual breakdown.

Figure 3.13. An example trial in the current task. The trial began with the temporal cue presented at the center of the screen. This represents the likely (75% predictive) interval between when the spacebar was pressed, and when the target was presented. Participants had to wait at least 1 sec after cue presentation before the task would let them initiate the timed portion of the task. The target was a randomly drawn colour from the response wheel, which was presented for either 67 or 84msec, before being replaced by a visual mask of random colours for 200 msec. Participants then used the trackpad on the laptop to select what colour best represented the target that was just presented. Once a selection was made, feedback was presented so participants could compare the target colour to their selected colour, as well as see how far away they were on the colour wheel (100%=perfect performance; 50% = opposite side of the wheel).



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[15] Angle of target is represented as 180, and angle of response is relative to this, with an equation of: angle of colour response/angle of target. Max score was 100%, minimum score was 50%.

3.7 Results & Interpretation

3.7.1 Participants

Fifty-two participants (average age of 19.1 [min = 18, max = 21]; gender: 13 men, 39 women, 0 non-binary; handedness: 50 right-handed, 2 left-handed) were run in this colour identification task. None of the participants had an average angular error greater than 85 degrees, so no participants were removed from analysis.

3.7.2 Bayesian Modeling Analysis

A Bayesian generalized multivariate model was fit to the data from the 400msec foreperiod condition using a von mises distribution via the brm function from the brms package in R (Bürkner, 2017). The model, with the notation of:

log(kappa) ~ validity + signal + validity:signal+ target duration + (1+validity|participant)

that included validity (validly cued or invalidly cued), signal (none, 50msec STOA, 400msec STOA), and target duration (67 and 84 msec) as population level effects. Interaction effects for validity and signal were included in the model. The validity effect and intercept varied based on each individual participant's performance. Priors were set for the intercept, the population effects, and the standard deviation[16]. Kappa was log-transformed for this analysis. Four model chains were run with 4000 iterations (1500 warm-up). R-hat values are reported as a measure of model convergence (total convergence of a model is represented by a value of 1.00).

The posterior distribution was generated for each parameter, and the certainty of validity and intensity effects were interpreted using the HDI around the median difference values. The posterior distributions represent the probability of a parameter being within a given range of

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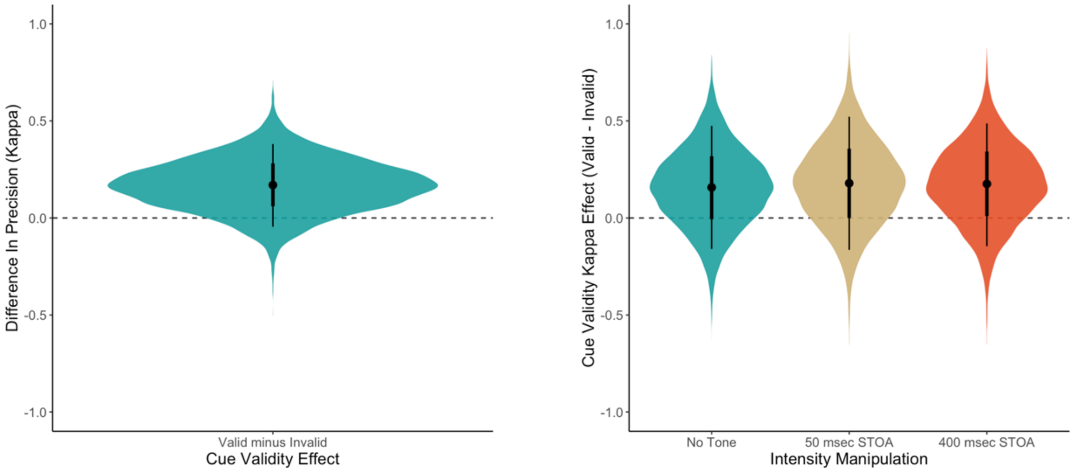
[16] Intercept = normal (1, 2) (log-kappa scale); intensity & validity = normal (0, 2) (log-kappa scale); SD = exponential (1)

values, which allows us to present the varying credibility of an effect along with the effect size. We are interested in the difference between the fidelity distributions for valid and invalid temporal cues, and between intense and isointense signals. If the 89% HDI for the difference of these values does not contain zero, this is considered a highly credible effect. If the 60% HDI does not contain zero, this is considered a weakly credible effect. If the 60% HDI captures zero, there is no credible effect. For a more in-depth explanation of the logic behind this method of analysis, see Hurst, Lawrence, and Klein (2019), who analyzed fidelity for a continuous response task within the spatial domain.

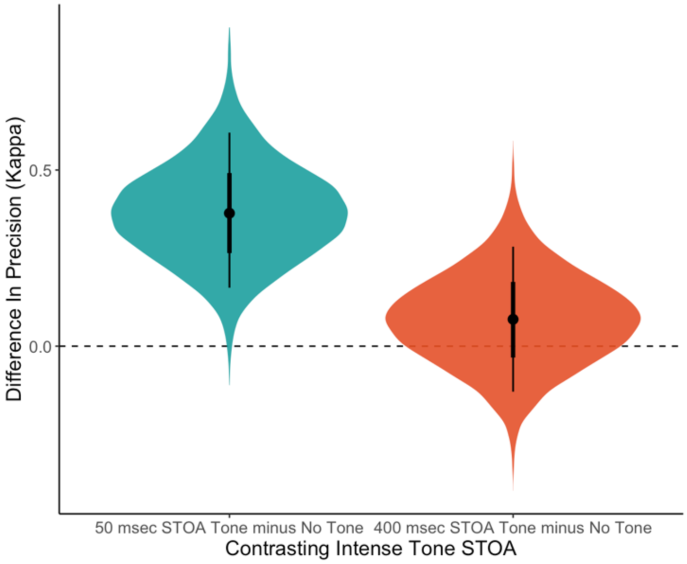
There was a small and weakly credible effect of Cue Validity (Valid - Invalid) on fidelity, with a median difference score of .17 (*HDI89%* = [-.05, .38], R-hat = 1.00; Figure 14, left). When comparing validity effects for each of the intensity conditions, they are nearly numerically identical (see Figure 3.14, right; Table 3.5).

Figure 3.14. Effect of temporal cue validity on fidelity performance (left) and temporal cueing effects across the three signal conditions. The posterior distribution of effect is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI.



For Signal Intensity, there are two contrasts: No Tone vs 400 msec STOA and No Tone vs 50 msec STOA. There was a small and uncredible effect of the tone at the 400 msec STOA on fidelity (Median difference = .08, *HDI89%* = [-.13, .28], R-hat= 1.00; see Figure 3.15) However, there was a highly credible effect of the 50msec STOA tone on fidelity performance (Median difference: .38; [.17, .61]. There was no difference in colour discrimination reporting time when comparing signaled and no signaled trials at the 50msec (-9msec, 95%CI [-30, 12]) or 400msec (-4msec, 95%CI [-21, 13]) STOA condition

Figure 3.15. Effect of a signal at two different time-points on fidelity performance. The posterior distribution of effect is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI.



Participants also had a higher fidelity of responses when the target was presented for 84msec vs when it was presented for 67msec with a median difference of 1.79 (*HDI89%* = [1.52, 2.11], R-hat = 1). There was also no difference in effect sizes for validity based on target duration (67msec: *HDI89%* = [-.03, .29], R-hat = 1; 84msec: *HDI89%* = [-.06, .47], R-hat = 1; Figure 3.16).

Figure 3.16. Effect of target duration on fidelity (left) and how target duration impacts temporal cueing validity effects (right). The posterior distribution of effect is mapped onto the violin plot, while the median and HDI are plotted in the center of the figure. The thick black line is a 60% HDI, and the line black line is an 89% HDI.

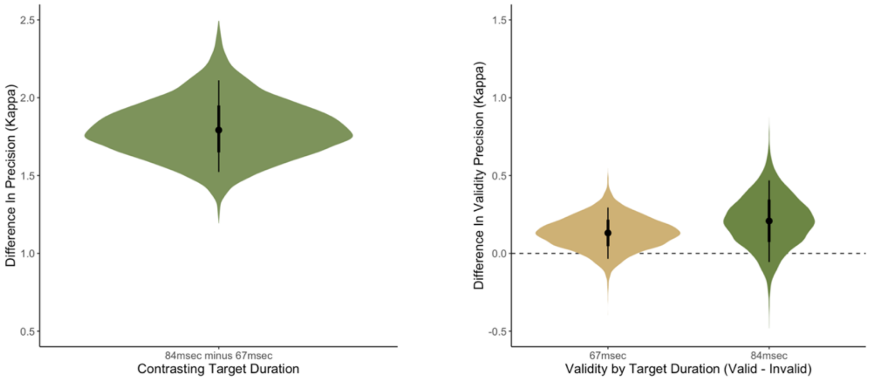
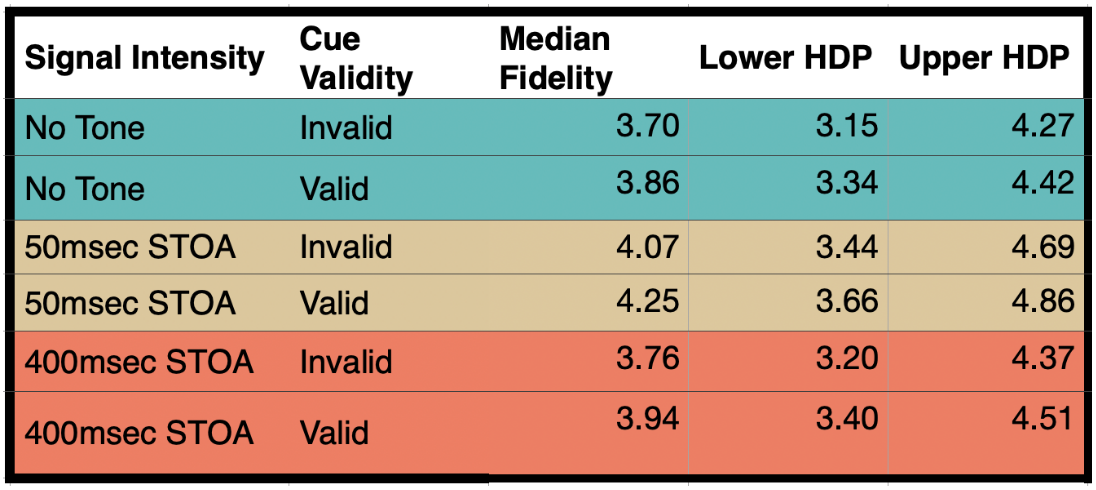


Table 3.5. Median fidelity and 89% highest posterior density (HPD) values for each condition within the short foreperiod (400msec) analysis.



Signal Intensity	Cue Validity	Median Fidelity	Lower HDP	Upper HDP
No Tone	Invalid	3.70	3.15	4.27
No Tone	Valid	3.86	3.34	4.42
50msec STOA	Invalid	4.07	3.44	4.69
50msec STOA	Valid	4.25	3.66	4.86
400msec STOA	Invalid	3.76	3.20	4.37
400msec STOA	Valid	3.94	3.40	4.51

3.7.2.1 Summary & Interpretation of the Fidelity Analysis

As expected, overall fidelity scores increased within this task in comparison to Experiment One (when contrasting Table 3.4 to 3.5), likely due to the described methodological features that made the task easier (self-initiation, longer target duration). Nevertheless, despite our predictions, the validity effect for this experiment still had a small effect-size like Experiment One. Relatedly, the target durations, which showed differences in fidelity size (longer target duration, higher fidelity), did not interact with the size of the validity effect (Figure 3.14). This seems to indicate that generally we can expect the effect of temporal cueing on fidelity, at least under the current methodological conditions, to be quite small regardless of overall fidelity score. It is also worth noting that the validity effects across the three signaling conditions are near-identical (Figure 3.11). This means that the endogenous mode generates consistent effects regardless of whether there is exogenous mode activation from the presentation of salient warning stimuli. The lack of an interaction between factors further supports the independence of endogenous and exogenous modes of temporal, meaning these are two functionally separate mechanisms (McCormick et al., 2018).

We have replicated the effect of warning signal intensity on fidelity observed in Experiment One. Participants generated higher fidelity scores when a warning signal was played 50msec before the target, in comparison to when no warning signal was played. There was an uncredible effect on fidelity when the warning signal was presented 400msec before the target, although the warning signal effect was in the same direction as Experiment One. Based on the warning signal fidelity effects at both STOAs, the exogenous mode of alerting appears to improve fidelity, with peak enhancement occurring at the peak of the exogenous mode activation (just before 100msec; Denison et al., 2021). The two warning signal STOA conditions did not differ in the speed at which participants provided colour-discrimination responses in comparison to the no warning signal condition, which has important implications when interpreting whether this effect is likely due to response criterion shits or information processing efficiency (as referenced in Experiment One's discussion section). No response speed difference for accuracy reporting further supports the proposal that these improvements are due to information processing efficiency enhancement due to the exogenous mode, and not related to difference in the point at which accumulated information is consulted, as is proposed in Posner's theory of alerting (1975). Performance in Experiment Two is distinct from Klein and Kerr's (1974) alerting target-detection experiment (involving brief target presentation), as Klein and Kerr observed peak performance around 400msec, and the lowest signal-related improvement at 50msec. However, in the context of Klein and Kerr using a binary discrimination response and confounding the exogenous and endogenous modes of preparation within their task (Weinbach and Henik, 2012), we would expect distinctions with experiments results. Considering that the six foreperiods used in Klein and Kerr's task were intermixed within a block, without any cues as to which interval was about to occur, and the no-warning-signal condition presented targets at a fixed interval of 370msec after the start of a trial, it is possible that hazard sensitivity had an effect on performance: expectation for a stimulus would be close to peaking at a time-point of 400msec, as this is the second last possible target presentation interval (meaning the anticipation for the target would be building) and when the no warning signal trials occurred (making it a more-likely interval for a stimulus to be presented). If a target had not happened up until this point in a trial, there were only two other possible moments in which it could occur.

The failure to replicate of the warning signal fidelity effect at a STOA of 400msec may have to do with the change in how the signal is presented in comparison to Experiment One. In Experiment One, the signal was presented unexpectedly at some random interval between 2 and 6 seconds. In the current task, the signal occurs a third of the time when the spacebar is pressed to initiate the interval. It is possible that the pairing of pressing the spacebar and hearing the noise makes this signal less salient, or reflexive, in comparison to when the warning signal is presented 50 msec before the target. Additionally, the signal in Experiment One was 100 msec in duration, while in Experiment Two it was 50 msec. The signal duration was reduced so that the signal did not overlap with the target presentation in the 50 msec STOA condition. This means that there may have been more decay of the exogenous mode at the 400msec STOA given that it was shorter (less intense) and the offset was a longer duration from the onset of the target stimulus. The signal was also less relevant to the task, as it no longer communicated the initiation of the STOA, which may have played into its saliency for participants.

3.8 General Discussion

We implemented a continuous response measure within a temporal cueing task that separates the influence of the endogenous and exogenous modes of temporal attention. These experiments are the first within the literature to measure accuracy as a continuous variable under conditions that deconfound endogenous and exogenous modes of temporal attention. Within our analysis, we observed that participants have enhanced fidelity when temporal attention was volitionally focused on a cued interval, in contrast when it was focused on a different interval, representing the effect of the endogenous mode on performance. We also observed the enhanced fidelity of participant responses when an intense warning signal was played before the presentation of a target, in contrast to no warning signal or an isointense signal, representing the effect of the exogenous mode on performance. The exogenous mode enhancement to response fidelity occurred without evidence of a difference in response speed between the warning signal and no warning signal conditions. These experiments support the proposal that both the endogenous and exogenous modes of alerting enhance the efficiency at which information is processed. While enhanced information processing generated by the endogenous mode of temporal attention has been suggested by prior researcher (Correa, Lupiáñez, and Tudela, 2005; Davranche et al., 2011; Vangkilde, Coull, and Bundesen, 2012; Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019), the novel outcome from these experiments is that the exogenous mode also generates fidelity improvements that rise and fall with its activation, indicating improvements to information processing efficiency. This outcome conflicts with Posner's theory (1975) that states warning signals improve speed through a shift in response criterion, trading off accuracy for additional speed without impacting the rate of information accumulation. This effect of the exogenous mode aligns with past temporal cueing research that controlled the influence of endogenous and exogenous modes, but with a 2-AFC task, and found improvements to response speed without a cost to accuracy when the exogenous network is activated (McCormick et al., 2023). In Lawrence and Klein (2013), the first study to separate endogenous and exogenous temporal mechanisms using the intense/isointense signaling method, they suggest that improvements to information processing generated by the exogenous mode could not be discounted in their data set just because a trade-off between speed and accuracy was observed within a warning signal manipulation. This is because any improvement to the speed that could have been generated by this temporal mode would be masked by any decrease in accuracy. Observing the current experiments response fidelity effects was possible through removing the influence that response speed had on target information accumulation, since response speed impacts the amount of information accumulation on each trial when a target remains on screen until the response is generated. Given the evidence from Chapter 2's meta-analysis of the literature (McCormick and Christie, Chapter 2), that only generated speed-accuracy trade-offs only at an STOA of 50msec (when the exogenous mode is at its peak activation) in combination with the current experiments analysis, it is very likely that the exogenous mode of temporal attention shifts response criterion *in addition to* improving the efficiency of information accumulation, at least at the shortest STOAs. In summary, the experiments presented in this paper advance our understanding of the exogenous mode and suggest that the activation of this reflexive mechanism improves the efficiency at which information accumulates, on top of shifting the criterion for when a response is generated.

3.8.1 Limitations and Future Directions

Future research should consider the conditions in which shifts in response criteria take place, and whether these shifts are independent from the improvement in information processing, as speed-accuracy trade-offs appear to be most prevalent at the duration where we are observing the largest fidelity improvements (Han and Proctor, 2022; McCormick & Christie, Chapter 2). For example, Han and Proctor (2022) observed improvements to response speed via warning signals without any increases in error rate when they did not provide RT feedback, indicating that shifts in response criteria associated with cue stimuli may be motivated by task-specific directions. Although intensity effects on fidelity seem to indicate the exogenous mode of alerting generates some improvement in the efficiency of processing information, the stage of processing that is impacted is uncertain. Fidelity enhancement could be generated through an increase in the speed at which information accumulates, or alternatively, through a faster information processing onset (via faster encoding), or what is sometimes referred to as a reduction in non-decision time. Prior research has found evidence for both the former (Vangkilde, Coull, and Bundesen, 2012; White & Curl, 2018; Jagannathan, Bareham, & Bekinschtein, 2022) and the latter (Jepma, Wagenmakers, & Nieuwenhuis, 2012; van den Brink et al., 2021) theories using more advanced modeling techniques. As mentioned previously, Klein and Kerr (1974) also theorize that in a task where the target is presented briefly, a shift in response criterion could result in improved accuracy for the warning signal condition, because a criterion shift means the information accumulated about a target is consulted sooner and experiences less information decay before a response is decided. Although colour discrimination response times did not differ between signaling conditions, indicating no difference in the amount of time information decay occurred, this is still a possible explanation of our pattern of results that fits within Posner's original theory of a criterion shift (1975). Future research should use analysis techniques like drift diffusion modeling to further evaluate distinctions between endogenous and exogenous modes of temporal cueing and determine whether these modes impact different processing stages, given that this analysis technique is explicitly focused on identifying processing stages. Additionally, event-related potential or other methods of neural-imaging could be integrated within temporal cueing tasks to separate the influence of endogenous and exogenous modes and determine processing stages impacted.

Experiment One exhibited a failure in improving the richness of the dataset for 1600 msec STOA trials, since these trials still did not accurately represent a contrast of the endogenous mode of temporal attention due to the reallocation of temporal attention, even though catch trials and never-cued STOAs were used. Being able to attend both cued and uncued time-points is an issue when working within the temporal dynamic as opposed to the spatial one: as the possible target-presentation duration continues, the probability that a target will be presented increases and the information a cue provides is devalued. Temporal cueing tasks can typically be completed quite effectively without the use of any cue, as attention can be dynamically shifted during a trial. This perceived lack-of-utility is likely one of the reasons why temporal cueing effects are often so small. The cueing procedure from Denison, Heeger, and Carrassco (2017) better encourages the following of temporal cues, but includes associated flaws with the controlling of the exogenous mode. Their procedure involves presenting multiple stimuli during a trial in close proximity (within 250msec) of one another, referred to as time one and time two. Near the beginning of a trial, participants are cued that they should either focus on time-point one, two, or both, via the use of a warning signal. Participants are then asked to report the identity of the stimulus presented at time one or time two. This allows for the comparison of trials where they were cued to the target they would be reporting, and trials in which they were told to attend to both stimuli (a neutral cue condition) or the other time-point stimuli (invalid cue condition). However, this procedure generates interference, both through the presentation of additional 'signal-like' stimuli which influence the activation of the exogenous mode (the stimulus at time one would elicit the exogenous mode, as well as provide an endogenous timing cue, for the stimulus at time two), and participants trying to remember the features of two different stimuli on neutral trials. One idea for a future temporal cueing task-design would be to cue a variety of possible foreperiods during a task via a temporally dynamic cue. The length of a tone/visual stimulus could be used to indicate the likely duration of the foreperiod (300 mesc tone = likely 300 msec between trial initiation and target onset). This would allow for the inclusion of more foreperiods during a block of trials, and relatedly, a reduction of hazard sensitivity through increased uncertainty during invalidly cued trials. Warning signals could also play at non-predictive intervals before the target, to manipulate the exogenous mode.

3.9 Conclusion

Both endogenous and exogenous modes of temporal attention generated fidelity improvements in a temporal cueing task, indicating some form of improvement in the efficiency of information processing from both temporal modes. The observation of a perceptual benefit related to the exogenous mode is a novel outcome within the field of temporal attention and provides evidence that Posner's theory of temporal attention (1975), which suggests that warning signals improve speed through a shift in response criterion without impacting the rate of information accumulation, is not generally applicable to conditions of reflexive or volitional temporal attention. Future research should further explore the temporal dynamics of the shifting criterion and improved information processing generated by the exogenous mode, as this is an understudied aspect of temporal attention. As well, it will be important to determine whether the endogenous and exogenous modes improve information processing through affecting the same stage of information processing, or distinct stages.

CHAPTER 4: DRIFT DIFFUSION MODELING OF THE MODES OF TEMPORAL ATTENTION

Colin R. McCormick

4.1 Introduction

Posner and colleagues conducted a series of experiments to test how alerting impacted information processing using speeded Two-Alternative Forced Choice (2-AFC) tasks (Posner & Boies, 1971; Posner, Klein, Summers, & Buggie, 1973). The first experiment was a letter-matching task conducted by Posner and Boies (1971), in which participants had to provide a discrimination response to report whether two letter stimuli were the same or different. Participants experienced both form cues (the identity of the first letter of the set) and warning signals (a tone presented at some interval before the target) at different intervals before the target. Researchers found that alerting was additive with encoding by contrasting performance between conditions when only a form cue or warning signal was used, and when both form cues and warning signals were used on the same trial. The additivity of effects within the 'both stimuli' trials led researchers to propose that the rate of information buildup was unaffected by alerting, since the rates of encoding the first form cue were consistent regardless of whether the participant was alerted or not. However, the accuracy scores across conditions were close to ceiling performance, and none of the different intervals for the alerting conditions showed any difference in accuracy rate. This was inconsistent with the proposal of consistent information accumulation for alerting, since alerting was improving response speed across the different signal-target intervals without trading off accuracy. Posner, Klein, Summers, & Buggie (1973) suggested that accuracy was too high in Posner and Boies' (1971) experiment to detect changes in accuracy between alerting conditions, and chose to conduct a follow-up study with a response-compatibility manipulation to increase the number of errors. Blocks of trials within Posner et al's experiment presented warning tones at a consistent duration before the target, except for one of the blocks, in which no tone was presented. Half of the trials required a spatially compatible response (i.e. left-side target, left button response), while the other half required a spatially incompatible response (i.e. left-side target, right button response). Using this modified paradigm, Posner and his colleagues tested whether alerting enhances the speed of information accumulation, or instead impacts response criterion without affecting the rate at which information accumulates. They reasoned that if alerting improved response speed without increasing error rates, this would indicate support for the ‘enhanced speed of processing’ theory of alerting. If instead there was evidence of a speed-accuracy trade-off (SAT), in which faster responses were associated with increases in error rate, this would support a ‘response criterion shift’ theory of alerting.

Posner et al. (1973) used eight different Signal[17]-Target Onset Asynchronies (STOAs), that provide insight into the time course of alerting. Overall error rates were higher within this experiment compared to Posner and Boies (1971) due to the response compatibility manipulation. The fastest reaction times were at around a STOA of 100 to 200 msec, with the other STOA conditions forming a U-shaped distribution around this peak (see Figure 4.1). Importantly, error rates increased as reaction time decreased across the STOAs. This SAT supported what came to be known as Posner’s theory of alerting (1975): alerting shifts the response criterion without impacting the rate at which information accumulates.

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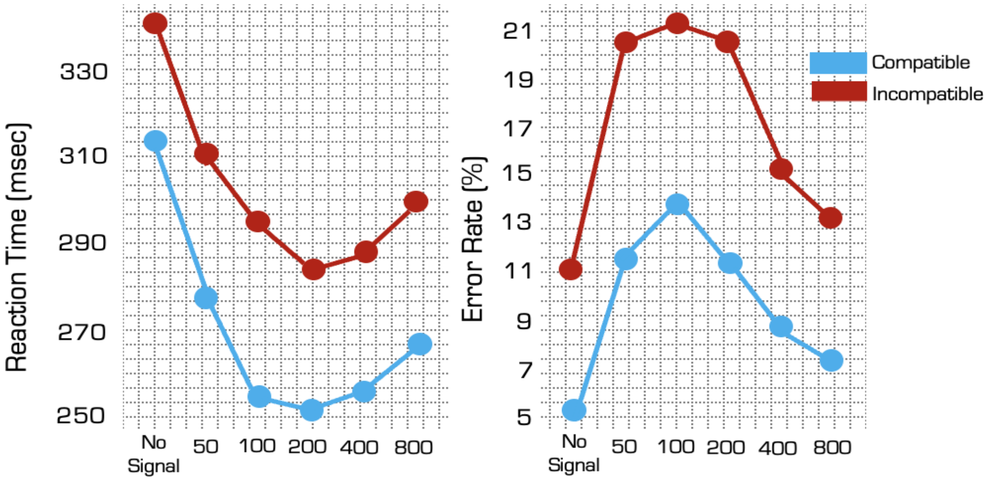
[17] Signal refers to any non-spatially informative stimulus. This includes auditory tones and visual stimuli.

Figure 4.1. The redrawn results from Posner, Klein, Summers, & Buggie (1973). Faster response times corresponded with higher error rates, commonly referred to as a speed-accuracy trade-off.



4.1.1 Recent Replications of Posner et al. (1973)

There have been two recent replications of Posner et al's (1973) seminal study. McCormick, Hurst, Redden, and Klein (2019) reported a successful replication, based on obtaining a significant effect of STOA on reaction time and error rate, with a 'U' and 'inverted-U' shape to their speed and accuracy plots (see Figure 4.3 in the results section). However, Han and Proctor (2022) ran two versions of the 2-AFC task: one that provided response time feedback -a feature of Posner et al. (1973)-, and another that did not. They did not find any evidence of an SAT within their no-feedback manipulation. When providing feedback, they found a speed-accuracy trade-off when comparing the 50 msec STOA and no signal conditions, but the 200 msec STOA generated faster reaction times in contrast to the no signal condition without producing a cost to accuracy, indicating that while a shift in response criterion may be occurring at the shortest STOAs, there does appear to be an improvement in the quality of responses generated by alerting when there is a longer STOA. When reassessing McCormick et al.'s (2019) replication under this suggestion, it appears to follow Han and Proctor's (2022) theorized outcome, suggesting that Posner et al.'s (1973) original experiment may not replicate exactly as expected.

In addition to these recent replications, a meta-analysis of 16 experiments that closely matched the features of Posner et al.'s alerting task indicated that while there is a U-shaped pattern of reaction times (RT) peaking at an STOA of 200msec, there is weak evidence of criterion shifts after the 50 msec STOA, with near-zero error rate (ER) effects when comparing the 200msec and 400 msec STOAs with a no-signal condition (McCormick & Christie, Chapter 2). This leads to the question of why Posner et al (1973) found such high ER differences across their warning signal conditions in contrast with no signal conditions (see Figure 4.1), leading to the conclusion that improvements to speed reflects trading off additional accuracy (Posner, 1975). The presence of an alerting signal has been found to increase bottom-up response activation, leading to alerted trials making incompatible response mappings more error-prone (Fischer, Plessow, & Kiesel, 2012). Posner et al. (1973) additionally instructed participants to respond quickly without regard for a particular level of accuracy, which appears to be a slightly more liberal instruction than other experiments.

4.1.2 Influence of Endogenous and Exogenous Modes

Klein (2022) presents a revised taxonomy of attention that introduces modes across the different domains in which attention can be allocated. Mode refers to whether the control of attention is reflexive (exogenous) or volitionally allocated (endogenous), while domain refers to whether attention is being allocated in time or space, or to a particular task. It is important to consider how endogenous and exogenous modes of temporal attention may distinctly impact task performance in the context of Posner’s theory of alerting (1975), as this distinction was not controlled for within Posner et al.’s (1973) experiment. For context, ‘alerting’ is analogous to attention in time, since participants are provided with non-spatially informative timing cues that provide an indication that a target will be presented shortly. However, the warning signals used in Posner et al.’s (1973) manipulation confounded both modes of temporal attention, with the intensity of their warning stimulus, which generated the reflexive and arousal-increasing effects of the exogenous mode, and the contingency of their signal being a fixed duration from the target within a block, which elicited the volitional endogenous mode and allowed participants to prepare for the target presentation. These modes have been defined as functionally independent (McCormick, Redden, Lawrence, & Klein, 2018), and characterized as having distinct time-courses of activation (Denison Carrasco, and Heeger, 2021) as well as effects on performance (Klein and Lawrence, 2013). The conflation of the modes of temporal attention is not a unique property of Posner et al. (1973), however. As noted by Weinbach and Henik (2012), most studies within the fields of alerting and temporal cueing claim to be studying the effects of one of these modes, while failing to control/account for the other.

McCormick et al. (2019) replicated Posner et al.’s (1973) previously described alerting task, with the addition of Lawrence and Klein’s (2013) signaling method to isolate the endogenous and exogenous modes of temporal attention. Lawrence and Klein’s signaling procedure involves playing mono white noise (identical streams of white noise presented to each ear) throughout trials, which then temporarily shifts to stereo white noise (uncorrelated noise in each ear) for 100 msec to serve as a warning signal. When the shift to stereo signaling increases in intensity, it provides an opportunity to observe how the exogenous mode differently modifies performance in the context of volitional preparation. This is because the increase in intensity initiates a reflexive response from the participant (the exogenous mode), while also indicating to the participants that a target is going to be presented shortly. When the shift to stereo noise is presented without a change in intensity (*isointense*, akin to isoluminance), participants can prepare for the upcoming target presentation (endogenous mode) without the often-associated increase in warning stimulus intensity. Lawrence and Klein (2013) were the first to use this method. They observed distinctions between the two intensity manipulations (2013). Purely endogenous temporal attention elicited by an isointense signal improves speed and accuracy over a no-signal condition. However, adding signal intensity generates a speed-accuracy trade-off, such that participants are faster to respond but less accurate. This signaling method provides the opportunity for a theoretically equivalent replication condition to contrast with Posner et al's (1973) results, and additionally allows for the comparison of how endogenous and exogenous modes of temporal attention differently impact speed and accuracy performance. When McCormick et al. (2019) replicated Posner et al.'s (1973) task using this signaling method, they expected that intense and isointense signals would produce a similar outcome to Lawrence and Klein's (2013) study, where intense signals generated a speed accuracy trade-off and isointense signals generated faster RTs without an increase in ER, when contrasting signaled trials to no signal trials. However, McCormick et al. did not observe this pattern of performance for speed and accuracy differences between signal intensity conditions. The only significant difference between these intense and isointense signal conditions was an interaction between signal intensity and STOA for reaction time, with faster RTs at a STOA of 100msec in the intense condition in comparison to the isointense condition. As described in McCormick and Christie's (Chapter 2) meta-analysis, the ER effects of a warning signal may have been inflated in Posner et al. (1973).

Chapter 3 included two experiments that furthered the study of endogenous and exogenous modes in a temporal cueing task. In this task, participants are cued with the likely (75% valid) STOA at which the target will be presented. Cue validity, or whether a temporal cue informed the participant of the correct interval or not, provided a measurement of how endogenous temporal attention impacts performance, while signal intensity (intense and isointense) was contrasted to observe how the exogenous mode impacted performance at two different time points (50 and 400 msec). Instead of using a 2-AFC paradigm, targets were a colour pulled from a continuous distribution, and participants were asked to provide the most accurate answer of what they saw on a colour wheel. This response accuracy was transformed into a measure of fidelity, which is a representation of the accuracy of a participant's encoding of the target stimulus. If any of the conditions improved the efficiency of information processing during the target's brief presentation interval, we would expect improved fidelity from the participant. Both cue validity and intensity generated improvements to the fidelity of responses, with the intense signal presented at a 50 msec STOA generating larger fidelity effects than the signal presented at a 400 msec STOA. While the endogenous mode has been previously theorized to improve perceptual processing around 400msec (Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019), the exogenous mode's fidelity effect from Chapter 3 has potentially interesting implications in the context of Posner's theory of alerting (1975), which claims that the response criterion shifts without changing the speed at which information accumulates. Observing improved fidelity when participants were intensely signaled indicates that the exogenous mode improves the rate at which information accumulates. The improvement in information processing may have been masked within prior speeded 2-AFC paradigms, in which the target remains on screen until a response is generated. In these tasks, a response criterion shift generated by an intense stimulus means that participants are getting less information from the target, which would then reduce a participant's accuracy. Reductions in accuracy are then typically interpreted as indicating that reaction time effects are solely due to a criterion shift, even though improvements in information processing may have also been present. The information processing enhancement is not masked in Chapter 3's continuous response metric task. This is because targets are presented briefly and responses are not speeded, so the information accumulated does not change based on when a response is provided. However, Klein and Kerr (1974) explain how a warning stimulus could improve accuracy within a similar task in the context of Posner's theory (1975). If a salient warning signal was used on a trial where the target is only presented briefly, it is possible that by shifting the response criterion and generating an accuracy response sooner, there would be less decay of information about the target, resulting in improvements to accuracy without the warning signal having affected the rate at which information accumulated. Chapter 3 outlines why a shift in the efficiency of information accumulation is more likely than Klein and Kerr's interpretation of how this outcome could still fit under Posner's theory (1975), but in order to solidify evidence for this theory, alternative parameters that can distinguish criterion shifts from information accumulation, like those generated by drift-diffusion modelling, should be consulted to determine the more probable theory.

4.1.3 Drift Diffusion Modeling in Temporal Attention

The studies discussed thus far (Posner et al., 1973; Lawrence & Klein, 2013; McCormick et al., 2019; Chapter 3) used measures of speed and/or accuracy to indirectly evaluate information accumulation speeds and shifting response-criterion boundaries. Drift diffusion modelling (DDM) is a better suited analysis to address how experimental factors are impacting information processing. DDM provides parameter estimations of drift rate, boundary separation, and non-decision time. The drift rate indicates the speed at which information accumulates toward a response threshold. Larger drift rates indicate a faster accumulation of information, leading to both higher accuracy and faster RTs. Boundary separation, or the response criterion, is a measure of how much information needs to accumulate before the response threshold is met and indexes the speed/accuracy tradeoff – smaller boundary separation requires less evidence to trigger a response, resulting in faster but less accurate responses. Finally, non-decision time is the time to execute non-decision-related processes, including the time to initiate encoding and motor-response generation. Non-decision time affects response speed but does not affect accuracy.

In the context of testing the theory of alerting presented by Posner et al. (1973) and supported by Lawrence and Klein (2013), a shift in response criterion would be evidence of shifts in the boundary separation. In contrast, changes in the speed at which information is processed would be evidence of changes in drift rate. No prior DDM studies have compared the endogenous and exogenous modes of temporal attention directly, but there have been analyses using both constant STOA designs, typical in alerting studies, in which the duration between signal and target is maintained for longer durations in comparison to temporal cues designs, in which the cue predicts the upcoming STOA probabilities. Both types of study involve contributions of the endogenous and exogenous modes, but to varying degrees.

White and Curl (2018) applied drift-diffusion modelling to data from the Attention Network Test (ANT), a popular tool for measuring the three networks of attention (Fan et al., 2002). Within this paradigm, alerting is manipulated via a non-spatially informative visual cue that is a consistent interval (750 msec) from the target so participants can volitionally prepare to provide a discrimination response. White and Curl observed evidence of enhanced speed of perceptual processing in the alerting cue condition in comparison to the no cue condition, along with some weaker evidence of differences in boundary separation and non-decision time. Interestingly, they found that alerting and orienting cues did not differ in their perceptual processing effects. While this conflicts with Posner's theory of alerting, it is congruent with studies where temporal cues reduce uncertainty about when targets are likely to appear (Rolke & Hofmann, 2007), along with research on the endogenous effects of temporal cue validity (Denison, Heeger, and Carrasco, 2017; also see Vangkilde, Coull, and Bundesen, 2012). Additionally, the STOA used in White and Curl's study is at the later end of the STOA distribution used in Posner et al.'s (1973) study. The longer STOAs make White and Curl's slightly more representative of a 'pure endogenous' condition, considering the time course of the exogenous mode of temporal attention would be significantly past its peak of 80 msec and would have less reflexive influence on performance, in comparison to when shorter STOAs are used (Denison et al., 2021). In another fixed-STOA alerting task, Jempa, Wagenmakers, and Nieuwenhuis (2012) found that a short 350 msec STOA had a shorter non-decision length compared to a long 1350 msec STOA condition. The authors considered this an effect of temporal certainty, given that the judgment of timing becomes less accurate as an interval increases, but the change in non-decision length could also be an effect of the exogenous mode of alerting, given the target presentation is closer in time to the salient warning signal. In contrast to White and Curl (2018), Jempa and colleagues (2012) did not have a no-signal condition for comparison, so it is challenging to observe the exact effects of temporal attention on performance, rather than time-course effects.

Drift diffusion models have also been applied to temporal cueing tasks. Temporal cueing tasks are like the previously mentioned fixed STOA alerting tasks, but have different STOA probabilities on each trial, indicated by a cue. These cues usually provide the correct interval a target will be presented at (75-80% valid temporal cues) but sometimes provide incorrect timing information (20-25% invalid temporal cues). The contrast of valid and invalid temporal cues allows for the comparison of when temporal attention is allocated vs when it is not. This is a better representation of the endogenous mode in contrast to when a temporal duration is fixed across a block of trials. When the duration is fixed across a block of trials, other temporal mechanisms can influence performance, including hazard sensitivity (reflexive expectation of when a stimulus is likely to appear based on experience) and sequence effects (when the prior trial's interval matches the current trials interval, participants are faster; Nobre & van Ede, 2018). If a researcher is interested in how the allocation of volitional attention in time impacts performance, temporal cues are a better choice of methodology. Diffusion models for temporal cueing indicate that validly cued trials reduce non-decision time in comparison to invalidly cued trials (van den Brink et al., 2021; Jempa, Wagenmakers, & Nieuwenhuis 2012). This finding supports a theory that temporal certainty reduces encoding time and does not impact the rate at which information accumulates (Bausenhart, Rolke, Seibold, & Ulrich, 2010; Seibold, Bausenhart, Rolke, & Ulrich, 2011). However, it is worth noting that these were detection tasks, as opposed to tasks in which participants must discriminate the target stimulus. Prior research indicates that temporal attention impacts different response processing stages based on whether the task requires a detection response (motor-preparation stage; Coull, Frith, Büchel, & Nobre, 2000) or a discrimination response (perceptual stage; Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019; Jepma, Wagenmakers, & Nieuwenhuis, 2012). For instance, Vangkilde, Coull, and Bundesen (2012), using a computational model based on the theory of visual attention, found that the endogenous mode of temporal attention improved accuracy on a discrimination task through improved processing speed, without impacting encoding time. In summary, not many studies have run drift diffusion models on paradigms that measure both speed and accuracy. Studies that measured detection responses indicated changes to non-decision time (van den Brink et al., 2021; Jepma, Wagenmakers, & Nieuwenhuis 2012), which likely represents the separate motor-preparation that is impacted within these single-button tasks. The most similar analysis to ours on speeded discrimination responses in the attention network test showed that warning signals impacted both boundary separation (a response criterion shift) and drift rate (faster information accumulation; White and Curl, 2018).

As may be evident from the divergent conclusions in the above paragraph, comparisons between temporal cueing studies and more traditional fixed-STOA designs should be made with caution: while temporal cueing studies involve a combination of endogenous and exogenous modes of attention in the same capacity as fixed-STOA alerting studies, as they use salient temporal cues that activate the exogenous mode to inform participants of when to allocate the endogenous mode, seemingly small modifications to temporal paradigms can introduce varying influences of other temporal mechanisms. These include the influence of sequence effects, which impact behavioural effects more in traditional alerting studies where STOAs are fixed across prolonged periods of time (Coull et al., 2004), as well as using different STOAs across cueing studies, from anywhere between 400msec and 2700msec. The duration between a signal and a target will impact a participant's accuracy in time-estimation, as well as introduce different levels of exogenous mode activation. Multiple temporal mechanisms can also be activated at once, with both additive and interactive effects based on the task being performed (Nobre & van Ede, 2023).

Contrasting on speed and accuracy effects for warning signal and no signal trials has not generated a clear consensus on how the modes of temporal attention impact information processing efficiency. This type of analysis lacks clarity in assessing what stage of processing is affected by temporal attention. Conducting a DDM analysis on data from a paradigm that explicitly manipulates the presence of the exogenous and endogenous modes allows for a critical evaluation of Posner's theory of alerting (1975). The current chapter's analysis will determine whether the endogenous and exogenous modes of temporal attention impact the rate at which information accumulates, as well as whether there are shifts in response criterion associated with their activation. Additionally, the time-course of these modes will be analyzed at three important points: 100 msec between the signal and the target, close to when we would expect peak exogenous mode activation (Denison et al., 2021), 250msec between the signal and the target, which is the earliest point at which we would expect the endogenous mode to be activated, as well as 850msec between the signal and the target, when we would expect participants to be able to fully prepare the endogenous mode to the target interval. Posner's theory of alerting (1975) will be revisited based on the outcome of this analysis.

4.1.4 Current Study

The current study involves re-analyzing data from McCormick, Hurst, Redden, & Klein (2019) using a drift-diffusion model. Their task was a 2-AFC paradigm that used intense and isointense signals at STOAs of 100 250, and 850 msec (a relevant subset of Posner's STOAs), along with a condition in which no signal was presented. The current analysis compares drift rate, non-decision time, and boundary separation between intense and isointense signals, with specific contrasts between STOA conditions. This will allow us to address how the endogenous and exogenous modes differently impact the stages of information processing.

4.1.5 Predictions

Posner's theory (1975) predicts that the intense signal condition will generate a larger shift in boundary separation in contrast to the isointense signal condition, with no difference in drift rate. This is based on prior research that found that as reaction time effects (no signal minus signal) became larger across foreperiod conditions, the error rate effects also grew, indicating that speed improvements were a result of a participant trading off accuracy performance (Posner et al., 1973). The criterion shift for intense signal conditions is also supported by Lawrence and Klein's (2013) performance contrasts when using an intense signal, with their analysis only covering the shortest signal-target intervals (around 100msec). Additionally, our recent meta-analysis (Chapter 2) found the most evidence of a speed-accuracy trade-off at STOAs of 50 to 100 msec, which is close to peak activation of the exogenous mode (Denison et al., 2021), and therefore lends support to the suggestion that the exogenous mode drives criterion shifts more so than the endogenous mode. That said, based on the fidelity effects in the intense condition of the non-speeded temporal cueing task reported in Chapter 3 (McCormick and Klein) —which suggests improvements in the efficiency of information processing related to the exogenous mode— we might also observe differences in drift rate or non-decision time for the intense signal compared to the isointense signal. Accordingly, all three of these metrics will be contrasted between signal intensity conditions.

The analysis will also involve comparing warning signal effects (signal minus no signal trials) across STOAs. We expect larger boundary separation shifts, or changes in the response criterion, when the target is presented at shorter time points before a target (100 and 250msec

STOA) in comparison to the later time-points (850 msec), since the exogenous mode would be near its peak activation post-warning signal. This effect of the shorter STOAs on boundary separation would be most likely for the intense condition. We also expect that temporal preparation, the endogenous mode, should improve the rate at which information accumulates (Vangkilde, Coull, & Bundesen, 2012; Davranche1, Nazarian, Vidal, & Coull, 2011; Denison, Heeger, Carrasco, 2017; Fernández, Denison, & Carrasco, 2019; Jepma, Wagenmakers, & Nieuwenhuis, 2012; White & Curl, 2018; Jagannathan, Bareham, & Bekinschtein, 2022). This prediction would be expected at the later STOA, when participants have had sufficient time to volitionally prepare. We expect higher drift rates at the later STOA in contrast with the earlier STOAs.

4.2 Method

These methods are rewritten from McCormick, Redden, Hurst, & Klein, 2019, with slight stylistic changes, given that the data come from this published experiment.

4.2.1 Participants

Forty-eight participants were run in the task, with 24 participants in the ‘intense’ signal condition, and 24 participants in the ‘isointense’ condition. All participants experienced 256 trials of the task.

4.2.2 Materials

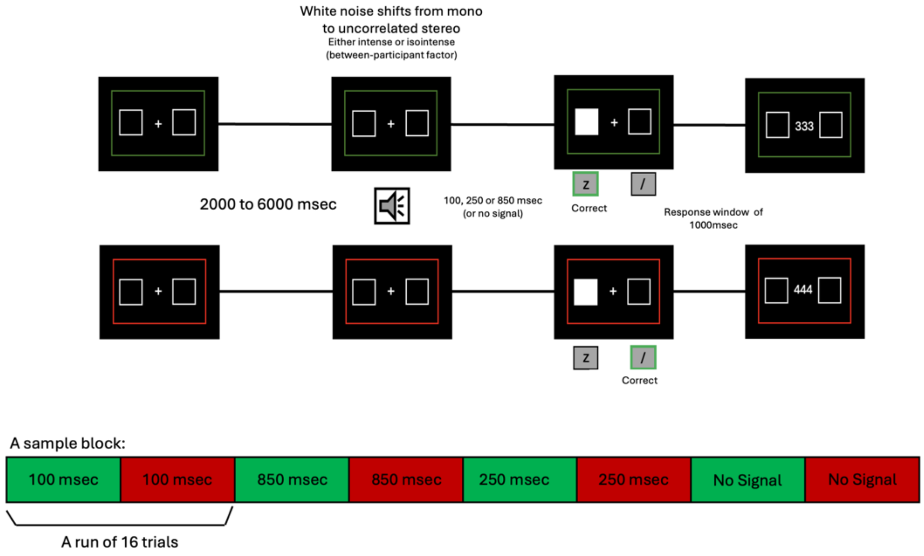
Stimuli were presented on 21.5” Apple iMac computers running OS X 10.9.5 in a group testing room at Dalhousie University. Visual stimuli were displayed at a resolution of 1920 × 1080 pixels with a refresh rate of 60 Hz. The audio was played at a sample rate of 44 100 Hz using headphones (Sony MDR- 101LP). Responses were collected using Apple USB keyboards (model A1243). The program was written in Python using the KLibs framework for cognitive psychology experiments. All stimuli are defined in terms of their perceptual size in degrees of visual angle.

A single channel of randomly generated uniform white noise was presented to both ears via the headphones (aka mono noise) at a preset volume. At the onset of each trial, a white fixation point (1.0° diameter, 0.4° inner stroke) was displayed in the middle of the black background. On either side of the display were white target placeholder boxes (1.0° size, 0.1° inner stroke, 11.1° horizontal offset from fixation). Surrounding these stimuli was a border cue (5.0° from all edges of the screen, 0.1° inner stroke) that indicated whether participants would have to make a compatible response (green) or an incompatible response (red) to the target on that trial. Experiment-related materials can be found on the following GitHub page: https://github.com/TheKleinLab/TaskSwitching.

4.2.3 Procedure

A visual depiction of a typical trial is presented in Figure 4.2. Participants completed four blocks of 64 trials each. Participants were offered a rest break after two blocks (128 trials). Each block contained four sets of 16 trials, one for each of the STOA conditions (no signal, 100, 250 and 850 ms). Each of these sets of 16 trials is referred to as a 'run'. During a run of trials, the STOA remained constant. The order the participant were presented the runs within a block was randomized across participants (see Figure 4.2, 'a sample block'). The colour of the border 'response compatibility' cue alternated every eight trials, resulting in eight 'compatible' and eight 'incompatible' trials for each signal delay condition in each block. After a random fixation interval between 2000 and 6000 ms, a brief (100 ms) auditory alerting signal was presented in 75% of all trials. This was a temporary shift in the white noise from mono to uncorrelated stereo. In the intense condition, the volume increased 100% (doubled relative to the white noise) for 100 msec. In the isointense condition, this involved a shift from mono to uncorrelated stereo for 100 msec that did not change in volume. On the 25% of trials without an alerting signal, the target was presented at the end of the fixation interval. On 75% of trials with an alerting signal, the target was presented at a STOA of 100, 250 or 850 msec. Once the target was presented, participants were given 1000 msec to make a spatial response using a ’left’ (z) and ’right’ (/) button. Participants were told to respond as quickly as possible, but that accuracy was still important. For compatible response mapping trials, participants were instructed to press the key on the same side as the target. For incompatible response mapping trials, participants were instructed to press the key on the side opposite to the target. Once a response was made, the fixation point was replaced with performance feedback. If the response was correct based on the compatibility manipulation, the speed of the response (in msec) was displayed in place of the fixation point. If an incorrect response was made, an ’X’ (a 1.0° cross rotated 45 degrees, 0.1° thick) was displayed. If no response was provided, the text ‘Too Slow!’ was displayed.

Figure 4.2. Top: a diagram of the trial procedure during this signaling task. Bottom: how the blocks were organized in relation to STOA and response compatibility. Green represents response compatible mapping trials, while red represents response incompatible mapping trials.

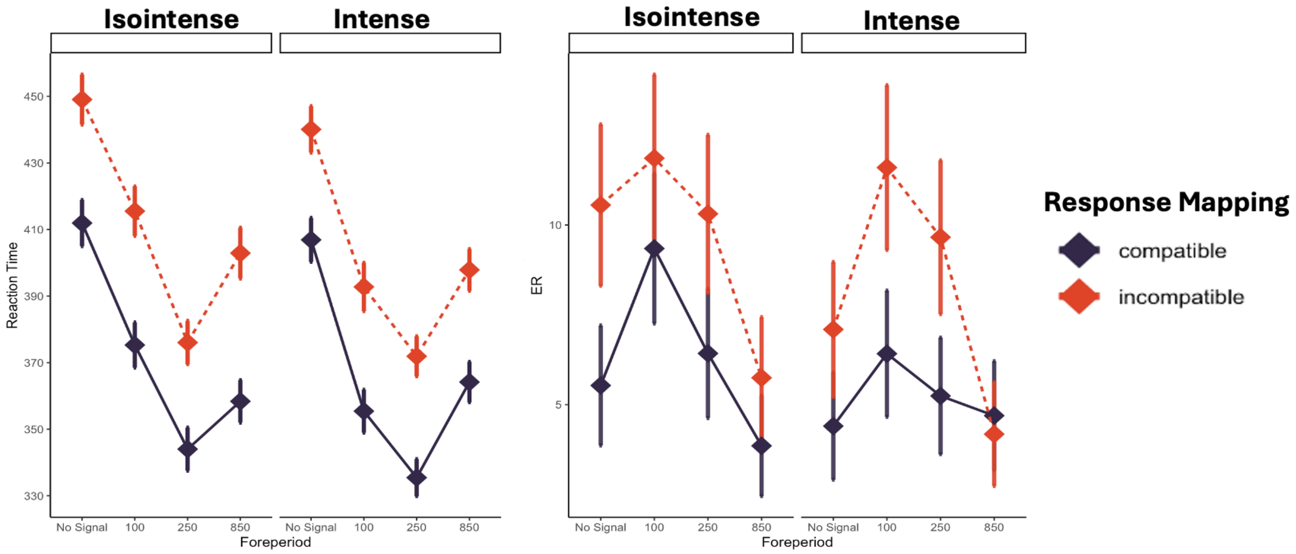


4.3 Results

4.3.1 A Review of Behavioral Effects

The behavioral data from this experiment were reported in McCormick et al. (2019). Their mixed-factorial Analysis of Variance (ANOVA) identified significant main effects of STOA and response compatibility for RT, with no significant effect of signal type. There was a significant interaction between signal type and STOA on RT. For ER, the mixed-factorial ANOVA identified a significant effect of STOA and compatibility and no significant effect for signal type. There was a significant interaction between compatibility and STOA (see Figure 4.3).

Figure 4.3. Redrawn RT (right) and ER (left) plots from McCormick, Redden, Hurst, and Klein, 2019. Error bars are 95% confidence intervals.



4.3.2 Drift Diffusion Analysis

The brms package in R (Bürkner, 2017) was used to estimate a Wiener model, which generates four-parameters (drift-rate, boundary separation, non-decision time, and bias) that can be used to assess which stages of processing are impacted by signal intensity (intense or isointense) and STOA (No Signal, 100, 250, or 850 msec)[18].

Our model formula was:

bf(rt| dec(response) ~ 0 + target_location:signal_type:stoa
+ (0 + target_location:signal_type:stoa|p|participant),
bs ~ 0 + signal_type:stoa + (0 + signal_type:stoa|p|participant),
ndt ~ 0 + signal_type:stoa,
bias ~ 0 + signal_type:stoa

The left of the tilde contains the reaction time variable as well as the component ‘dec(response)’, which represents the button response (left or right) made by the participant. The counterpart to the response variable in this model (right of the tilde) is the ‘target location’ (left or right), which allowed for the evaluation of information accumulation toward a left or right response in relation to the target stimulus present on that trial. The two conditions of interest for this analysis, signal type (intense or isointense) and STOA (No Signal, 100, 250, or 850), were included as predictors. The intercept was suppressed for each parameter, so that the model generated a parameter value for each level of predictor condition. The first line of the model formula represents the equation corresponding to the ‘drift rate’, in which the target location, signal type, and STOA were all included and allowed to interact. For the other three parameters, boundary separation (bs), nondecision time (ndt) and response bias (bias), only signal type and STOA were included as potentially interacting factors; target location was ignored. Along with these fixed effects, random effects were also generated for drift rate and boundary separation, so that values varied for each participant’s performance. Weakly informative priors, based on

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[18] Guidance for the execution of this modeling was provided by a blogpost tutorial written by Singmann (2017).

knowledge of the general distribution of parameter values from past related analyses, were used to guide the model. The priors set were:

Drift rate: *Cauchy (.01, 5),* Boundary Separation: *Normal (1.5, 1),*

Non-Decision Time: *Normal (.15, 0.15),* Bias: *Normal (0.5, 0.2)*

Our model was run with 3000 iterations, with 1200 warm-up iterations. Our max tree-depth was 10, with adapt-delta set at .9. All other modeling related details can be found in our analysis R code, which has been posted at this link.

4.3.3 Model Fit

4.3.3.1 R-Hat, Effective Samples, and Trace plots

R-hat is a measure of convergence, with R-hat values between 1 and 1.05 considered as acceptable for use. All our parameters generated R-hat values equal to 1. The smallest effective sample size (ESS) for a parameter, which are used to evaluate the sampling efficiency in the bulk of the posterior, was 1693. When this metric is greater than 100, it indicates that the model converged on a fixed distribution. Considering both R-hat and ESS factors, there was evidence that our model effectively converged.

4.3.3.2 Model Fit via Aggregated Data & Scatterplots

We compared the model-generated (predicted) values to the mean values from the actual dataset (observed) to determine whether the model adequately described the data (Figure 4.4). The predicted and observed values were compared across our different signal and STOA conditions (Figure 5.5). The concordance correlation coefficient (CCC), which is an adjusted measure of correlation between predicted and observed values, is also reported within Figure 5.5.

Figure 4.4 Median Responses (Response Left Side), Median Responses (Response Right Side), and Response Probabilities for predicted data (grey is credible range, 95% for thin line, 80% for thick line; median is black circle) in contrast with the median for the observed data (red x is mean value). Labels describe the STOA: intensity combinations (purple intense, black isointense).

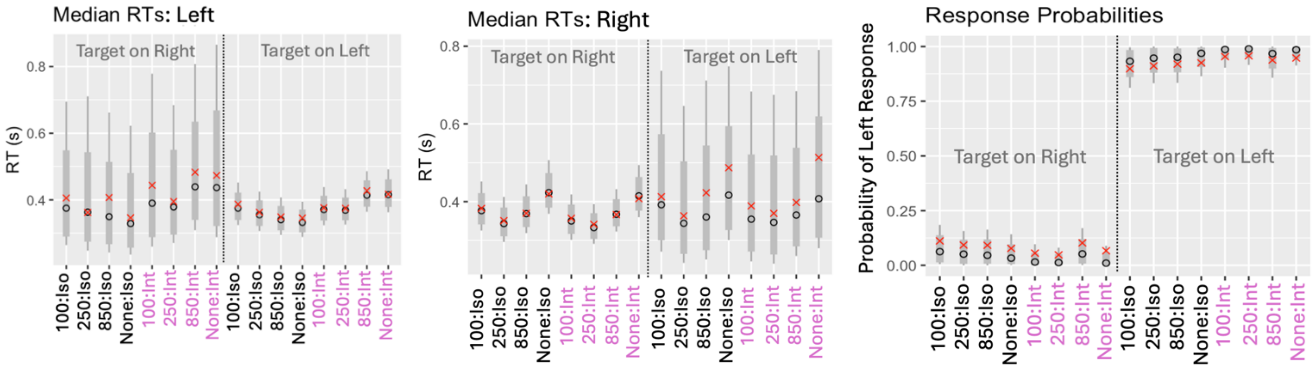
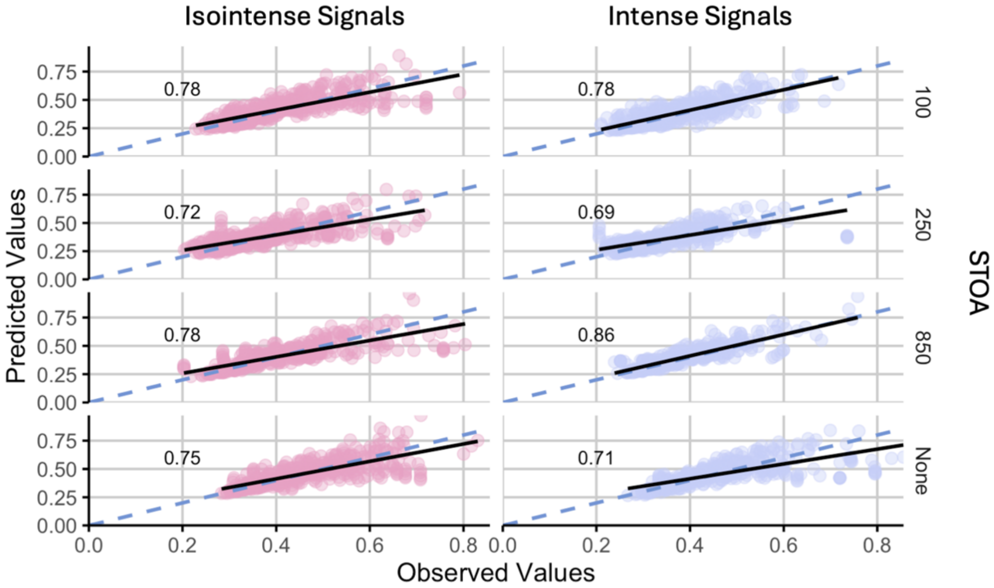


Figure 4.5 Predicted values (y-axis) in comparison to observed values (x-axis) for the combination of signal intensity and STOA conditions. The dashed line represents a perfect correlation, while the black line represents the real correlation. The concordance correlation coefficient (CCC), an adjusted measure of correlation, is included for each plot.



We can see that the median from the observed values (red x) was captured within the 80% credible interval for all the conditions (Figure 4.4), and quite close to the predicted median values themselves (black circles). This is especially the case for correct responses (response matched with target presentation side). For incorrect responses (response-presentation mismatch), the model estimates were less accurate, but this is as to be expected as there was considerably less data available to inform the model. The predicted accuracy was underestimated for both left and right responses, as can be seen in the 'probability of left response plot (Figure 4.4, plot 3), but was nevertheless still captured within the credible interval.

For the predicted and observed correlation scatterplots (Figure 4.5), there was some deviance from the observed values, but overall, the patterns represented what was observed in the data. That said, the predicted values appeared to deviate more at the higher observed values than at the lower values. Overall, the fit of the predicted values to the observed values was acceptable. We were able to proceed with the analysis and used the model parameters to evaluate how different stages of processing influenced the behavioral data.

4.3.4 Drift Diffusion Parameter Effects

Highest density intervals (HDI) were generated to report effect sizes and parameter values. This is the narrowest interval that captures 89% of the probable values from the posterior distribution. Violin plots, which show the posterior distribution, as well as the 89% (thin line) and 60% (thick line) HDIs, were used to visualize these effects.

When contrasting the signal intensities, 'no signal' trials were not included. There was an effect of signal intensity (intense - isointense) on drift rate, such that intense signals had a larger drift rate, indicating faster information accrual, with a magnitude of difference somewhere between .10 and .48 (*HDI89%*; Figure 4.6, plot A). There was no evidence of a difference between intense signal boundary separation values in comparison to isointense signal values, with a difference somewhere between -.04 and .10 (HDI89%; Figure 4.6 plot B). Larger boundary separation values indicate more information accumulation was required before a response was generated. Additionally, there was a difference in non-decision time, with faster non-decision time for intense signal trials vs isointense signal trials, by a magnitude of 4 msec (.01, .00 HDI89%; Figure 4.6, plot C). Non-decision time is measured in time units.

The individual STOA contrasts comparing signal and no signal conditions for each of the intensity conditions are presented in Figure 4.7 for drift rate, Figure 4.8 for boundary separation, and Figure 4.9 for non-decision time. The tables built within these figures present the associated means and 89% HDIs. There was a negative effect of the warning signal on drift rate, relative to the no warning signal condition, at the 100msec STOA (strong evidence for intense, weak evidence for isointense), weak evidence of a positive effect of the warning signal on drift rate at a 250msec STOA (for both signal intensities), and strong evidence for a positive effect of warning signal on drift rate at the 850msec STOA (for both signal intensities; Figure 4.6). For boundary separation, there was a larger negative boundary separation shift associated with the intense warning signal effect, in contrast with the isointense warning signal effect, at both the 100 and 250msec STOAs. At the 850msec STOA, there was still weak evidence of a negative boundary separation shift for the intense warning signal effect, but the isointense warning signal effect showed strong evidence of a positive boundary separation shift (Figure 4.7). For non-decision time, there were negative warning signal effects, representing faster responses, for all the STOAs across both signal intensity conditions (Figure 4.8).

Figure 4.6 The main effects of intensity (Intense minus Isointense) on drift rate (A) boundary separation (B) and non-decision time (C). Lines are 89% (thin line) and 60% (thick line) HDIs, with the mean value marked with a black dot. A different scale is used on the non-decision time figure to better represent the metric (seconds) and size of the effect.

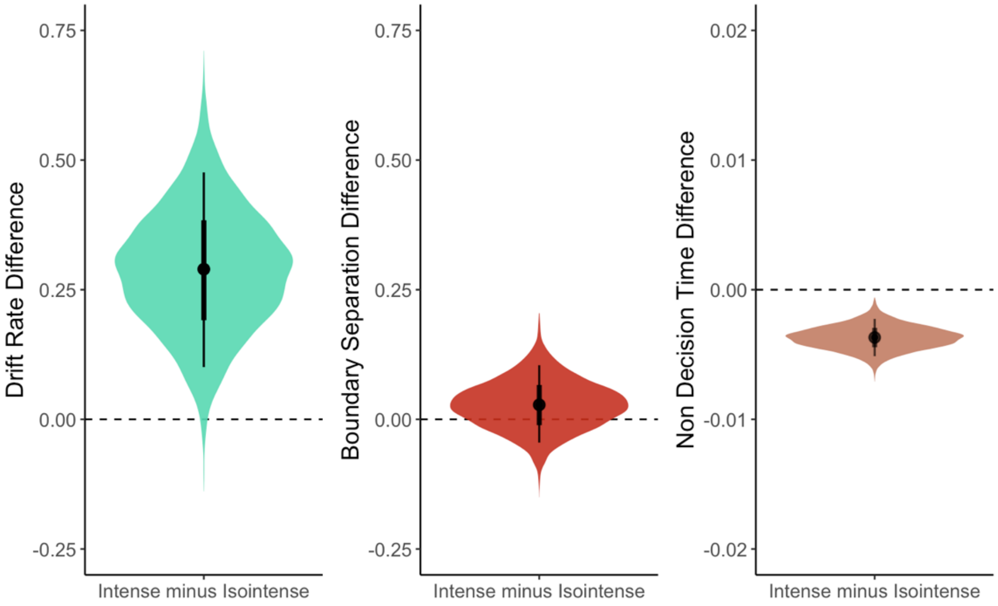
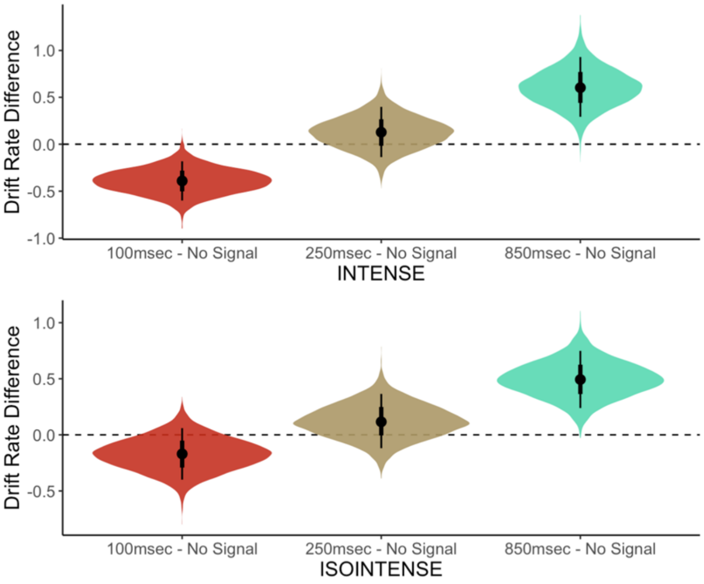
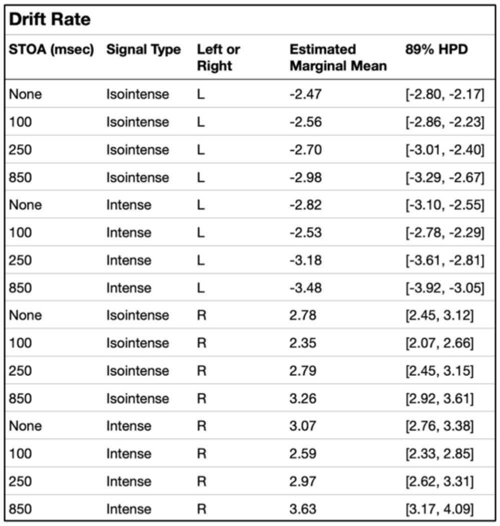


Figure 4.7 The effect of each of the signal conditions (signal minus no signal; intense top, isointense bottom) on drift rate across the different STOA manipulations. Lines are 89% (thin line) and 60% (thick line) HDIs, with the mean value marked with a black dot.

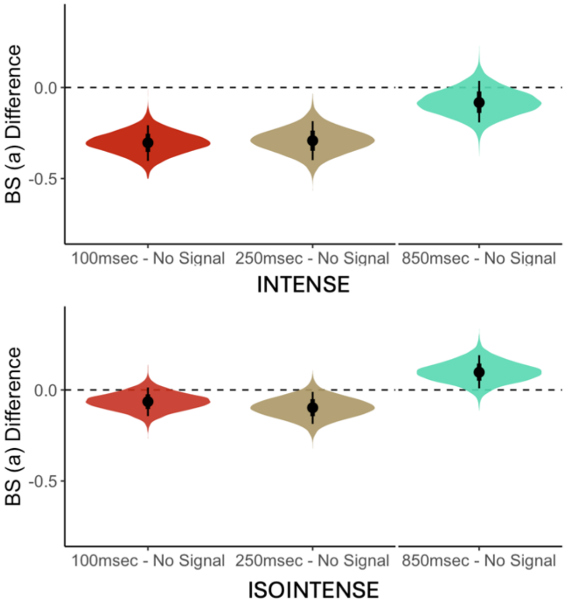


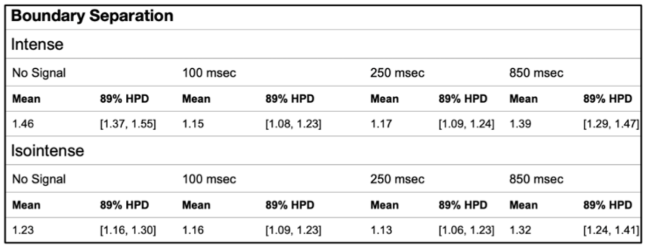


Drift Rate

STOA (msec)	Signal Type	Left or Right	Estimated Marginal Mean	89% HPD
None	Isointense	L	-2.47	[-2.80, -2.17]
100	Isointense	L	-2.56	[-2.86, -2.23]
250	Isointense	L	-2.70	[-3.01, -2.40]
850	Isointense	L	-2.98	[-3.29, -2.67]
None	Intense	L	-2.82	[-3.10, -2.55]
100	Intense	L	-2.53	[-2.78, -2.29]
250	Intense	L	-3.18	[-3.61, -2.81]
850	Intense	L	-3.48	[-3.92, -3.05]
None	Isointense	R	2.78	[2.45, 3.12]
100	Isointense	R	2.35	[2.07, 2.66]
250	Isointense	R	2.79	[2.45, 3.15]
850	Isointense	R	3.26	[2.92, 3.61]
None	Intense	R	3.07	[2.76, 3.38]
100	Intense	R	2.59	[2.33, 2.85]
250	Intense	R	2.97	[2.62, 3.31]
850	Intense	R	3.63	[3.17, 4.09]

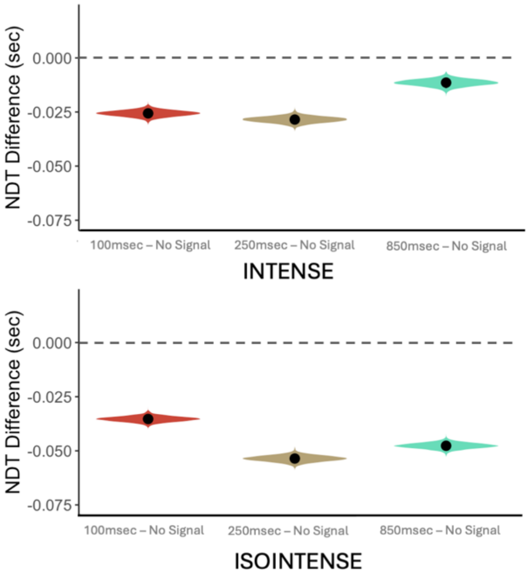
Figure 4.8 The effect of each of the signal conditions (signal minus no signal; intense top, isointense bottom) on boundary separation across the different STOA manipulations. Lines are 89% (thin line) and 60% (thick line) HDIs, with the mean value marked with a black dot.

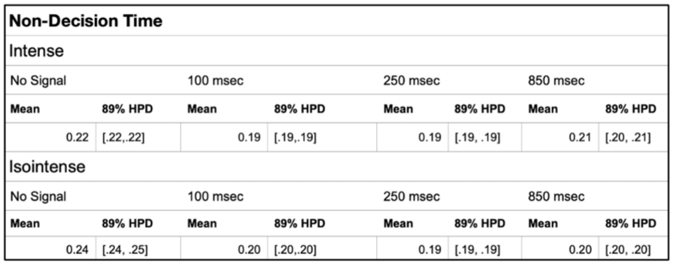




Boundary Separation							
Intense							
No Signal		100 msec		250 msec		850 msec	
Mean	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**
1.46	[1.37, 1.55]	1.15	[1.08, 1.23]	1.17	[1.09, 1.24]	1.39	[1.29, 1.47]
Isointense							
No Signal		100 msec		250 msec		850 msec	
Mean	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**
1.23	[1.16, 1.30]	1.16	[1.09, 1.23]	1.13	[1.06, 1.23]	1.32	[1.24, 1.41]

Figure 4.9 The effect of each of the signal conditions (signal minus no signal; intense top, isointense bottom) on non-decision time across the different STOA manipulations. Lines are 89% (thin line) and 60% (thick line) HDIs, with the mean value marked with a black dot.





Non-Decision Time							
Intense							
No Signal		100 msec		250 msec		850 msec	
Mean	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**
0.22	[.22,.22]	0.19	[.19,.19]	0.19	[.19, .19]	0.21	[.20, .21]
Isointense							
No Signal		100 msec		250 msec		850 msec	
Mean	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**	**Mean**	**89% HPD**
0.24	[.24, .25]	0.20	[.20,.20]	0.19	[.19, .19]	0.20	[.20, .20]

4.4 Discussion

4.4.1 Interpretation of Diffusion Parameters

This analysis was conducted to improve the understanding of how endogenous and exogenous modes of temporal attention impact the processing of information. Prior evidence suggested that while the endogenous mode improves the efficiency of information processing, the exogenous mode shifts the response criterion so that responses are generated faster with less information available. The outcome of this diffusion model challenges this theory.

4.4.1.1 Drift Rate

Intense signals generated a larger drift rate than isointense signals, indicating that the exogenous mode of temporal attention increases the rate at which information accumulates. This is a novel effect within the field that aligns with the fidelity analysis of Chapter 3. When comparing signal and no-signal trials across the different STOAs, our manipulation of the endogenous mode, we observed that the signaling condition did not clearly outperform the no signal condition for drift rate until the longest interval, however there was some trending evidence of a benefit at 250msec. This provides evidence of the endogenous mode's effect on information accumulation. While volitional preparation for a temporal interval has been observed as early as 200msec in discrimination paradigms (Yeshurun and Tkacz-Domb, 2021; McCormick, Redden, and Klein, 2023), the 250msec STOA that participants experienced in the current experiment is a short interval to prepare after a signal is presented. Therefore, the 850msec STOA was the most likely interval for attention to be focused on the anticipated moment since it provided enough time for volitional preparation. Interestingly, there is a decrease in drift rate at the shortest signaled interval of 100msec. This is a distinguishing feature of the shortest interval which may resemble some sort of potential interference between initiating preparation for the upcoming temporal interval and the processing of the target stimulus, since the signal was the feature that indicated to participants that the STOA had initiated. It is unlikely that this drift-rate reduction was a property of the detection or processing of the signal, given that the intensity of this stimulus did not have any impact on the magnitude of this effect. The STOA at which this reduction was observed is the same as that at which McCormick and Christie found their strongest evidence for a speed-accuracy trade-off in their meta-analysis of the alerting literature (Chapter 2). Before running this DDM, it was assumed performance at this time-point was influenced by the criterion shift associated with the exogenous mode, since it would be near peak activation, but it appears that this is evidence of interference between the endogenous mode of preparation and the processing of relevant stimuli. Future research may consider investigating how the processing of information is impacted by different task-demands, including volitional preparation for a target, as we know that task demands can impact an individual's capacity to allocate attention in time (Correa et al., 2004; McCormick et al, 2018).

4.4.1.2 Boundary Separation

Intense signal trials did not differ from isointense signal trials in overall boundary separation, which was a bit surprising given that we expected the exogenous mode of temporal attention to shift boundary criterion. When contrasting across the specific STOAs, the boundary separation effect was larger in the expected direction for the intense signal trials in contrast to the no signal trials at the earlier two STOAs, in contrast with the same comparison for isointense signal trials. This means there was a larger shift in response criterion following intense signals, favouring speed at the cost of accuracy, specifically at those STOAs when we would expect the exogenous mode to be near its peak. This shift is what we had anticipated based on conceptual results on the effects of alerting (Posner et al., 1973; Lawrence and Klein, 2013). However, this larger shift in boundary separation was being driven by the values in the intense no signal manipulation, in which subjects were more conservative (highest boundary separation values) than participants in the isointense no signal manipulation. Signal intensity was a between-subject manipulation, so participants either experienced intense or isointense signals throughout all their trials, which could certainly impact baseline arousal, or introduce other behavioural effects, in comparison to the analogous isointense contrasts.

4.4.1.3 Non-Decision Time

The non-decision time parameter was not of central interest to our predictions, given that it relates to the cumulative time before and after the processing of information. Nevertheless, in theory, this factor could influence the reaction-time effects previously observed. Based on our analysis, it appeared that the intense signal might reduce non-decision time somewhere between 0 and 10 msec in comparison to the isointense condition. The effects of the isointense signal are larger for the specific STOA signal-no-signal comparisons in contrast to the intense signal, but this is because no-signal trials for the isointense condition had longer non-decision time in contrast with the intense condition, likely due to tonic arousal levels. It has been pointed out, however, that non-decision time is a parameter informed by a minuscule proportion of the data: it involves comparing minimum RTs from participants across each condition (Ratcliff & Tuerlinckx, 2002; Singmann, 2018). The limited set of data the current analysis uses to calculate non-decision time makes it unreliable as a metric informing our theories on temporal attention. Relatedly, our model makes unbelievably precise predictions for the different non-decision time effects. For these reasons, and because it is not central to our research question, we will leave our analysis to be considered by the reader, but with the disclaimer that our non-decision time result is likely not worth much consideration.

4.4.2 Implications for the Field of Temporal Attention

The current drift-diffusion analysis provides novel evidence that the exogenous mode of temporal attention generates improvements to the rate at which information is processed. The exogenous mode also likely shifts the point at which information is consulted to generate a response, trading off the accumulation of more information for speed. Posner's (1975) proposal that alertness generates rapid responding without improving the buildup of target information requires a major amendment: the exogenous mode of temporal attention produces more rapid responses while also improving the rate at which information accumulates. This is a substantial update to an almost five-decade old proposal in how our attention system operates in reaction to salient changes in the environment. Prior research that informed and supported Posner's theory (1975) relied on contrasts between speed and accuracy differences to theorize what stages of responding were being affected by the modes of temporal attention (Posner et al., 1973; Lawrence and Klein, 2013; Klein, 2023). Decreases in accuracy for signaled conditions, associated with the exogenous mode's criterion shift, masked evidence that there were improvements to the rate at which information accumulated. This prior method of analysis lacked the ability to identify that both criterion shifts and improvements to the rate of information processing were happening concurrently. The current DDM analysis provided the parameters to distinguish this.

The endogenous mode also enhanced the rate at which information accumulates, supporting prior literature on preparation for an interval (Denison, Heeger, and Carrasco, 2017; Vangkilde, Coull, & Bundesen, 2012; Rolke & Hofmann, 2007; see White & Curl, 2018 for an alerting study). This conclusion was based on drift rate improvements at the 850msec STOA between signal and no signal conditions, since this provided participants enough time to prepare;

250msec between the signal and target was seemingly too short, although there was evidence that improvements in information processing were beginning. We would anticipate that future researchers who conduct drift-diffusion analyses on temporal cueing experiments would find these same improvements to drift rate at earlier intervals as well, including the often-cued 400msec STOA, since prior behavioural evidence shows improved performance at intervals earlier than 850msec (Coull & Nobre, 1998; Correa et al, 2004; McCormick, Redden, and Klein, 2023). Additionally, the additivity of effects from each mode is worth noting: the drift rate was overall higher for the intense signal in comparison to the isointense signal, but the temporal cue effects (signal minus no signal) remained a consistent magnitude across the STOAs regardless of intensity level. This further supports the result of McCormick, Redden, Lawrence, & Klein (2018) that these two modes are functionally independent of one another. This further emphasizes that researchers should adopt revised taxonomies that account for both endogenous and exogenous modes (Klein, 2022), and more temporal attention researchers consider the lesser-studied exogenous mode within their research designs.

As reported in Chapter 3, McCormick and Klein's temporal cueing task with intense and isointense signals revealed improved fidelity effects associated with both the endogenous and exogenous modes. Their temporal cueing task required participants to report the colour of a target stimulus which was presented very briefly (between 34 and 84msec). However, the mechanism behind these fidelity improvements could only be speculated. When consulting the current chapter's DDM, we can be confident in suggesting that the exogenous and endogenous modes of temporal attention, through intense warning signals and temporal cues, respectively, allowed participants to increase the rate at which target information accumulated. These results together strengthen the overall proposal of how the endogenous and exogenous modes of temporal attention impact the processing of information, as these are two distinct tasks (Chapter 3: a temporal cueing paradigm with a continuous response metric, Chapter 4: fixed-interval warning signal paradigm that requires discrimination responses) that produce theoretically compatible outcomes.

4.4.3 Future Directions

We exercise caution in the interpretation of our boundary-separation analysis given that the two no-signal conditions were so different across our intense and isointense signal conditions, a result of the intensity manipulation being between-subjects. The boundary-separation was higher in the ‘no-signal’ condition for participants who experienced intense signals, leading to larger boundary-separation effects across the STOAs. Behavioral differences generated by increases in the tonic, or baseline, levels of alerting (Posner, 2008) would be expected when a participant experiences frequent intense stimuli. A follow-up experiment that manipulates signal intensity within-participant would address this effectively. Adding more STOAs within this paradigm would also be informative on the time-course of boundary shifts and drift-rates.

Studies that have the interval between the signal and target fixed for extended durations are distinct from temporal cueing studies, in which the participant is cued to the likely STOA on each trial and may elicit different effects on information processing. When the interval is fixed for a run or block of trials, sequence effects, in which the response on the trial prior primes the current trial response, can increase the size of the cueing effect (Correa, et al, 2004). This means that in the context of alerting studies that use fixed intervals between the signal and the target, including the current study (McCormick et al., 2019), the behavioral effect does not represent purely volitional preparation. The current studies results should be contrasted with a follow-up diffusion analysis which looks at the effect of signal intensity in a cued-temporal attention paradigm. We do, however, anticipate that the general pattern of results from this current study would be replicated in this context, despite these methodological differences.

Another component of temporal attention which would be interesting in the context of diffusion modeling is hazard sensitivity. This has to do with the probability at which a target will appear at a time-point, which does not require explicit cueing. If a target is 80% likely to occur at one time point, and 20% at other time points, there are observed performance benefits at the more likely time point (Schoffelen, Oostenveld, & Fries, 2005). Interestingly, this temporal mechanism can benefit performance via subconscious influence (Janssen & Shadlen, 2005; see exogenous temporal expectations in Coull & Nobre, 2008). It would be interesting to test whether the same drift-rate and boundary effects were present at temporal intervals in which stimuli were more likely, but participants did not volitionally prepare. This would address the reported confounding of attention and expectation (Denison, 2024).

4.4.4. Conclusion

The endogenous mode of temporal attention was observed to improve the rate in which information accumulates, while the exogenous mode of temporal attention both improved the rate of information processing and shifted response criterion. This supports prior research on the volitional components of temporal attention and provides novel insight toward how the reflexive components of our attention system react to salient changes in the environment. This represents a departure from the dominant theory within the field over the last five decades (Posner, 1975), and will hopefully encourage researchers to consider both the endogenous and exogenous modes of temporal attention within their research to better understand how they uniquely contribute to our ability to allocate attention across moments in time.

CHAPTER 5: CONCLUSION

5.1 Contributions to our Understanding of the Modes of Temporal Attention

This dissertation began by distinguishing two modes of temporal attention. The endogenous mode involves the volitional allocation of attention to a point in time at which the participant expects a task-relevant event to occur. The exogenous mode involves a reflexive increase in arousal generated by a salient change in one's environment. Both modes contribute to the processing of task-relevant information. An important proposal for positioning the main research question of this dissertation is that these two modes are often confounded within research in the 'alerting' literature, a moniker which is used in the context of the Posnerian model of attention (Petersen & Posner, 2012), as well as in the 'temporal cueing' literature (Weinbach & Henik, 2012). In the alerting literature, a salient non-spatial cue is presented to warn participants of an upcoming target. There is often a fixed interval between the cue and the target that allows participants to effectively time their attention. In the temporal cueing literature, a cue informs participants of the likely temporal interval of the target on a particular trial, while also serving to saliently initiate the timing of that interval. Recent attempts to distinguish these modes within experimental paradigms have provided evidence that they are independent (McCormick et al., 2018), have distinct time courses (Denison et al., 2021), and have different influences on information processing and setting response criteria (Lawrence & Klein, 2013).

A multi-pronged approach was implemented in this dissertation to improve our understanding of how these two modes of attention in the temporal domain affect our mental processes. This was inspired in part by a failure to replicate the expected effects of the exogenous mode within a temporal cueing study (McCormick, Redden, and Klein, 2023). The converging evidence generated across Chapters 2, 3, and 4 challenge conventional theories on how temporal attention impacts the processing of information using the endogenous and exogenous modes, emphasizing the importance of a revised taxonomy. Chapter 2 involved running a meta-analysis inspired by Posner's theory of alerting (1975), using the data from 16 two-alternative forced choice studies across three foreperiod conditions that had a warning signal. These warning signal conditions were compared to a no warning signal condition. Posner theorized that alerting shifts the response criterion of a participant, so responses are generated faster without increasing the speed at which information accumulates. Posner's theory was informed by a seminal study that generated a speed-accuracy trade-off, in which participants became less accurate as response speed increased across several foreperiod conditions (Posner et al., 1973). The meta-analytic model indicated that warning signals generate large reaction time (RT) effects, in which signaled trials were faster than non-signaled trials, comparable in size to Posner and colleagues' original study (1973) when averaging across the included studies. However, the associated error rate (ER) effects were substantially smaller than Posner et al's (1973). More specifically, ER effects were smaller at the 200 and 400 millisecond (msec) foreperiod conditions, in contrast to the ER at 50 msec foreperiod condition. The outcome of this meta-analysis indicates that, at least at foreperiods of 200 and 400msec in which ER effects are small and RT effects are large, there is evidence of enhancement to the efficiency at which information is processed, generated by warning signals. Improvements to information processing may also be present at foreperiods of 50 msec, but there is likely also a stronger shift in response criterion at this interval. Differing contributions of the exogenous and endogenous modes across these foreperiods likely generate the shifts in performance. For example, the exogenous mode, elicited by the salient warning stimuli, would have a stronger influence at the 50msec condition in comparison to the 200 and 400msec foreperiods, whereas the endogenous mode would not reach its effective peak until the 200 and 400 msec foreperiods (Denison et al., 2021;

McCormick, Redden, & Klein, 2023). An important consideration in the context of recent publications that claim support of Posner's theory via empirical replications (McCormick et al., 2019) or re-analyses of past data (Klein, 2024) is that enhancements to information processing can still be present in the context of a speed-accuracy trade-off. One needs to evaluate the size of the speed and accuracy effects together and consider that small shifts in accuracy may not be able to account for large improvements in response speed. Our meta-analysis provides the clearest representation of this by generating the most likely ranges of effect-size based on the available literature. Although the meta-analysis in Chapter 2 suggests that a change in information processing efficiency can likely be generated by salient warning signals, we do not know whether this occurs only once endogenous temporal attention is nearing peak activation, or whether this also occurs at the shorter 50 msec signaled foreperiod, but is masked by a stronger shift in response criterion. Better isolation of these two modes of temporal attention is required to make the distinction in how they may differently impact performance and information processing stages.

Chapter 3 addressed how the two modes affect information processing, using a temporal cueing paradigm which required a continuous-accuracy judgement of a briefly presented coloured target. This allowed for a comparison of how endogenous and exogenous modes differently impact information processing efficiency. Because the target was presented for only a very brief duration, and the quality of the response was not impacted by how quickly the response was generated, as is the case in the 2-alternative forced choice tasks included in the meta-analysis (Chapter 2), where the target is presented until a response is generated, the fidelity measures provided insight into how information accumulates during the brief period of target presentation. Studies with similar research methods using briefly presented targets have suggested improvement to information processing speed via preparation that resembles the endogenous mode (Vangkilde, Coull, & Bundesen, 2012). We manipulated the presence of the exogenous mode within an endogenous cueing paradigm in two separate ways. In Experiment One, we utilized Lawrence and Klein's isointense signaling procedure. Temporal cues were presented at the beginning of a trial to indicate the likely interval between a signal and the target. A signal, which was either intense or isointense, indicated that the interval was starting. Isointense signals allow participants to prepare without a sudden change in salience, while intense signals add the influence of the exogenous mode. In Experiment Two, participants were presented with the temporal cue at the beginning of a trial and were then able to volitionally initiate the timed interval by pressing the spacebar. In this case, there was a condition in which no signal was presented, a condition in which the signal played at the initiation of the interval (effectively replicating the timing of when the intense signal occurred in Experiment 1), and a condition where the signal played 50 msec before the onset of a target.

Surprisingly, both the endogenous and exogenous modes generated improvements in colour-reporting accuracy, indicating that each mode generates increases in the efficiency of information processing. Prior research suggested that only the endogenous mode would generate improvements (Lawrence and Klein, 2013; see also Correa, Lupiãnéz, & Tudela, 2005; Vangkilde, Coull, & Bundesen, 2012; Denison, Heeger, & Carrasco, 2017). Response fidelity, which is a participant's accuracy of target colour encoding based on their colour-reporting, was improved by the exogenous mode at both 50 and 400-msec intervals between the signal and target as well. In combination with the results from Chapter 2, this suggested that the exogenous mode improves the efficiency of information processing to some degree, while also shifting the response criterion of participants, so that responses are generated faster. Although the results of this study provided important insight into the behavioural effects of endogenous and exogenous temporal mechanisms, showing that there are improvements to the efficiency in which information accumulates under the activation of both modes, the exact stages of information processing behind these improvements to performance are unknown. The improvements to response fidelity could be due to these modes impacting the rate at which information accumulates, or the onset of the decision-making process (or both). Additionally, in the context of the meta-analysis in Chapter 2, a criterion shift is likely also being generated by the exogenous mode on top of an improvement in information processing efficiency, to differing degrees across different foreperiods between the signal and the target. To uncover more detail on how the two modes of temporal attention impact information processing stages, more advanced behavioural analysis was required.

Chapter 4, a drift-diffusion model was applied to data from a prior replication of Posner, Klein, Summers, & Buggie (1973) which used Lawrence and Klein's signaling method (2013). This allowed for a more conceptually relevant contrast of how the endogenous and exogenous modes of temporal attention influence the processing of information. The parameters generated by a drift-diffusion model specifically address information processing efficiency, in comparison to just comparing the size and direction of speed and accuracy effects within the data. These parameters include drift rate, boundary separation, and non-decision time. The drift rate indicates the speed at which information accumulates toward a response threshold. Boundary separation is a measure of how much information needs to accumulate before the response threshold is met and indexes the speed/accuracy tradeoff. Non-decision time is the time to execute non-decision-related processes, including the time to initiate encoding and motor-response generation.

Based on Posner's theory (1975), and Lawrence and Klein's prior study (2013), the intense signal was expected to generate a shift in boundary separation, or the response criterion, without impacting the drift rate. However, the drift rate was larger in the intense signal condition than in the isointense signal condition, suggesting that the exogenous mode of alerting increases the rate at which target information accumulates. This was in addition to the improvement in drift rate generated by the endogenous mode. There was also evidence of a larger boundary separation when comparing intense signal and no-signal trials (in contrast with the same isointense signal contrasts), indicating that participants trade-off the accumulation of more information to inform their response for improved response speed. This trade-off of additional accuracy for speed suggests that the exogenous mode increases the rate at which information accumulates, while also shifting response-criteria. The shift in boundary separation observed within the intense signal condition supports the proposal that the criterion shifts in past studies likely masked evidence of an improvement in processing efficiency, at least at the shortest foreperiod intervals (as observed in Chapter 2), underscoring the need for future researchers to proceed with caution when using speed-accuracy trade-offs to assess information processing. The signal intensity drift rate effect also supports the view that the intense signal in Chapter 3 improved fidelity by increasing the amount of target information accumulated during the short target presentation interval.

Together, the chapters in this dissertation advance our understanding of how the modes of temporal attention impact the processing of information. Volitional preparation for an interval in time, or activation of the endogenous mode, improves the rate at which information accumulates, as indicated in past work (Chapters 2, 3, and 4; Correa, Lupiãnéz, & Tudela, 2005; Vangkilde, Coull, & Bundesen, 2012; Denison, Heeger, & Carrasco, 2017). The reflexive component of temporal attention that initiates in response to salient events, or the exogenous mode, also improves the rate at which information accumulates while additionally influencing the response criterion for when a response is generated (Chapters 2, 3, and 4). The effect of the exogenous mode on information processing is strongest around the time in which the exogenous system is proposed to peak, according to past models of temporal attention (Denison, Carrasco, and Heeger, 2021). Posner and his colleagues' proposal (1975; Posner, Klein, Summers and Buggie, 1973) that temporal attention does not impact the rate at which information accumulates is incorrect, when considering the research conducted in this dissertation that systematically analyzed the independent contributions of endogenous and exogenous temporal modes across various methodological and analytic procedures. Research supporting Posner's theory (McCormick et al., 2019; Klein, 2023) interpret the speed-accuracy trade-off between warning signal and no warning signal conditions as solely indicative of a criterion shift. However, the data across this dissertation suggests that both criterion shifts and improvements in information processing efficiency can occur simultaneously. Researchers interested in understanding how a manipulation impacts information processing should consider methods beyond speed-accuracy contrasts in a 2-Alternative Forced Choice paradigm.

It is important to recognize that studies that do not control for salient stimuli within a temporal cueing task (cues, signals, multiple targets) are potentially observing behavioral effects influenced by both endogenous and exogenous temporal attention. As reported, a significant portion of the temporal cueing literature, who report to be studying the endogenous mode, fail to control for how task features influence the activation of the exogenous mode (Weinbach and Henik, 2012). The behavioural effects obtained within these studies will vary depending on the time-course of task features (e.g., the interval between signals/cues and targets) as the closer a target is to a salient task-feature, the more the participant will be influenced by the exogenous mode. If the salient stimuli are presented equal distances from the target in both comparison conditions, the effect of cue validity should remain the same, as we have observed that there is independence between the exogenous and endogenous modes across these chapters, as well in past research (McCormick et al., 2018). However, in conditions where there are other task features, including multiple target stimuli, or alerting signals being compared to no signal conditions across different STOAs, this varying degree of influence of the exogenous mode will impact the replicability and consistency of an experiment's effects, if the researcher is not controlling for, or at least reporting on, how this component of temporal attention is involved in their task. Also, without considering the effect of the exogenous mode, researchers are missing out on a key mechanism of temporal attention that allows us to improve our processing of information, which is often elicited in the context of our daily lives. For this reason, researchers need to consult modern taxonomies of temporal attention to generate accurate and replicable research furthering our understanding of the mechanisms of temporal attention (Klein and Lawrence, 2012; Denison, 2024).

5.2 Future Directions

There are unique challenges in designing paradigms to study temporal attention. Having stimuli presented within a dynamic dimension, in contrast with a static dimension like space, allows for participants to attend multiple time-points during the span of a trial, as attention can be flexibly re-allocated during the interval in which targets can appear. As observed in Chapter 3, the RT effect sizes for temporal cues are generally quite small. While it is possible that the endogenous mode of temporal attention simply does not generate a large effect size, hazard sensitivity, the allocation of attentional resources based on event probability, certainly have an influence and may contaminate the effects at the invalid cue condition. Hazard sensitivity is defined as when participants attend to intervals in which stimuli are likely. When there are only a few possible intervals in which stimuli can be presented (most tasks involve a ‘short’ and ‘long’ interval, ours was 400msec and 1600msec), participants may be attending all possible target intervals to varying degrees, either as a strategic strategy that ensures no possible presentation interval goes unattended, or as a subconscious process (see Janssen & Shadlen, 2005). In this case, temporal cue effect sizes would be reduced because trials that are invalidly cued still have some level of temporal attention allocated to them, just to a lesser degree. In a recent review, Denison (2024) suggests that temporal attention, a task-relevant allocation of attention, and temporal expectation, a probabilistic mapping of the likelihood of stimulus presentation, are confounded within many temporal cueing paradigms. This applies to our temporal cueing designs, as the two time points (or three, in the case of Chapter 3, Experiment One) in which stimuli can be presented contain task-relevant information. This makes hazard sensitivity an effective mechanism for improving overall performance. Future research should investigate how these two processes, attention and expectation, interact with one another within tasks such as this one, as well as how they may differently impact information processing and response criteria. Deconfounding attention and expectation may result in more accurate representations of the endogenous temporal modes within temporal cueing tasks. Introducing more intervals in which target stimuli are presented, as well as more irrelevant stimuli which require participants to further rely on temporal cue information, may generate conditions which allow for better measurement of the endogenous mode, better isolating it from expectation effects. In the case of increasing the number of task-irrelevant stimuli which are presented in time, there are interesting results from the ‘attentional blink’ literature. The attentional blink is studied using a paradigm called the rapid serial visual presentation task, in which brief visual stimuli are presented in succession. Typically, there are two targets within the stream of stimuli that a participant must detect and report. When the two targets are presented in close temporal proximity to one another, participants often miss the second target due to a stage of information processing being occupied, hence the term ‘attentional blink’. When the second target is maintained at the same temporal position after the first target within a block, and participants are not informed of this position, there is no enhancement to the processing of the second stimulus. However, when cued to the likely time-point of the second target, representing the endogenous form of temporal attention, there are observed improvements in the accuracy of reporting of the second stimulus (Martens & Johnson, 2005). This methodological manipulation shows that it is possible to separate temporal expectation interference from temporal attention, as the target stimulus being repeated within the array at the same point does not enhance the processing of the stimulus in the attentional blink paradigm, but processing does improve when temporal attention is volitionally allocated.

If uncertainty regarding when a target is going to be presented is increased by introducing multiple intervals of presentation, this would reduce the predictability of stimulus onset would be presented, at least in the context of catch trials, and better capture the effect of the endogenous mode. Manipulating more intervals within a temporal cueing paradigm would also be valuable in generating more data on the time course of activation for the endogenous and exogenous modes across different tasks, to see how metrics of performance vary at different signal-target intervals. One avenue for doing this could be through using a dynamic cue procedure, in which the temporal cue communicates the likely interval through the length between its onset/offset. For example: if the likely interval between the start of a trial and the target being presented was 650msec, the visual stimulus would flash for 650msec, and then participants could initiate the interval. Participants could then be cued for any reasonable duration, and the cues would reduce uncertainty on when the target would be presented to a much higher degree than when there are only two possible target presentation intervals.

Our revised taxonomy for studying temporal attention, through the identification of endogenous and exogenous modes, is not exhaustive. There are several distinct mechanisms related to the allocation of attention across time that have been identified and that do not neatly fall into the endogenous and exogenous categories. This includes hazard sensitivity and sequence effects, which have been referenced in the context of some of the prior chapters. Researchers have only recently begun investigating the intricacies of temporal attention. It is important to consider the influence of all the distinct temporal mechanisms, and how they may influence various tasks, especially considering these mechanisms have been found to operate in tandem and either generate additive or interactive effects (Nobre & van Ede, 2018). Denison (2024) introduced the most comprehensive framework to categorize the mechanisms, which includes these various mechanisms identified by both Nobre & van Ede, as well as Klein (2018; 2022). This framework, which aims to "categorize performance fluctuations across time", includes three main categories: arousal, temporal, spatial, and feature-based (TSF) prioritization, and rhythmic processes. The two modes investigated within this dissertation, exogenous and endogenous temporal attention, fall into the arousal and TSF categories, respectively. There is utility in consulting both Denison's (2024) and Klein's (2022) categorizations when designing future research studies. Denison's organization of effects is certainly more exhaustive and includes prioritization across several different domains of attention. However, Klein's dichotomous distinction provides a clear starting point that is more closely aligned with the prior taxonomy used for decades of alerting research. Additionally, as stated, the endogenous and exogenous modes have been confounded within most paradigms studying temporal attention (Weinbach and Henik, 2012; Lawrence and Klein, 2013). With evidence of the independence of the endogenous and exogenous modes (McCormick et al., 2018) and how they impact information processing efficiency and response criterion, it is worth looking at implementing procedures that at least consider their impact on behaviour effects, if not controlling and manipulating their influence.

The chapters in this dissertation contribute evidence through distinct measures, that include different dependent variables, paradigms, or analysis techniques. However, there is still quite a bit of homogeneity involving task structure, which is common across the literature. Temporal attention can affect different mental operations based on task demands, including motor preparation (Coull, Frith, Büchel, & Nobre, 2000), and various stages of information processing (Denison, Heeger, & Carrasco, 2017; Vangkilde, Coull, and Bundesen, 2012; Correa, Lupiáñez, & Tudela, 2005; our results from Chapter 3 and 4). Diversifying the tasks and behavioural measures recorded will generate more informative converging evidence toward classification of the mechanisms of temporal attention than when there is ridged methodological consistency. If a mechanism of attention is proposed to affect a particular aspect of information processing based on a behavioural result, it should do so across many contexts and experimental manipulations (at least for the theory to be useful in informing us on how attention operates). Attempting to better control the influence of all the components of temporal attention identified so far is one way to introduce a diversity of methodology (Nobre & van Ede, 2018; 2023; Denison, 2024). It is also worth considering how temporal attention is applied outside of the lab, and the ecological validity of our constructs and measures. While it has been important to isolate temporal attention from spatial attention in lab manipulations, we often use temporal attention to aid us in interacting with dynamic spatial environments. One clear example is within sport.

When operating in a high-velocity environment, hockey players must rely on a variety of temporal cues for decision-making and motor planning: goaltenders watch for when players wind up for a shot to determine when the puck will reach the net, and players have to time passes so they wind up where another player will be, not where they are currently. It may be telling to study athletic experts in timing within noisy, demanding environments to see how preparation for moments in time impacts perceptual abilities. Additionally, a common real-world task that involves both modes of temporal attention is driving a motor vehicle. Our exogenous temporal mode is activated whenever our car's monitoring system detects braking is required, or when another car horn indicates that our attention is required. Additionally, the endogenous mode is important for timing lane changes and merging on the highway. Errors within these tasks come at a very high cost, making it critical to determine whether performance on our in-lab manipulations of endogenous and exogenous temporal attention are associated with better driving outcomes within a simulated driving environment. If lab measures of endogenous and exogenous modes of temporal attention were directly associated with driving behaviours, more research could go into which disorders of attention may pose a risk to driving safety based on whether they impact temporal attention mechanisms.

Finally, it would be worthwhile to further explore the clinical relevance of the modes of temporal attention, and whether various disorders generate distinct limitations in activation. The current Attention Network Task and its variants use either a spatially neutral visual cue or auditory warning signal, at a consistent and predictable foreperiod, to measure alerting (Fan et al., 2002). It is possible that exploring both the exogenous and endogenous modes of temporal attention across several time courses may be able to differentiate performance to identify different disorders of attention. This has been observed for MS and ASD patients, where each disorder differently impacts the size of endogenous and exogenous spatial cueing effects (Tabibian et al., 2023; Renner, Grofer-Klinger, & Klinger 2006). If different disorders of attention were associated with differing effects on the endogenous and exogenous modes of temporal attention, this could lead to the development of better diagnostic measures, while also informing researchers on the mechanistic components of temporal attention. Distinguishing between the endogenous and exogenous modes across the different domains of attention is a feature of a recently introduced variant of the ANT, the Combined Attention Systems Test (Lawrence, 2018; also Good, 2023).

5.3 Final Remarks

The work presented in this dissertation demonstrates that both the endogenous and exogenous modes of temporal attention increase the rate at which information is processed. The exogenous mode additionally generates a shift in response criterion, such that participants respond faster at a cost to additional accuracy. The shift in response criterion likely masked evidence of an increase in perceptual efficiency in past research using a 2-alternative forced choice paradigm. These conclusions have been supported through evidence generated by multiple research methods, including a meta-analysis, an empirical study on temporal cueing and response fidelity, and a drift diffusion analysis contrasting drift rate and boundary separation for intense and isointense signals. Future research on the mechanisms of temporal attention should consider the independent contributions of these modes in an attempt to generate more accurate representations of behavioural effects and their theoretical implications.

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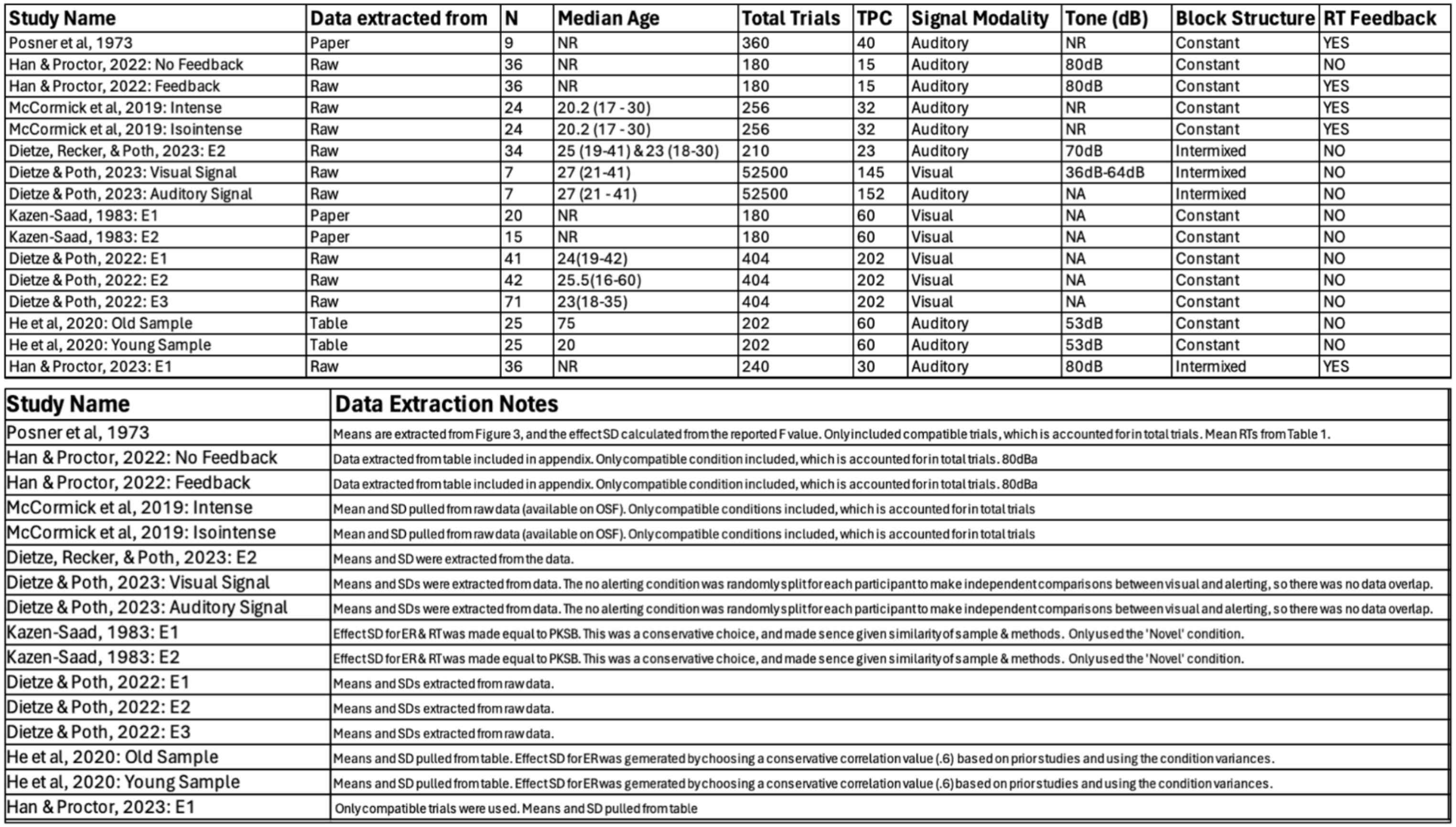
Appendix A

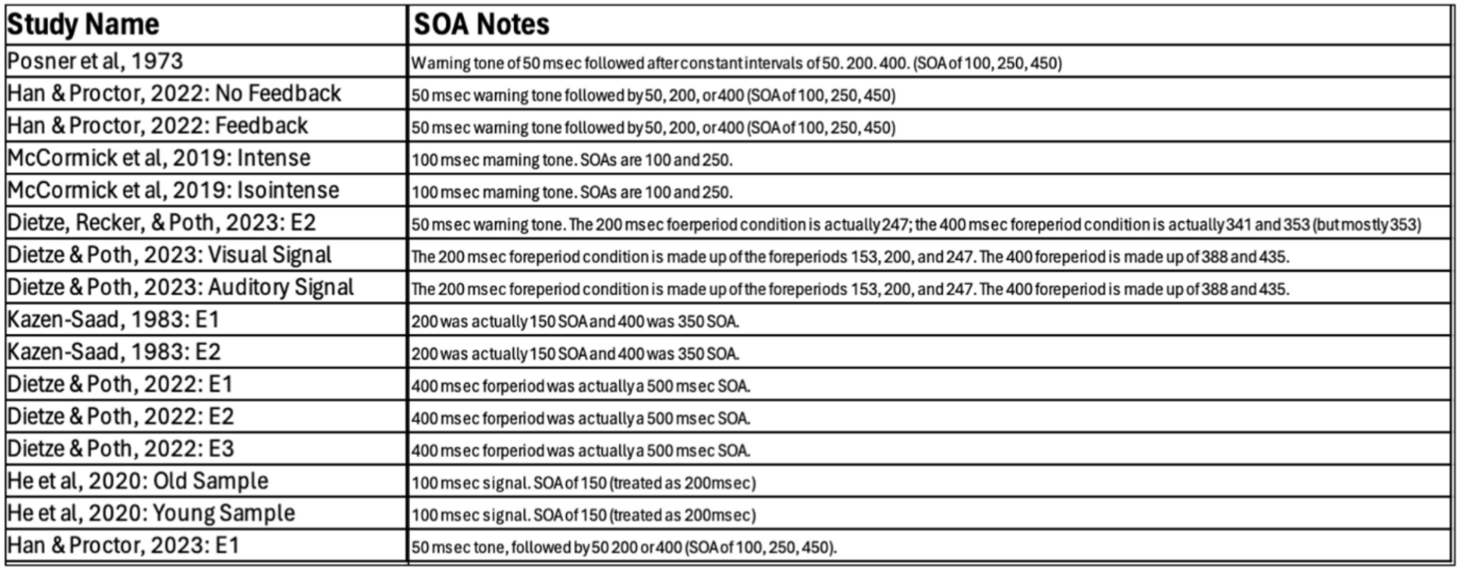
Appendix Table A1. Design features for experiments included in the meta-analysis



Study Name	Data extracted from	N	Median Age	Total Trials	TPC	Signal Modality	Tone (dB)	Block Structure	RT Feedback
Posner et al, 1973	Paper	9	NR	360	40	Auditory	NR	Constant	YES
Han & Proctor, 2022: No Feedback	Raw	36	NR	180	15	Auditory	80dB	Constant	NO
Han & Proctor, 2022: Feedback	Raw	36	NR	180	15	Auditory	80dB	Constant	YES
McCormick et al, 2019: Intense	Raw	24	20.2 (17 - 30)	256	32	Auditory	NR	Constant	YES
McCormick et al, 2019: Isointense	Raw	24	20.2 (17 - 30)	256	32	Auditory	NR	Constant	YES
Dietze, Recker, & Poth, 2023: E2	Raw	34	25 (19-41) & 23 (18-30)	210	23	Auditory	70dB	Intermixed	NO
Dietze & Poth, 2023: Visual Signal	Raw	7	27 (21-41)	52500	145	Visual	36dB-64dB	Intermixed	NO
Dietze & Poth, 2023: Auditory Signal	Raw	7	27 (21 - 41)	52500	152	Auditory	NA	Intermixed	NO
Kazen-Saad, 1983: E1	Paper	20	NR	180	60	Visual	NA	Constant	NO
Kazen-Saad, 1983: E2	Paper	15	NR	180	60	Visual	NA	Constant	NO
Dietze & Poth, 2022: E1	Raw	41	24(19-42)	404	202	Visual	NA	Constant	NO
Dietze & Poth, 2022: E2	Raw	42	25.5(16-60)	404	202	Visual	NA	Constant	NO
Dietze & Poth, 2022: E3	Raw	71	23(18-35)	404	202	Visual	NA	Constant	NO
He et al, 2020: Old Sample	Table	25	75	202	60	Auditory	53dB	Constant	NO
He et al, 2020: Young Sample	Table	25	20	202	60	Auditory	53dB	Constant	NO
Han & Proctor, 2023: E1	Raw	36	NR	240	30	Auditory	80dB	Intermixed	YES

Study Name	Data Extraction Notes
Posner et al, 1973	Means are extracted from Figure 3, and the effect SD calculated from the reported F value. Only included compatible trials, which is accounted for in total trials. Mean RTs from Table 1.
Han & Proctor, 2022: No Feedback	Data extracted from table included in appendix. Only compatible condition included, which is accounted for in total trials. 80dBa
Han & Proctor, 2022: Feedback	Data extracted from table included in appendix. Only compatible condition included, which is accounted for in total trials. 80dBa
McCormick et al, 2019: Intense	Mean and SD pulled from raw data (available on OSF). Only compatible conditions included, which is accounted for in total trials
McCormick et al, 2019: Isointense	Mean and SD pulled from raw data (available on OSF). Only compatible conditions included, which is accounted for in total trials
Dietze, Recker, & Poth, 2023: E2	Means and SD were extracted from the data.
Dietze & Poth, 2023: Visual Signal	Means and SDs were extracted from data. The no alerting condition was randomly split for each participant to make independent comparisons between visual and alerting, so there was no data overlap.
Dietze & Poth, 2023: Auditory Signal	Means and SDs were extracted from data. The no alerting condition was randomly split for each participant to make independent comparisons between visual and alerting, so there was no data overlap.
Kazen-Saad, 1983: E1	Effect SD for ER & RT was made equal to PKSB. This was a conservative choice, and made sence given similarity of sample & methods. Only used the 'Novel' condition.
Kazen-Saad, 1983: E2	Effect SD for ER & RT was made equal to PKSB. This was a conservative choice, and made sence given similarity of sample & methods. Only used the 'Novel' condition.
Dietze & Poth, 2022: E1	Means and SDs extracted from raw data.
Dietze & Poth, 2022: E2	Means and SDs extracted from raw data.
Dietze & Poth, 2022: E3	Means and SDs extracted from raw data.
He et al, 2020: Old Sample	Means and SD pulled from table. Effect SD for ER was gemerated by choosing a conservative correlation value (.6) based on prior studies and using the condition variances.
He et al, 2020: Young Sample	Means and SD pulled from table. Effect SD for ER was gemerated by choosing a conservative correlation value (.6) based on prior studies and using the condition variances.
Han & Proctor, 2023: E1	Only compatible trials were used. Means and SD pulled from table

Appendix Table A2. Distinctions in foreperiods across included experiments in the meta-analysis



Study Name	SOA Notes
Posner et al, 1973	Warning tone of 50 msec followed after constant intervals of 50. 200. 400. (SOA of 100, 250, 450)
Han & Proctor, 2022: No Feedback	50 msec warning tone followed by 50, 200, or 400 (SOA of 100, 250, 450)
Han & Proctor, 2022: Feedback	50 msec warning tone followed by 50, 200, or 400 (SOA of 100, 250, 450)
McCormick et al, 2019: Intense	100 msec marning tone. SOAs are 100 and 250.
McCormick et al, 2019: Isointense	100 msec marning tone. SOAs are 100 and 250.
Dietze, Recker, & Poth, 2023: E2	50 msec warning tone. The 200 msec foerperiod condition is actually 247; the 400 msec foreperiod condition is actually 341 and 353 (but mostly 353)
Dietze & Poth, 2023: Visual Signal	The 200 msec foreperiod condition is made up of the foreperiods 153, 200, and 247. The 400 foreperiod is made up of 388 and 435.
Dietze & Poth, 2023: Auditory Signal	The 200 msec foreperiod condition is made up of the foreperiods 153, 200, and 247. The 400 foreperiod is made up of 388 and 435.
Kazen-Saad, 1983: E1	200 was actually 150 SOA and 400 was 350 SOA.
Kazen-Saad, 1983: E2	200 was actually 150 SOA and 400 was 350 SOA.
Dietze & Poth, 2022: E1	400 msec forperiod was actually a 500 msec SOA.
Dietze & Poth, 2022: E2	400 msec forperiod was actually a 500 msec SOA.
Dietze & Poth, 2022: E3	400 msec forperiod was actually a 500 msec SOA.
He et al, 2020: Old Sample	100 msec signal. SOA of 150 (treated as 200msec)
He et al, 2020: Young Sample	100 msec signal. SOA of 150 (treated as 200msec)
Han & Proctor, 2023: E1	50 msec tone, followed by 50 200 or 400 (SOA of 100, 250, 450).

Appendix Figure A1. Funnel plots run without moderators in model. The x-axis represents the effect sizes. The line is the mean effect size across all experiments, the white triangle represents the likely values across the various standard error values (y-axis). In non-biased fields, experiments should be arranged symmetrically around the center line. Because many of these papers come from the same researchers, and we want to be able to detect possible 'biases' based on this, points are marked based on which author published the study. Experiments that generated larger mean effect values are labeled.