

**CONTRIBUTIONS OF ATTENTIONAL MECHANISMS TO URGENT
PERCEPTUAL DECISION MAKING**

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LIST OF ABBREVIATIONS

ART- accelerated race to threshold

CS - compelled saccade

CAS - compelled antisaccade

FEF - frontal eye field

ms - milliseconds

NHP - non-human primate

rPT - raw processing time

SOA - stimulus onset asynchrony

TPJ - temporoparietal junction

ABSTRACT

In daily life, our visual system receives constant input from our environment. Visual attention is the mechanism by which we select information from the visual scene to dedicate our limited computational resources to processing further. Traditionally, tasks aimed at uncovering how these mechanisms drive perceptual decision-making have implemented a rigid structure, impacting their generalizability to more natural viewing conditions. To address this limitation, we have developed SpotChase, a gamified task aimed to replicate natural viewing conditions more faithfully by removing the structure imposed in traditional tasks and keep participants engaged by including a scoring system. The present study aimed to use SpotChase as a means to explore how attentional mechanisms interact and contribute to our decision of where to look next in a more dynamic environment. The behavioral measure of interest, the tachometric curve, served as a means to compare this paradigm to traditional trial-based tasks used previously by our lab. What we found is that SpotChase is both able to replicate findings from traditional tasks, as well as uncover other previously unobserved behavioral phenomena. This establishes SpotChase as a viable platform for additional investigation, and possible adaptation as a clinical tool.

Introduction

Background:

Throughout daily life, our visual system receives a constant stream of input from our environment. Due to our limited computational resources on hand, this wealth of information is simply too much to process in full, and often contains information that is not relevant to our goals, or pertinent to our immediate survival. Visual attention is the process by which we are able to sort through this information, allocating further processing and computation to those objects in visual space that serve to aid in our behavioral goals, or represent relevant changes in our environment (Carrasco, 2011; Lindsay, 2020). This direction of attention can be further characterized into overt and covert components. Overt refers to the direction of gaze, and foveation, on a target. As the fovea represents the section of the retina that produces the highest visual acuity and therefore is crucial for high-resolution processing. Covert attention is the process by which attention is allocated to a location in space without a rapid eye movement (saccade) to that location. Here I will be focusing on the exogenous and endogenous components of covert spatial attention as well as the effects of prior experience on visual search.

When confronted with a visual scene, our gaze is often drawn towards items that pop out from the background, take, for example, a lone orange which stands out in a bushel of red apples. This capture of our attention is driven by the salience of the relevant stimulus. Multiple features of a stimulus can contribute to its salience. These include the color, motion, orientation, and size of the stimulus (Wolfe and Horowitz, 2017; Itti and Koch, 2001). This bottom-up, or exogenous, processing is deployed involuntarily, and is

transient, rapidly responding to salient stimuli and subsiding shortly thereafter (Carrasco, 2011). This exogenous mechanism may serve the vital evolutionary function of quickly alerting an organism to changes in the environment that may be behaviorally relevant, an adaptation that may be crucial in survival situations (Carrasco, 2011).

The automatic and transient properties of exogenous attention are complemented by the volitional and sustained nature of endogenous, or bottom-up, attention. This cognitive function is crucial as it allows us to be more than responsive agents, reacting always and only to salient events in the periphery. We are capable of establishing behavioral goals and deploying attention to gather information in pursuit of these goals. Endogenous attention is the mechanism by which we attend to objects in our environment that are behaviorally relevant to our goals (Theeuwes, 2010). Say for example you are looking for a friend at a crowded event and are aware of the fact that they are wearing a gray shirt. With this knowledge, you can scan the crowd for gray objects until you achieve your goal of locating your friend by matching what you perceive in the environment with the internal representation of your goals. This type of willful deployment of attention to achieve some goal lags behind that of exogenous attention, taking longer to deploy, and capable of being sustained for longer durations (Carrasco, 2011).

It has become clear, however, that these exogenous and endogenous mechanisms are necessary, but not sufficient in, explaining observed behavioral phenomena where visual selection is, seemingly, not driven by either internal goals or stimulus salience. This has been observed in various behavioral tasks (Wolfe and Horowitz, 2017). This implicates yet another factor at play in the decision of where to direct attention in space.

One potential source of this phenomenon are history effects or prior experiences that biases our current selection behavior (Awh, Belopolsky, & Theeuwes, 2012). For instance, completion of a task in which a green cue is the target may result in lingering effects on a task in which the green cue is a distractor. These factors: exogenous attention, endogenous attention, and history effects, are thought to be the driving forces in our selection of where to direct visual attention. What has been lacking until recently are task paradigms capable of tracking the perceptual decision of where to look on a timescale that captures the interactions of these mechanisms.

Innovative task design:

Exogenous responses to salient stimuli occur rapidly, typically on a timescale of 10-30ms, and the neural responses caused by these events are not substantial enough to cause an overt response independently of an ongoing motor plan (Salinas and Stanford, 2021). For this reason, traditional eye-tracking paradigms have failed to capture the true contributions of exogenous attention to saccadic decisions as these types of tasks typically implement a structured task design, require a period of fixation, and routinely take upwards of 1 second for each trial. This design, effectively, nullifies the contributions of exogenous attention to decision making and neglects the crucial fact that in natural viewing conflicting motor plans are constantly being produced. As a means to address these shortcomings, Stanford et al. (2010) developed and implemented urgent versions of more traditional visuomotor tasks by removing the strict serial order of events, allowing for the examination of how perception drives decision making when motor plans are ongoing. This is known as the compelled saccade (CS) task as participants are compelled to make a decision as perceptual evidence is accumulating and

motor plans are ongoing. One distinct advantage of urgent tasks over traditional nonurgent tasks is that they allow for the calculation of processing time, a measure of how long a participant had to view the relevant visual information before a decision was made. This measure is much more informative than the traditional response time that it is used in nonurgent tasks and allows for the examination of the evolution of perceptual decision-making like never before.

The tachometric curve, a psychophysical measure that tracks perceptual performance as a function of processing time, provides a metric by which to observe the attentional contributions to urgent decision making. This is accomplished by analyzing perceptual performance across the processing times corresponding to the deployment of exogenous and endogenous attention. Perhaps the starkest example of this metric is the tachometric curve produced from participant data recorded during the compelled antisaccade (CAS) task which allows for a clear dissociation between exogenous and endogenous contributions (Salinas et al. 2019; Stanford and Salinas 2021; Goldstein, Stanford, & Salinas, 2022). The initial stage of this curve consists of early processing times of less than roughly 90 ms. During this early stage, participants do not have sufficient time to view the stimulus, and chance level performance reflects this. Following this, the influence of the cue emerges as a steep decline in performance is observed in a window of ~90-140 ms and implicates an initial capture of attention caused by the salience of the appearing cue. This brief drop in performance is followed by a period of recovery, and eventual consistent near-perfect performance attributable to there being enough time for endogenous factors to cause an eye movement away from the

distractor, resulting in a correct response. The tachometric curve captures the temporal evolution of these processes with unprecedented resolution.

While urgent versions of these visuomotor tasks have provided a means to uncover the true interplay between attentional mechanisms, there are still adaptations that would serve to create a task that better replicates natural viewing conditions. This objective led to the development of SpotChase, a gamified task that combines urgent versions of the compelled saccade and compelled antisaccade tasks. The first key alteration made for SpotChase was the elimination of intermediate fixation periods between trials. This allows the participant to continuously plan and execute saccades, which more closely aligns with natural viewing where a saccade is executed every ~250 ms. To achieve this, trials must alternate between horizontal, where targets appear on the left and right of the screen, and vertical trials where targets appear at the top and bottom of the screen. A second crucial alteration is that participants do not complete blocks of predetermined trial amounts, as is the case in trial-based tasks, but rather they complete 'runs' each lasting 60-90 seconds allowing the participants to make as many choices as possible. To induce urgency, and keep participants engaged, a scoring system is implemented. This scoring system takes into account both the overall accuracy and number of trials completed and is provided to the participant at the end of each run to incentivize a strategy that strikes a balance between speed and accuracy.

The main objective of SpotChase is to develop a highly modifiable platform that allows for the investigation of the contributions of exogenous, endogenous, and history effects on perceptual performance in a more naturalistic setting. This is the basis for the three experiments that will be put forth, as well as future investigations. The measure of

interest for SpotChase will once again be the tachometric curve that has been used in urgent trial-based versions of similar tasks. The nature of SpotChase is such that we will still be able to calculate the two essential measures, raw processing time (rPT) and accuracy, while avoiding the limitations that trial-based tasks impose. Using tachometric curves, we will be able to extract key information to determine how these factors contribute to perceptual decision making and provide a behavioral framework by which to explore the neural mechanisms underlying such decisions.

Neural Underpinnings:

It has become increasingly clear through lesion, electrophysiological, and imaging research, that the process of orienting attention in visual space is dependent on an interplay between subcortical structures, sensory cortices, and an array of other cortical regions (Kastner and Ungerleider, 2000; Baluch and Itti, 2011). Imaging work, in particular, has led to the discovery of a subset of cortical areas known as the frontoparietal network, whose activity is implicated in the deployment of attention. This network is, broadly, separated into ventral and dorsal components, with dorsal regions being largely associated with the voluntary deployment of attention (top-down), and ventral regions being involved in the process of orienting to salient stimuli in the environment (bottom-up) (Vossel, Geng, & Fink, 2014; Corbetta and Shulman, 2002). This conceptual framework has guided further research into elucidating the precise neural mechanisms within each of these regions that coordinate these phenomena, and how they may contribute to our understanding of how these computations are carried out.

Within the frontoparietal network, various structures and cortical regions have been further explored using a variety of methods in a variety of animal models. This has

been crucial in furthering our knowledge of the distinct contributions these regions put forth in driving behavior. Key cortical regions implicated in bottom-up, saliency driven, attention include, in particular, the right ventral frontal cortex, and temporoparietal junction (TPJ) while purported regions supporting the top-down deployment of attention include the frontal eye fields (FEF) and intraparietal sulci (Corbetta and Shulman, 2002; Baluch and Itti, 2011). While this dorsal-ventral dichotomy is broad, oversimplified, and incomplete in capturing the rich interplay of neuronal activity underlying attention, there is still utility in making these overarching distinctions so that further work may resolve the neural mechanisms at play within these regions with higher precision. One region that will be discussed further here is the primate frontal eye field.

Work by Stanford, Salinas and colleagues has explored the mechanisms in the frontal eye fields during the aforementioned urgent task conditions using single-unit recordings in non-human primates (NHPs) (Stanford, Shankar, Massoglia, Costello & Salinas, 2009; Scerra, Costello, Salinas & Stanford, 2019; Costello, Zhu, Salinas & Stanford, 2013). This work has served to elucidate the function of distinct neuronal types in the FEF and how perception interacts with motor plans that ultimately culminate in a saccade. The prior belief was that visual cells within the FEF respond to external stimuli based on behavioral relevance, this, in turn, transforms the activity of motor cells to prepare a saccade to that location (Schall, 2015; Murray, Jaramillo & Wang, 2017). This paradigmatic view imposes a strict serial order of events in which perception always informs movement. In urgent tasks, however, there is not always time for perception to precede the decision of where to look. It has been established that visual activity within the FEF is not requisite for correct motor plans to be implemented and may only be

responsible for signaling saliency as opposed to other features (Costello, Zhu, Salinas & Stanford, 2013; Scerra, Costello, Salinas & Stanford, 2019).

Neurophysiological findings from oculomotor circuits such as those found in the FEF provide insight into the neural mechanisms that correspond to behavioral and conceptual interpretations of attentional phenomena. One way this is accomplished is through computational modeling. One such example is the accelerated race-to-threshold (ART) model developed by Salinas, Stanford and colleagues, a physiologically feasible model that replicates the rich array of behavioral findings from urgent behavioral tasks with great fidelity (Stanford and Salinas, 2021; Salinas and Stanford, 2013; Salinas et al., 2010). This model serves to provide a mechanistic understanding of how these processes unfold and allows for predictions to be made about various experimental alterations. Of particular relevance to this study are the characteristic difference between prosaccade and antisaccade performance predicted by the model as these are the trial types implemented in SpotChase (Goldstein, Stanford, & Salinas, 2022). This mechanistic understanding is guided by the ample research into the neural underpinnings of these processes and serves to guide the rational for, and predictions about, the following experiments.

Materials and Methods

Subjects and setup:

Subjects were 11 healthy human volunteers, 3 male and 8 female, with a median age of 28 ranging between 22-57. Participants were recruited from the Wake Forest School of Medicine and the surrounding Winston-Salem area. All participants had normal to corrected-to-normal vision. Each participant provided informed written consent before the experiment. All experimental procedures were approved by the Institutional Review Board (IRB) of Wake Forest School of Medicine.

Experiments took place in a dimly lit room. Participants sat in an adjustable chair, with their chin and forehead supported, and were presented stimuli on a VIEWPixx LED monitor (VPixx Technologies Inc., Saint Bruno, Quebec, Canada; 1920 x 1200 screen resolution, 120 Hz refresh rate, 12-bit color) at a distance of 57 cm. Participants' eye movements were tracked using an EyeLink 1000 infrared camera and tracking system (SR Research, Ottawa, Canada; 1000 Hz sampling rate). In this experiment, the presentation of stimuli and data collection were controlled using custom Matlab scripts and the Psychtoolbox 3.0 package (Brainard, 1997; Kleiner, 2007).

Behavioral tasks:

Variants of SpotChase with different stimuli, rules, or task parameters, are referred to as 'levels'. The first level completed by participants in all experimental conditions, level 10, served as a baseline measure for performance. Level 10 consisted of interleaved prosaccade and antisaccade trials occurring randomly and at the same rate. A schematic of a possible sequence of events for level 10 is shown in Figure 1a. Each 90 second block, or run, of SpotChase began with participants fixating on a red dot presented at the

top center of the screen. The offset of the fixation target was followed by a horizontal trial, in which targets appeared on the left and right of the screen. At the onset of each trial, both targets appeared yellow. The onset of the two yellow targets was followed by a randomly selected stimulus onset asynchrony (SOA) drawn from a range of 50-300 ms and segmented into 50 ms increments. Following the SOA, one of the targets then switched to red or blue.

The scoring convention for this condition was such that red dots were worth more than yellow dots which were, in turn, worth more than blue dots. This indicated to participants that they were to look towards any cue that turned red (akin to making a prosaccade to a salient stimulus) and away from any blue cue (akin to making an antisaccade away from a salient stimulus). Scoring was based on a combination of the number of choices made and the accuracy of those choices. This dual scoring system discouraged participants from making rapid guesses or waiting too long to make a selection, two potential pitfalls in this paradigm. A choice was considered made when participants made a saccade into one of the response windows surrounding the left or right target. This choice was then followed by an intertrial interval of 150 ms, after which a vertical trial appeared with targets at the top and bottom of the screen, and the same series of events started over. Horizontal and vertical choices continued to alternate as participants made choices throughout the 90-second duration of the run.

Experiment 1: Manipulation of Task Statistics

Upon completing level 10, the 4 participants in Experiment 1 completed a series of additional variations, or levels, to assess the effects of task statistics on performance as compared to baseline performance. The first four variations completed by participants

varied the frequency with which trial types occurred. For instance, in level 73, prosaccade (red-yellow) trials occurred at a rate of 3:1 compared to the antisaccade (blue-yellow) trials. This bias was further increased in level 74, in which prosaccade trials outnumbered antisaccade trials 6:1. For levels 83 and 84, these ratios were preserved but the bias was reversed, meaning that in level 83, antisaccade trials occurred at a rate of 3:1 compared to prosaccade trials, and in level 84 antisaccade and prosaccade trials occurred at a ratio of 6:1. Upon completing these variations, participants performed the baseline condition twice more. In the first, participants were informed that anti saccade trials would be weighted more heavily in calculating their score, while in the second, they were told pro saccade trials would be worth more. This served to incentivize enhanced performance on one trial type over the other and allowed for the quantification of differences in performance caused by the top-down manipulation of task rules.

Experiment 2: Manipulation of Luminance

The 7 participants in experiment 2, completed level 50, a variation of SpotChase, aimed at exploring the effects of cue luminance on task performance (Fig. 1b). In level 50, the task dynamics were the same as in the baseline condition. Participants were told to saccade towards red cues and away from blue cues. The key manipulation in this experimental condition was the luminance of the targets and cues. The initial targets appeared as two low-luminance yellow targets. After the SOA, the informative cue changed to a low-luminance red or blue, while the non-informative target changed to a high-luminance yellow. This manipulation served to further elucidate the effects of stimulus salience on the early, involuntary, exogenous capture of attention.

Experiment 3: Manipulation of Covert Spatial Attention

7 participants also completed experiment 3, which comprised two more variations of Spotchase, levels 90 and 91. As for our other manipulations, the task rules remained the same: saccade towards red and away from blue. The key distinction was that in level 90, participants were informed that the informative cue (red or blue), would always appear at the top location on vertical trials and on the left in horizontal trials. In level 91, the fixed cue locations were shifted to the bottom and right locations. The rationale for this manipulation was to assess the effects on task performance of allocating covert attention to these locations.

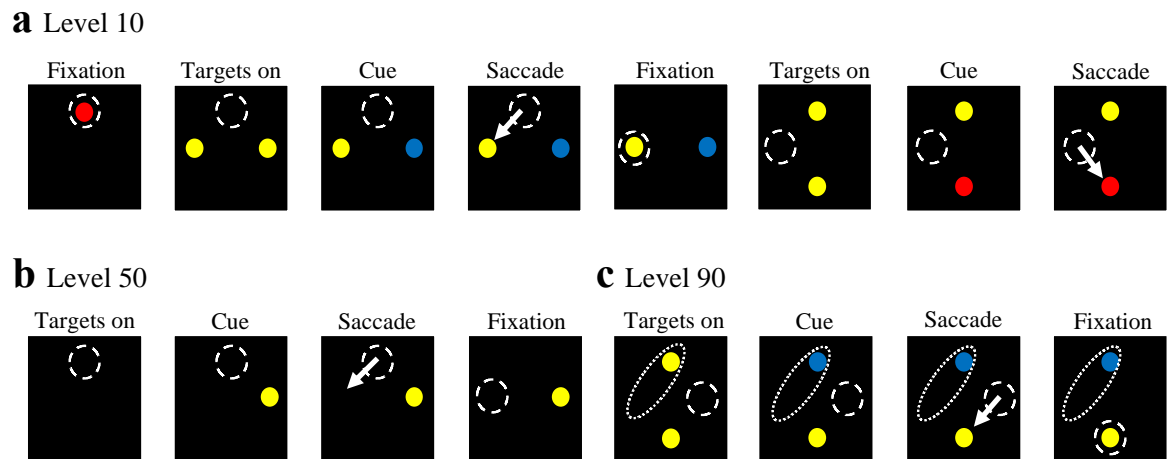


Figure 1. Schematic representation of levels of SpotChase. **a**, Sequence of events for level 10. This level begins with a period of fixation followed by the appearance of two yellow horizontal targets. After a variable gap, one target switches to blue or red prompting participants to make an antisaccade or prosaccade respectively. Once a choice is made, a vertical trial appears, and the process repeats. **b**, Level 50 representative trial. Targets appear as low luminance yellow. Following a gap, a low luminance informative cue and high luminance non-informative cue appear. **c**, Level 90. Participants are informed that informative cues will always appear on top or left. Dotted line indicates deployment of covert attention to those locations, dashed line indicates locus of overt attention.

Data Analysis:

All data analyses were performed using custom Matlab Scripts (The MathWorks, Natick, MA). The main psychophysical measure, the tachometric curve, was computed by calculating the rPT for each trial. Trials analyzed included both choices where a saccade was made directly into a response window, and those with intermediate saccades (typically to the center of the screen), as this simply corresponded to a choice with a higher processing time. Processing time was calculated by subtracting the SOA from the reaction time, so, in accordance with its original definition, the rPT corresponded to the time the participant had to view the cue before a selection was made. The data were sorted into rPT bins that were 21 ms wide bins and were shifted every 1 ms along the processing time axis. The tachometric curve consisted of the fraction of correct responses in each bin. Continuous analytical functions were then used to fit the empirical tachometric curves as described in earlier studies (Salinas et al., 2019; Goldstein et al., 2022). This allowed for the quantification of the participants' perceptual performance, and also served as the foundation for further analyses based on key parameters calculated from these functions including the rise point for prosaccade and antisaccade trials, the drop point for antisaccade curves, and overall asymptotic performance.

Results

Baseline:

In general, the results from the baseline version (level 10) of SpotChase faithfully replicated the characteristic patterns observed in a trial-based version of a similar task by Goldstein et al. (2022). This is clearly demonstrated when analyzing the tachometric curves generated from cumulative participant datasets (Fig. 1a). At early processing times (<100 ms), performance remains at chance levels due to there being insufficient time for the participant to develop an informed perceptual judgment upon which to act. This period is followed shortly thereafter by a window of processing times (~100-180 ms) where exogenous attention is automatically captured by the salience created by the onset of the cue. This window of exogenous capture impacts performance differentially depending on the trial type. For prosaccade trials, there is a steep increase in performance as the exogenous capture is aligned with the color-based value of the cued target. The inverse is seen for antisaccade trials, in which this exogenous capture results in a substantial drop in performance. Succeeding this epoch of exogenous capture, participants reach asymptotic performance. This indicates that with ample processing time, they can consistently execute correct decisions driven by top-down mechanisms.

Two comparisons were made from these data. The first was between the rise point of the prosaccade curve and the drop point of the antisaccade curve (Fig. 1b). Although the general trend observed by Goldstein et al. was preserved, significance was not reached, possibly due to participant variability or changes in the nature of the task. The second comparison was made between the probability of exogenous capture on antisaccade trials for each participant and the rise point of the corresponding curves (Fig.

1c). Again, this relationship did not reach significance suggesting that these two measures are under the influence of distinct mechanisms with bottom-up attention driving the capture, and top-down mechanisms governing the rise point. Overall, behavioral findings from the baseline version closely replicate those obtained from a preceding trial-based version of a similar urgent pro- and antisaccade task. This served to validate SpotChase as a paradigm capable of revealing contributions of distinct attentional mechanisms to perceptual performance.

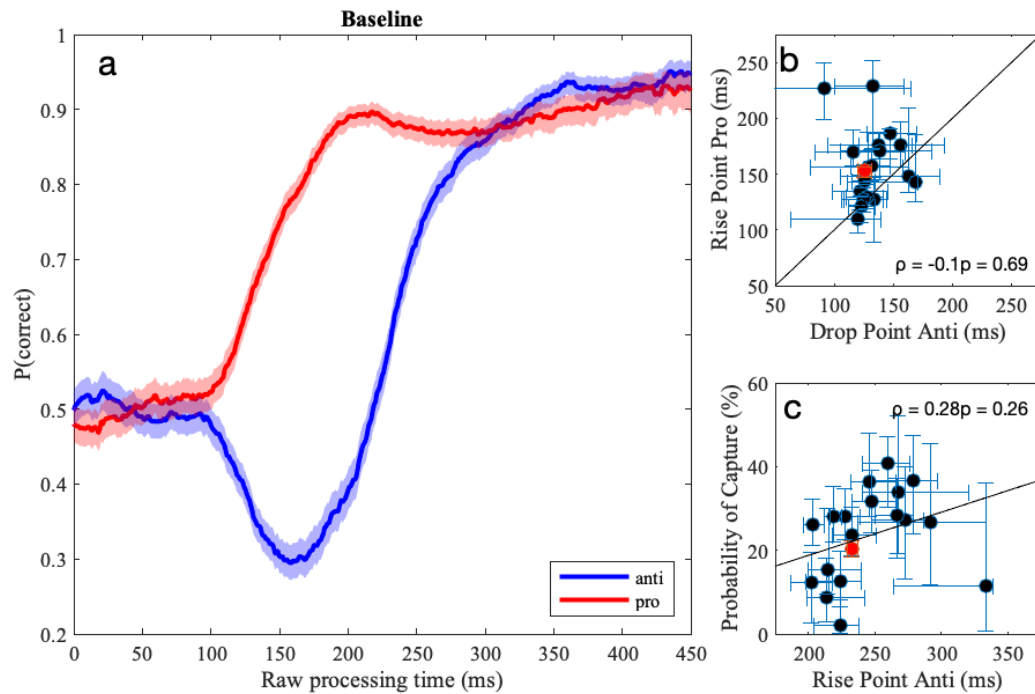


Figure 2: Behavioral results for baseline condition. **a**, Cumulative tachometric curves for pro- (red, 20,510 trials) and antisaccade trials (blue, 19,835 trials) combined across 19 participants. Shaded regions indicate 95% confidence intervals (CIs) across trials. **b**, Comparison between anti drop point (x-axis, early drop in performance caused by exogenous capture) and pro rise point (y-axis, early increase in performance caused by exogenous capture) with correlation and significance shown. The red point indicates data from pooled tachometric curve. **c**, Comparison between anti rise point (x-axis, later endogenously driven increase in performance) and probability of capture (probability of exogenous capture of attention), format the same as **b**.

Experiment 1:

There were two primary manipulations in experiment 1. The first was altering the relative frequency with which prosaccade and antisaccade trials occurred across levels, and the second was modifying the scoring convention used for two follow-up completions of the baseline condition. In levels 73, 74, 83, and 84, participants played SpotChase following the ruleset that was established in the baseline condition with the critical distinction between levels being the rate at which trial types occurred. In levels 73 & 74 prosaccade trials occurred more frequently than antisaccade trials at rates of 3:1 and 6:1 respectively. In levels 83 & 84, the magnitude of the biases remained the same, but the ratios were reversed, favoring antisaccade trials over prosaccade trials. Tachometric curves were then constructed for both pro- and antisaccade trials across the range of biases. One key finding was that altering the task statistics systematically impacted performance on the task. This effect was particularly pronounced for antisaccade trials (Fig. 3a) with systematic changes in measures of vortex width, rise point, and the probability of exogenous capture (Fig. 3b). Alterations in prosaccade performance were also observed (Fig. 3c). Namely, there seemed to be a distinct stratification of performance at later processing times (Fig. 3d). These results suggest, first, that the endogenous response to a stimulus can be modified by task statistics, and second, that consistent exposure to one trial type enhances performance at the expense of the opposing trial type.

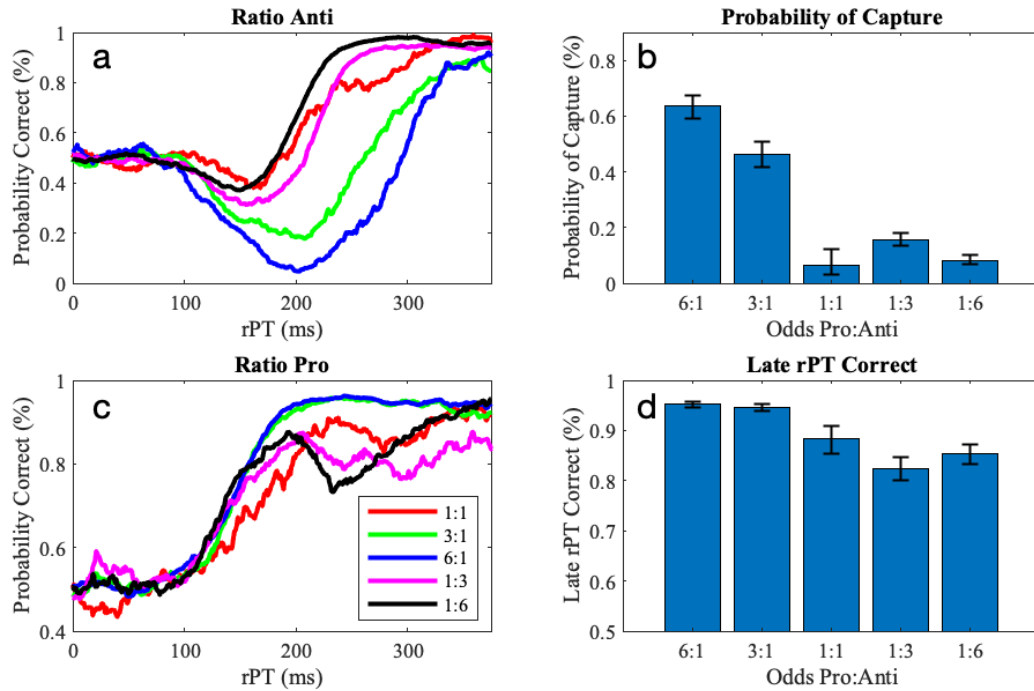


Figure 3: Results from experiment 1. **a**, Tachometric curves for antisaccade trials across the range of ratios (cumulative data from 3 participants). **b**, Probability of exogenous capture for ratio conditions shown in **a**. Error bars indicate 95% confidence intervals. **c**, Tachometric curves for prosaccade trials corresponding to ratios shown in **a**. **d**, Percentage of correct responses at later processing times for prosaccade trials (any trial completed at a processing time > rise point + 60 ms).

To investigate the possibility that this was due to the implementation of a top-down strategy, participants completed two additional versions of the baseline condition with each following a different scoring convention. In the first, the punishment for incorrectly responding to antisaccade trials was increased (participants lost points) to prioritize performance on these trials. In the second, the punishment for incorrect antisaccade trials was minimized and the reward for correct prosaccade trials was increased (participants earned more points), prompting participants to focus performance on prosaccade trials. This allowed us to gauge the effects of explicit top-down rule changes on performance compared to the putative exogenous effects observed in the ratio manipulation. What we found is, that there were slight, but insignificant, differences

between these baseline conditions (Fig. 4a) as seen by comparing the rise points (Fig. 4b) and probability of capture (Fig. 4c) between the two conditions. This would indicate that performance on this task cannot be significantly altered based on top-down rule changes, and that the large modulation observed in the ratio manipulation was an automatic adaptation in response to the altered task statistics.

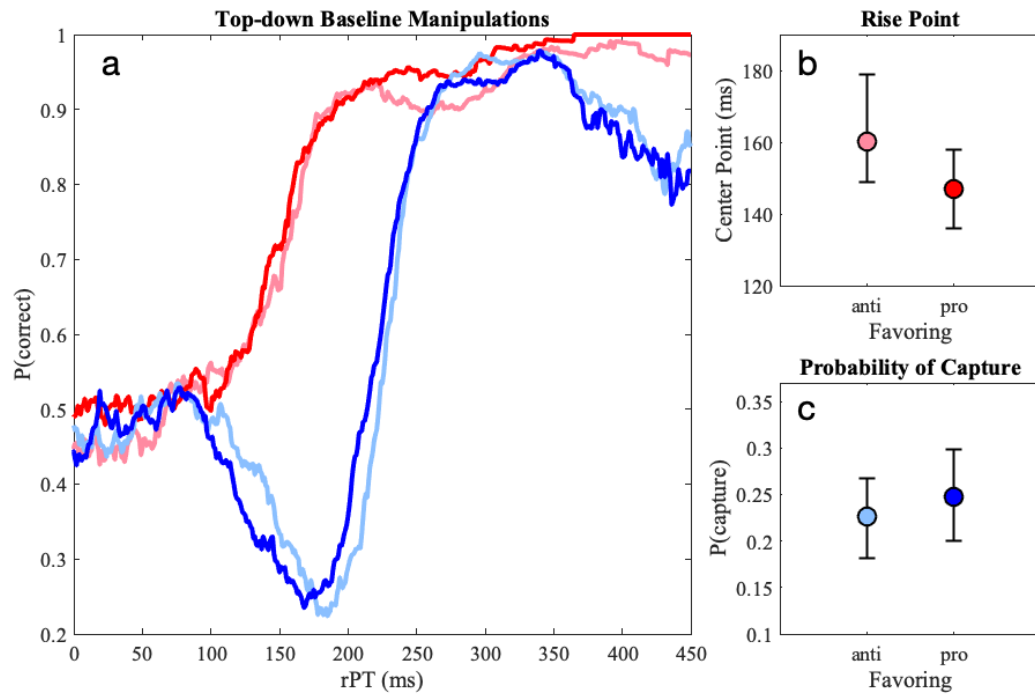


Figure 4: Top-down manipulations of baseline condition. **a**, Tachometric curves produced from cumulative data from 3 participants. Light blue and red indicate condition in which antisaccade performance was incentivized, dark blue and red represent condition in which prosaccade trials were incentivized. **b**, Rise points for curves prosaccade curves shown in **a**. **c**, Probability of capture for antisaccade curves shown in **a**.

Experiment 2:

Experiment 2 aimed to further demonstrate that responses at early processing times are dictated by exogenous responses to stimuli. To achieve this, we altered the luminance of the targets and cues in level 50 of SpotChase. At the onset of each trial, two low luminance yellow targets would appear followed by the onset of a high luminance yellow distractor and low luminance cue. Task rules remained as previously stated. Were it the case that early responses are exogenously driven, it would be expected that this manipulation would cause marked differences between performance on the two trial types. For antisaccade trials, the appearance of the high luminance distractor should lead to an increase in performance as the distractor captures attention away from the cue. On prosaccade trials, the opposite should be observed, with attention being drawn to the distractor as opposed to the cue resulting in incorrect responses.

Indeed, this is what we observed, as shown by the cumulative tachometric curves in Fig. 5a. The onset of the salient distractor proved to be beneficial for antisaccade performance and detrimental to prosaccade performance. Now the curve for prosaccades possesses a vortex indicating an exogenously driven capture of attention caused by the onset of the salient distractor. This is nicely shown when performance on level 50 and baseline are compared. As is shown in Fig. 5b, during the defined rPT window, in the baseline condition there is a significant difference in performance between the pro and antisaccade tasks, with antisaccade performance dipping below chance due to exogenous capture. This trend is preserved but reversed, for level 50. Antisaccade performance rises

above chance as the salient distractor draws attention away from the cue whereas performance on the prosaccade trials is hindered. This serves as additional validation of the idea that decisions made at early processing times are exogenously driven.

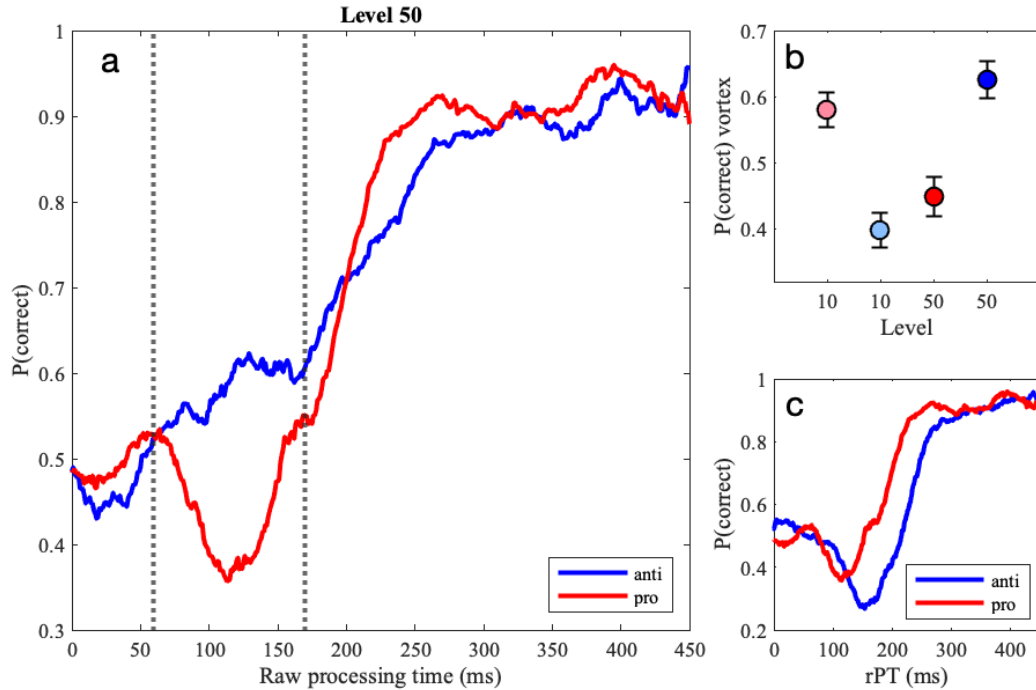


Figure 5: Data for luminance manipulation. **a**, Cumulative tachometric curves for level 50 across 6 participants. Region of exogenous capture and recovery shown in dashed lines. **b**, Percentage of correct responses for prosaccade and antisaccade trials shown within dashed lines for baseline and level 50. **c**, Tachometric curves for antisaccade trials in baseline condition (blue) and prosaccade trials in level 50 (red).

Experiment 3:

In experiment 3, participants completed two conditions in which they were made aware in advance of the locations where the informative cue would appear. The rationale for this manipulation was that this would allow for the deployment of covert spatial attention to these locations. It was expected that this would lead to a general increase in performance. What we observed, however, was that participants' performance could be broadly split into one of two categories. In one group, covertly attending to the potential cue locations led to an increase in guesses to those locations. This resulted in a large

spatial bias being observed in the tachometric curves favoring the prosaccade trials. The other group did precisely the opposite, participants showed a bias away from the cue locations resulting in increased guessing performance on antisaccade trials and decreased guessing performance on prosaccade trials. This can be observed in Fig. 6a and b, showing data from two representative participants from each of these two bias groups for level 91, in which the informative cue always appeared at the bottom and right locations. Fig 6c shows participant performance in the range of guessing rPTs for level 91 as compared to baseline. This analysis reveals that the overwhelming majority of participants in this condition showed a significant deviation in guessing performance compared to their respective baseline performance as a result of this manipulation. These findings are consistent with the tight link between saccade planning and the deployment of spatial attention (Moore and Zirnsak, 2017).

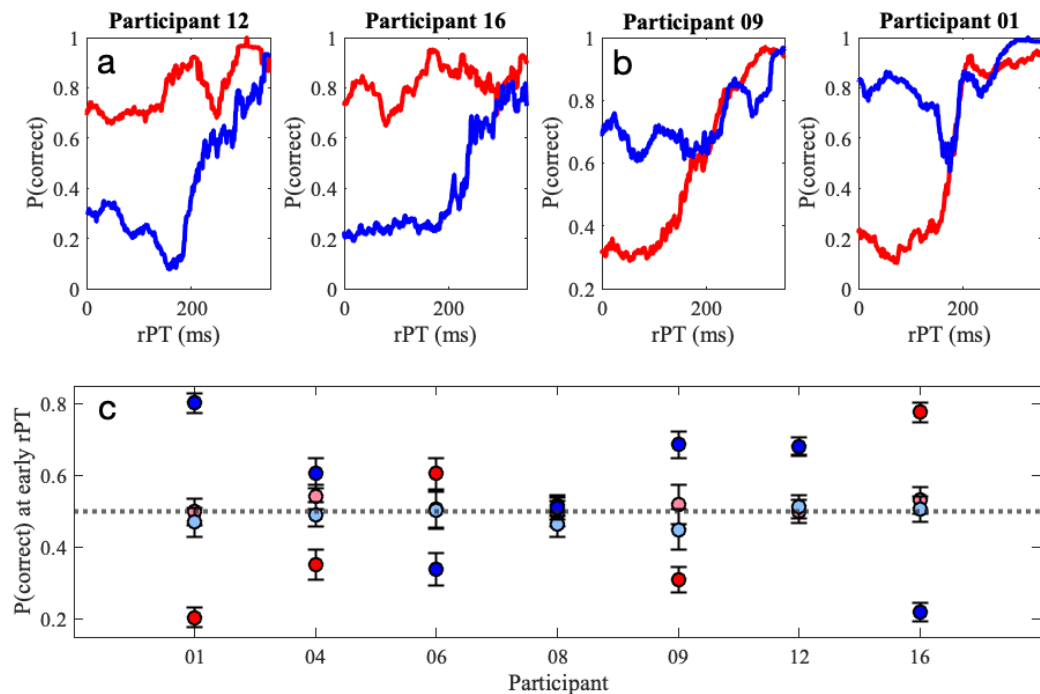


Figure 6: Data for spatial manipulation. **a**, Tachometric curves for two participants demonstrating a bias towards covertly attended cue locations (prosaccade curves shown in red, antisaccade curves shown in blue). **b**, Tachometric curves for two individual participants showing a bias away from known cue locations. **c**, Percentage of correct responses at early processing times (<100 ms) for each participant’s baseline condition (dark blue and red), and level 50 (light blue and red).

Discussion

SpotChase as a paradigm to investigate attentional mechanisms:

Previous work done by our lab has relied on trial-based tasks (Stanford TR, Shankar S, Massoglia, Costello Salinas, 2010; Salinas, Shankar, Costello, Zhu, Stanford, 2010).

While these tasks have been, and continue to be, crucial in furthering our understanding of visual attention, they are limited in their ability to replicate natural viewing conditions.

SpotChase was developed to advance this line of research by creating more naturalistic viewing conditions by getting rid of the rigid task structure and fixation period, and by implementing a scoring system designed to keep participants engaged. Findings from the baseline version of SpotChase closely replicate those obtained in a traditional trial-based version of an urgent pro- and antisaccade task utilized by Goldstein et. al (2022). For instance, behavioral data collected from SpotChase was used to produce tachometric curves that demonstrated the same characteristic patterns observed previously. The versatility of SpotChase also allowed for the development of paradigms capable of investigating the various attentional mechanisms that were explored here and establishes SpotChase as a potentially valuable clinical tool.

Modification of exogenous response via altered task statistics:

Experiment 1 explored the effects of task statistics on overall performance. In essence, our question was, how will performance be affected by biasing the rate at which trial types occur? The answer is that when participants are exposed to a trial-type more frequently, their performance on that trial type improves at the expense of performance on the opposing trial type. Specifically, exogenous responses to stimuli were altered

according to the task statistics. This is particularly evident in the case of antisaccade performance, where there is an immense discrepancy in the probability of exogenous capture between levels in which they are the predominant trial type, and when they occur sparsely. To ensure that these alterations in performance were truly due to changes in exogenous response, two additional versions of the baseline were performed in which one trial type was incentivized over the other. Results between these conditions were slight and insignificant, indicating that performance on the task is largely unaffected by top-down strategies and that the changes in performance were due to some degree of learning that took place automatically.

Early responses to stimuli driven by exogenous mechanisms:

It has been well documented that exogenous attention is stimulus-driven and transient in nature (Carrasco, 2011; Theeuwes, 2010). This observation has been tested directly in our lab using urgent perceptual decision tasks, which consistently show a drop in performance on the antisaccade task during the time window corresponding to the exogenous response to a stimulus (Salinas et al. 2019; Stanford and Salinas 2021; Goldstein, Stanford, & Salinas, 2022). It can, and has been, argued that this decrease in performance on the antisaccade task is indicative of a failure of cognitive control (Munoz and Everling, 2004; Hutton and Ettinger 2006). What is becoming apparent, however, is that this is not the case. Errors in the antisaccade task are attributable to the involuntary, stimulus-driven, capture of exogenous attention occurring at timescales preceding the deployment of any top-down cognitive mechanism (Salinas and Stanford, 2021). To further demonstrate this, participants in this study completed level 50 of SpotChase. The

previously established rules remained the same, the key difference was altered luminance of the cues and distractors. With the salient distractor present, performance on prosaccade trials decreased, mirroring the effects observed in the baseline condition on the antisaccade task. This again shows that exogenous attention is quickly and automatically captured by the onset of salient stimuli.

Deployment of covert spatial attention leads to spatial biases in a dynamic task:

The deployment of covert spatial attention has been shown to enhance processing of stimuli at the attended location (Moore, Armstrong, & Fallah, 2003). In levels 90 and 91, participants were made aware in advance the potential locations of the cues. It was expected that this prior knowledge of cue locations would lead to enhanced performance by allowing for faster decoding of the stimuli, resulting in decisions being made at a faster rate. It was not evident whether participants would even be sensitive to such knowledge given the highly dynamic nature of SpotChase and the prolonged fixation requirements that are typically imposed during covert attention tasks. What we observed, however, is that this led to massive spatial biases with participants falling broadly into one of two categories. In the first, participants were biased toward the cue locations, directing the majority of guesses to those locations. The opposite was true for the other group which made a disproportionate number of guesses away from the known cue locations. One possible explanation for this phenomenon is the relationship between saccade planning and the deployment of covert attention. It has been observed that it is possible to simultaneously direct covert attention to one location and plan a saccade to another. Further, visual activity produced from saccade planning rivaled, and often

surpassed, activity produced via covertly attending to a separate location (Steinmetz and Moore, 2014). Therefore, some participants may have planned saccades away from the known cue locations, possibly to prioritize antisaccade performance, while others planned saccades to the covertly attended locations. This could account for the observed behavioral results.

Future directions:

These results suggest that SpotChase is a capable tool in the exploration of various attentional mechanisms. The dynamic nature of SpotChase allows not only for a platform capable of replicating findings from previous trial-based tasks, but also as a unique instrument to investigate these mechanisms in more naturalistic settings. This has led to novel discoveries, such as those seen in Experiment 1, that have yet to be observed in trial-based tasks. In addition to this dynamic format, SpotChase is also highly modifiable, allowing for the investigation into various attentional mechanisms with minimal alterations. This makes SpotChase an attractive option for development as a potential biomarker for neurological disorders, as time is of the essence in clinical settings. This work aims to establish SpotChase as a platform by which to develop and answer further questions about the interplay between attention and perceptual decision-making.

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Education

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Research Experience

Graduate Student Researcher May 2021 - Present
Department of Neurobiology and Anatomy, Wake Forest School of Medicine
Advisors: Emilio Salinas & Terrence Stanford

- Programmed an urgent choice eye tracking task to examine visual attention and decision making.
- Perform statistical modeling and analysis on collected behavioral data using custom MATLAB code.
- Interpret results from data collection.

Graduate Student Researcher August 2020 – May 2021
Department of Neurobiology and Anatomy, Wake Forest School of Medicine
Advisor: Christos Constantinidis

- Collaborated as part of a team working to uncover neural mechanisms underlying working memory.
- Analyzed neural data collected from non-human primates.
- Interpret results from data collection.

Research Assistant August 2018 – May 2019
Department of Psychology, Appalachian State University
Advisor: Christopher Dickinson

- Led groups of participants through various eye tracking tasks involving cognitive control and attention.
- Collected participant data from tasks.
- Worked as part of a team to develop research questions.

Abstracts

1. Junda Zhu, Austin W Lodish, Leonardo Silenzi, Evan A Kattner, GD Myatt, Du Gu, Macrae Robertson, Xuelian Qi, Terrence R Stanford, Emilio Salinas, Christos Constantinidis (2021). *Working Memory and Prefrontal Neural Activity of Macaques in Early Adolescence*. *Journal of Vision*, 21 (9): 2913-2913
2. J. Zhu, C. M. Garin, X. Qi, A. W. Lodish, L. Silenzi, E. A. Kattner, G. D. Myatt, T. R. Stanford, E. Salinas, C. T. Whitlow, B. Luna, C. Constantinidis. (2021).

Prefrontal Neural changes in Early Adolescence related to working memory.
Society for Neuroscience Abstracts, 807.09.

Technical Skills

Software: Proficient in MALAB. Experience with SPSS.