Non-singleton colors are not attended faster than categories, but they are encoded faster: A combined approach of behavior, modeling and ERPs

Chloe Callahan-Flintoft *, Brad Wyble

404 Moore Building, The Pennsylvania State University, University Park, PA 16802, USA

ABSTRACT

The visual system is able to detect targets according to a variety of criteria, such as by categorical (letter vs digit) or featural attributes (color). These criteria are often used interchangeably in rapid serial visual presentation (RSVP) studies but little is known about how rapidly they are processed. The aim of this work was to compare the time course of attentional selection and memory encoding for different types of target criteria. We conducted two experiments where participants reported one or two targets (T1, T2) presented in lateral RSVP streams. Targets were marked either by being a singleton color (red letter among black letters), being categorically distinct (digits among letters) or non-singleton color (target color letter among heterogeneously colored letters). Using event related potential (ERPs) associated with attention and memory encoding (the N2pc and the P3 respectively), we compared the relative latency of these two processing stages for these three kinds of targets. In addition to these ERP measures, we obtained convergent behavioral measures for attention and memory encoding by presenting two targets in immediate sequence and comparing their relative accuracy and proportion of temporal order errors. Both behavioral and EEG measures revealed that singleton color targets were attended much more quickly than either non-singleton color or categorical targets, and there was very little difference between attention latencies to non-singleton color and categorical targets. There was however a difference in the speed of memory encoding for non-singleton color and category latencies in both behavioral and EEG measures, which shows that encoding latency differences do not always mirror attention latency differences.

1. Introduction

The field of visual cognition seeks to understand the processes by which the visual system detects and remembers important information. These processes can be measured by asking subjects to detect targets presented among a spatially or temporally distributed array of items, where targets can be signified in a variety of ways such as being a singleton (Theeuwes, 1992), a specific color (Folk, Remington, & Wright, 1994) or even a member from a category; (Potter, 1976; Schneider & Shiffrin, 1977; Wyble, Bowman, & Potter, 2009). Comparing between the processing of different kinds of targets has the potential to reveal and distinguish different mechanisms of information processing within the visual system, attention and memory encoding.

The ability to report a target involves a succession of processing stages that is typically thought to include, at a minimum, an initial stage of attentional deployment upon detection of a target, and a subsequent stage of working memory encoding so that it can be reported later. The idea that these two distinct stages exist is supported by behavioral results from rapid serial visual presentation experiments (RSVP) in which a rapidly presented target can trigger the deployment of attention that affects a subsequent target, even when the first target is itself not perceived (Wyble et al., 2009). This idea of distinct attention and memory encoding stages forms the core basis of two-stage models of visual perception (Chun & Potter, 1995) as well as computational models of target processing (Bundesen, 1990; Shih, 2008; Wyble, Bowman, & Nieuwenstein, 2009). Further support for this distinction comes from recent findings that information can be directly attended in order to complete a task without leaving a reportable memory trace (Chen & Wyble, 2015, 2016).
One means of studying different stages of processing is to measure when they occur for different kinds of targets. By time-locking event related potentials (ERPs) to target onset, we can measure correlates of cognitive processes such as attention and memory encoding that are triggered by the target. In the case of RSVP a series of non-targets is presented before and after the target. This means that stimulus onset is not synonymous with target presentation and therefore differences between the target-elicited ERP and a distractor-elicited ERP are necessarily related to the neural processes of target processing rather than the mere onset of new information. While the ERPs of targets and distractors do overlap with one another (Smith & Kutas, 2015), by presenting a stream of distractors prior to the target one can see the ERP elicited by distractors alone (through an observable steady state visually evoked potential, SSVEP), and the subsequent changes to the ERP when a target is added to the stream. Furthermore, as will be discussed in later sections RSVP offers behavioral measures of reporting sequential targets that provide converging evidence for timing differences at sequential processing stages using a computational model. There are, however, limitations in the RSVP paradigm such as the fact that stimuli only appear at one of a few designated locations which are known in advance of target onset. Because these experiments require us to record data from sequentially presented targets, RSVP was chosen over visual search arrays.

Previous research indicates that observers are surprisingly good at reporting targets from RSVP regardless of whether they are defined by color (Maki, Couture, Frigen, & Lien, 1997), character category (e.g., letters among digits Raymond, Shapiro, & Arnell, 1992) or word category (Barnard, Ramponi, Battye, & Mackintosh, 2005). This ability to easily detect targets of many different types in RSVP creates a promising platform for determining how the visual system detects and remembers stimuli of various kinds.

The present studies will directly compare differences in processing speed at the levels of attentional deployment and memory encoding using three target types (singleton color, non-singleton color, and category). The use of different target types within the same experiment was inspired by Verleger et al. (2009), however in the current work our interest is in the processing speed of different target types and not left/right hemifield differences. These kinds of targets are frequently used in RSVP research to study different types and not left/right hemifield differences. These experiments require us to record data from sequentially presented targets, RSVP was chosen over visual search arrays.

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An important contribution of this work is to find convergent behavioral and neural correlates within the same experiment. Often, an EEG finding will be offered as standalone evidence for a conclusion about cognitive function. This can be problematic because while an ERP component has been linked to a cognitive function in one particular paradigm, a similar ERP component may not be related to that same function in a different paradigm. To ensure that our ERPs address the constructs of interest, we developed parallel behavioral and EEG measures of our constructs, namely attentional latency and memory encoding latency. Data analysis will be conducted in two distinct sections for clarity. First, we will measure the latency of ERP components assumed to reflect attention (N2pc) and memory encoding (P3) operations. The second analysis section will develop a novel method of measuring differences in attention and encoding speed through behavioral responses using data from the same experiments. The EEG analysis will provide absolute measures of attention and encoding lattencies while the behavioral analysis will provide relative comparisons (i.e., faster/slower). The analyses are presented separately and in this order for clarity, since analysis 2 (behavioral) is novel and involves predictions from a computational model of sequential target processing.

1.1. Analysis 1: Electrophysiological signatures of processing speed

The EEG analysis will focus on two event-related potentials (ERPs), the N2pc and the P3. These components are thought to be the result of target processing from the deployment of attention (N2pc; Eimer, 1996; Luck & Hillyard, 1994; Tan & Wyble, 2015) to the updating of working memory with new information (P3; Donchin, 1981), though the evidence for the latter is less clear (Rac-Lubeshevsly & Kessler, 2016). Measuring these two ERP components in one study not only allows us to observe the effects of target type on early and late stages of processing but also what time locking, if any, there is between the N2pc and the P3 onset latencies.

The N2pc (N2 posterior contralateral) is a negativity in the posterior electrodes contralateral to the presentation of a lateral visual target which occurs around 250 ms after target onset. This component has been thought to reflect the deployment of spatial attention causing some combination of spatial filtering (Luck & Hillyard, 1994), target enhancement (Eimer, 1996), integration (Mazza & Caramazza, 2011) and target localization (Tan & Wyble, 2015). We invoke the N2pc here not to adjudicate between these competing theories, but as a measurement of attentional onset.

The component we use as a measure of memory encoding latency is the P3. The P3, or P300 as it is often termed, is a positive deflection relative to baseline that begins 300–400 ms after stimulus onset. It has two distinct subcomponents: the P3a and the P3b. The P3a occurs slightly earlier, predominantly in the anterior electrodes and is sometime referred to as the ‘novelty P3’ as it is elicited by infrequent stimuli and has been linked to an orienting response (Friedman, Cycowicz, & Gaeta, 2001; Squires, Squires, & Hillyard, 1975). The P3b is slightly later than the P3a and maximal in the parietal electrodes. One hypothesis is that the P3b reflects the updating of working memory (Polich, 2007), however this link between the P3b and memory is debated (Verleger, 2008). While the exact set of mechanisms reflected in the P3 is unknown, it does have a strong relationship with the ability to later report a target (e.g., Kranzioch, Debener, & Engel, 2003; Vogel & Luck, 2002). Additionally the P3 has also been linked to decision making and information processing (Nieuwenhuis, Aston-Jones, & Cohen, 2005) as well as being used as a measure for processing capacity (Kok, 2001). Similarly, there are seemingly conflicting results across studies in whether the P3 latency is related to reaction times depending on if the experimental paradigm has difficult to decide answers (e.g., Kranczioch, Debener, & Engel, 2003; Vogel & Luck, 2002).
store the information into working memory. Therefore, we interpret the P3 latency as a measure of the onset of encoding a target into memory.

1.2. Analysis 2: Behavioral signatures of processing speed

Traditionally, reaction times are used as a behavioral measure of processing speed, but they are not suitable in this case. Reaction time reflects the sum of attention and decision making components, with the addition of a motor response component, making it difficult to distinguish measures of attentional latency from measures of memory encoding latency. Therefore instead of reaction time, we use two novel measures. Two-target accuracy, and for trials in which both are reported, in what order they are reported (i.e. correct or temporally swapped), can be related to underlying attention and memory encoding processes respectively, according to simulations of a computational model of sequential target processing (Wyble et al., 2009). In order to present the results in a more coherent way, we postpone the description of the model until the behavioral results section below. This ordering makes it easier for the reader to focus on the ERP analyses at first.

1.3. Experimental approach

To compare the speed of processing across different types of targets we ran three experiments, each using a dual, bilateral RSVP paradigm. In experiment 1 streams consisted of distractors defined as black letters and targets defined as red letters (singleton color targets), or black digits (categorical targets). In experiment 2, the RSVPs are composed of colored letter distractors, and targets which were letters of a specific color (non-singleton color targets) or digits of any color (categorical targets). Experiment 3 was run to ensure we are in fact tapping into the processing speeds of targets defined by category and not simply digits. In this experiment distractors were digits and categorical targets were letters. This experiment confirmed the results of the first two. To aid in the comparison of the three different target types within the two experiments, the methods and results of these experiments have been combined.

1 All data and analysis scripts will be uploaded to Scholarsphere (https://scholarsphere.psu.edu/collections/79407x18h).

The within-subjects design of experiments 1 & 2 ensures that participants have the same attentional set when viewing either kind of target in each experiment (i.e. all participants, on every trial were tasked with identifying both red letters and black digits in experiment 1 or target-colored letters and digits of any color in experiment 2) so that any observed differences between conditions are not due to block-wise differences in motivation, or task set. Mixed trial types are of particular importance when measuring latency, as predictable distractor/target similarity has been shown to have an effect on the latency of components (Töllner, Conci, & Müller, 2015).

2. Methods

2.1. Participants

Data from twenty-five subjects were collected for the first experiment and twenty for the second experiment. All subjects volunteered from the Pennsylvania State University psychology subject pool for this study. Participants all had normal or corrected-to-normal vision and were between the ages of 18 and 23 years old. Informed consent was obtained for each participant prior to each study in accordance with the IRB office of Penn State. Subjects were excluded for having too few usable trials per condition (threshold: 25) after discarding trials for inaccurate responses and EEG artifacts. This left nineteen subjects for analysis for experiment 1 and eighteen for experiment 2. While participants were not directly tested for color vision, no subjects reported difficulty seeing the colored targets, and the lowest single target accuracy for color-marked targets across experiments was 0.65 suggesting that all participants had at least adequate color vision to complete the task. All data was collected in accordance with the Code of Ethics of the World Medical Associations (Declaration of Helsinki) except that the analyses were not pre-registered.

2.2. Stimuli & apparatus

Stimuli were black alphanumeric characters in size 55 Arial font (1.26 × 0.63° of visual angle), presented on a grey background. The computer had an 18 inch CRT that was placed 90 cm away from the participants (1024 × 768, 60 Hz refresh rate). Stimuli were presented using MATLAB 2012 with Psychophysics Toolbox-3 extension (Brainard, 1997). Categorical targets were black digits and singleton color targets were red letters ([255, 0, 0]) in experiment 1. This target color was the same for all participants. Distractors were black letters. Distractors and singleton color targets were drawn from the following collection of letters: A, B, C, D, E, F, G, H, J, K, L, N, P, Q, R, T, U, V, X, Y. Letters that resembled digits, such as ‘O’, ‘S’, ‘Z’ and ‘I’, were excluded as well as wider letters such as ‘M’ and ‘W’. The digits used as categorical targets were: 2, 3, 4, 5, 6, 7, 8, 9. In experiment 2 the stimuli and apparatus were the same except that one class of targets were letters of a designated randomly selected target color (one out of five possible) and digit targets and distractors were presented in the remaining four colors with the constraint that the same color was not presented twice in the same frame or in sequential frames. The colors used were: green (0, 255, 0), red (255, 0, 0), blue (0, 0, 255), cyan (0, 225, 225) and yellow (225, 225, 0).

2.3. Procedure

2.3.1. Experiments 1 & 2

On every trial participants were presented with two RSVP streams and a fixation cross (Fig. 1a). The center of each stream was three degrees from the center of the fixation cross. The left and right stimuli were updated simultaneously at 150 ms stimulus onset asynchrony (SOA) with no inter-stimulus-interval. There were either seven or eight distractors in each stream before target onset. Every trial had one or two targets. If there was a second target (T2) it always appeared in the same stream as the first target (T1) and was immediately afterwards. No letter or digit was repeated for at least two sequential frames. The fixation cross remained on the screen throughout the trial. Eight distractor pairs followed the final target presentation. At the end of the stream the cross was replaced with either a period or a comma for 150 ms. Two practice trials were used within the instruction block to demonstrate the task.

Instructions and responses. In both experiments participants were told that all trials would contain either one or two targets and that they would be asked to report any targets they saw during the trial. Participants were also told that they should look for the dot or comma at the end of the stream as they would sometimes be asked to report that as well. At the end of the RSVP stream, participants were asked for the first and second target and told to press Enter to skip through if they did not see a target. Participants entered their responses using the keyboard, used backspace to correct their answer and pressed Enter when they were satisfied with each answer. On 33% of trials, after being asked for the targets, participants were asked to report whether a dot or comma
had followed the fixation cross. This was done in order to encourage participants to remain engaged, with their eyes on fixation, for the entire stream and not just until the target(s) appeared. While this technique was used to discourage eye movements, eye movements were detected and eliminated with EEG measures described below. At the end of each trial, feedback was provided by showing the participants what targets were shown as well as what punctuation had replaced the fixation cross (dot or comma).

2.3.2. Experiment 1

Half of targets were singleton color (red letter among black letters) and the rest were categorical (black digits among black letters). These targets were combined in six different conditions: singleton color target alone (SC), categorical target alone (Cat), singleton color target immediately followed by a categorical target (SC-Cat), categorical immediately followed by a singleton color (Cat-SC), two sequential singleton color targets (SC-SC) or two sequential categorical targets (Cat-Cat). The conditions with mixed target types (i.e. SC-Cat and Cat-SC) were included for a different purpose that is not the focus of the current work and so are mentioned here as part of the experimental design but will not be discussed further in this paper or used in analysis.

Each participant had a total of 280 trials distributed across the 6 conditions. There were 60 trials in both the SC-SC and Cat-Cat conditions to compensate for the increased difficulty of these trials. The remaining conditions had 40 trials each. Trial types were intermixed within one block so participants did not know how many or what type of targets to expect on any given trial. After every 20 trials the participants were given a self-paced break.

2.3.3. Experiment 2

The procedure for experiment 2 was the same as in experiment 1 except that now the targets were defined by a non-singleton color (letters of a specific target color among letter distractors of the colors: green, red, blue, cyan, yellow, see Stimuli & Apparatus section for RGB values) or, again, category (digit among letters—equally likely to appear in any of the four distractor colors) (Fig. 1b). Each subject had one designated non-singleton color as a target that was selected according to their subject number and remained constant throughout the experiment. There were only four conditions: non-singleton color target alone (NSC), categorical target alone (Cat), non-singleton color followed immediately by another non-singleton color target (NSC-NSC) and categorical followed by another categorical target (Cat-Cat). Again, participants were told that every trial would contain at least one target and that they would need to report any digit or target colored letter they saw during the trial as well as the end-of-stream dot/comma. There were 280 trials randomly ordered within block and equally divided across the four conditions (70 trials in each).

2.4. EEG recordings

EEG activity was recorded using a 32-channel sintered Ag/AgCl electrode array mounted in an elastic cap according to the 10–20
A Neuroscan Synamps amplifier was used with a band pass filter of 0.05–100 Hz and a sampling rate of 500 Hz. The data was reduced offline to 250 Hz for analysis. Other than the online bandpass and resampling offline, no further filtering was applied to the waveforms. Impedance for all electrodes was lower than 5 kΩ before the experiment began. The tip of the nose was used as a reference. VEOG electrodes were placed on the lower and upper orbital ridge of the left eye. Right and left HEOG electrodes were placed on the outer canthus of the eye. All ERPs were time locked to the first target onset. The length of each epoch was −1000 ms to 2000 ms relative to T1 onset with the average voltage during −200 ms to 0 ms subtracted from each trial as a baseline. Trials were considered accurate and used for analysis if participants correctly reported the first target. Trials were also rejected if participants made any horizontal or vertical eye movements within a window of −500 to 1200 ms relative to T1 onset. Horizontal eye movements were judged by taking the average difference between right and left HEOG electrodes in a moving 32 ms time window. If this difference exceeded 20 μV, the trial was rejected. For vertical eye movements, if the difference between VEOG electrodes increased more than 100 μV, the trial was rejected. Additionally, if any channel exceeded an absolute value of 100 μV during the epoched window, that trial was rejected. All artifact rejection and EEG analysis was performed with a combination of custom MATLAB 2012 script and EEGLab 13.3.2b functions (Delorme & Makeig, 2004). To maximize the number of trials per participant, single and two target conditions were combined across target type. Thus in experiment 1, trials from the SC and SC-SC conditions were pooled as were Cat and Cat-Cat trials. Likewise in experiment 2, NSC and NSC-NSC trials were pooled together as were Cat with Cat-Cat trials. Only participants that had more than 25 accurate trials for each target type to make it through artifact rejection were used in analysis. Trials were considered usable if participants reported the identity of T1 accurately, regardless of the order in which they reported it and if the trial passed the EEG exclusion criteria described above. Of the participants included in analysis, the mean number of trials to pass the rejection criteria was 24 for SC, 27 for Cat, 25 for SC-SC and 35 for Cat-Cat. As all trials with like target types were combined in the presented analysis here, the mean trial count then for singleton color trials was 49, and 61 for categorical targets.

As pooling across trial type is unconventional, the ERPs and analyses for single and double target conditions were performed separately and presented in the Appendix. As previously mentioned, the behavioral metrics of interest require the presentation of two targets and so the behavioral analysis will focus only on the SC-SC, NSC-NSC and two Cat-Cat conditions. However the same set of subjects are used throughout.

3. Results

3.1. Target report

To ensure that subjects could reliably report all of the target types, we analyzed accuracy of reporting single targets. There was no significant difference in experiment 1 between the accuracy of reporting a single target in the SC (M = 0.90, SE = 0.02) and Cat conditions (M = 0.91, SE = 0.02), F(1,18) = 0.06, p = 0.80. Likewise in experiment 2, there was no significant difference between accuracy scores of reporting single targets for NSC condition (M = 0.86, SE = 0.02) and Cat condition (M = 0.87, SE = 0.02), F(1,17) = 0.11, p = 0.75. The joint accuracies per condition were 0.68 (SC-Cat), 0.53 (Cat-SC), 0.62 (SC-SC) and 0.72 (Cat-Cat) for
For experiment 2 they were 0.55 (NSC-NSC) and 0.69 (Cat-Cat). A more detailed analysis of the behavioral results is provided below.

### 3.2. Analysis 1: EEG

#### 3.2.1. N2pc

Electrodes P7/P8 were used for all N2pc analyses as they are where the component is maximal in amplitude and roughly correspond to electrodes P07/P08 used in previous N2pc work, which were unavailable in the EEG caps used here. Contralateral and ipsilateral waveforms for the four conditions of the two experiments are shown in Fig. 2. To test for the presence of an N2pc in each condition, a permutation analysis was conducted using a MATLAB script that randomized the subtraction between contra and ipsilateral waveform for each participant. A thousand iterations of this process were run, making a null hypothesis distribution for each 20 ms time step. A window was considered significant if at least 4 time steps in a row had a p-value less than 0.05. Importantly there were no significant windows in the range of $-1000$ to $150$ ms relative to target onset for any of the conditions, demonstrating that this conservative criterion did not allow for significant windows to be found by chance. For experiment 1, the singleton color condition showed a significant laterality in the time windows of 160–280 ms post T1 onset as did the categorical condition in the time window 180–300 ms, consistent with previous findings of the N2pc. For experiment 2, there was a significant window of laterality at 200–300 ms for the non-singleton color and 180–300 ms for the categorical condition. This permutation analysis shows that each target type was successful in eliciting an N2pc. Other significant windows were also found after 340 ms post T1 onset (after the time window of the N2pc), possibly reflecting other lateral components such as the contralateral delay activity (CDA) (Vogel, McCollough, & Machizawa, 2005). As these components are not the focus of the work presented here, they are not discussed further.

For the N2pc latency analysis, a jackknife repeated measure ANOVA with corrected F-value was used to analyze the latency of the N2pcs (Ulrich & Miller, 2001). To mark the latency of the component we used the point at which the component reached 50% peak amplitude as this relative measure has shown the greatest sensitivity in finding latency difference for both the N2pc and the P3 in simulation studies (Kiesel, Miller, Jolicœur, & Brisson, 2008). Based on previous studies of the N2pc, the window for analysis was set from 100 ms to 300 ms post T1 onset in order to be large enough to catch varying latencies. N2pc latency was also computed and analyzed using the point of 50% of area under the curve and the same results were found as presented below.

#### 3.2.2. N2pc latency results for experiments 1 & 2

In experiment 1 there was a significant difference between the latency of the N2pc in response to a singleton color target ($M = 166$ ms, $SE = 9$) as opposed to a categorical target ($M = 206$ ms, $SE = 19$), $F(1,18) = 5.32$, $p = 0.03$ (Fig. 3a). However, in experiment 2, no significant difference was found between N2pc latency to non-singleton color ($M = 213$ ms, $SE = 40$) and categorical targets ($M = 210$ ms, $SE = 40$), $F(1,17) = 0.003$, $p > 0.05$ (Fig. 3b). Taken together, these results suggest that it is the increase in target saliency that results in singleton color targets being attended to earlier, as simply having a target defined by color does not show any speed advantage over targets defined by category.

#### 3.2.3. P3

The P3 in both experiments was analyzed using the data from the Pz electrode. The same jackknife method was used, with the window boundaries being 0–600 ms post T1 onset.

#### 3.2.4. P3 latency results for experiments 1 & 2

In experiment 1 there was a significant difference between the onset of the P3s elicited by singleton color targets ($M = 296$ ms, $SE = 10$) and categorical targets ($M = 374$ ms, $SE = 11$), $F(1,18) = 37.67$, $p < 0.001$ (Fig. 4a). Experiment 2 showed a significant difference as well between the non-singleton color target’s P3 onset latency ($M = 336$ ms, $SE = 52$) and the categorical’s ($M = 395$ ms, $SE = 26$), $F(1,17) = 18.48$, $p < 0.001$ (Fig. 4b). These findings suggest that despite the fact that non-singleton color and categorical targets trigger attention at the same speed (according to the N2pc analysis), non-singleton color targets are encoded earlier.
3.3. Analysis 2: Convergent behavioral measures of attention and memory encoding latency

To obtain a behavioral measure for the speed of attention and encoding into memory, we will look at the results from trials with two consecutive targets of the same type in both experiments. This method takes advantage of theories that attention carries over from one stimulus to the next as seen when two targets are presented in immediate succession and at the same location (i.e. at lag 1; Bowman & Wyble, 2007; Chun & Potter, 1995; Olivers & Meeter, 2008; Shih, 2008), or when a spatial cue precedes a target (Carrasco & McElree, 2001; Yeshurun & Carrasco, 1998). As described below, we can make inferences about the relative speed of attention and memory encoding by examining the relative accuracy of reporting the two targets (T1 and T2) and the proportion of times that they are reported in the correct order.

This theory of sequential target processing has been formalized in a computational model that simulates the time course of attending to targets and then encoding them into memory using simulated neurons (Episodic Simultaneous Type, Serial Token; eSTST; Wyble et al., 2009). The eSTST model’s overall architecture is depicted in Fig. 5, and a more detailed description of the neural mechanisms and parameters of the model can be found in Wyble et al. (2009) and Wyble, Potter, Bowman & Nieuwenstein (2011). For the present purposes it is only necessary to understand that the model has a two-stage architecture in which targets are detected at a first stage (Types). Once detected, targets trigger attention that enhances the processing of information at the target’s location so as to create a memory representation in the second stage (Tokens). Tokens allow the model to represent the memory trace of multiple targets and their sequential order. An important contribution of this model is to simulate how changes in the state of attention affect the encoding of items into memory, and their temporal order. Thus the model provides a formalized means to map changes in internal parameters, such as the speed of attention and memory encoding, to observable behavioral measures such as the relative accuracy for two targets and temporal order errors. This is a slightly different use of a computational model than is typically done. Here, the model is not being fitted to a particular data set, but rather is used to understand how behavioral measures might be related to underlying neural mechanisms and thereby form a bridge between behavioral and EEG data.

This analysis will focus on two parameters of the Wyble et al. (2009) model: bdelay, and typeweight. The parameter bdelay represents attentional latency for a given type of target, such that lower values represent a shorter latency. The second parameter, typeweight, affects the speed of memory encoding, by gating the speed of information flow into the binding pool, which stores information in working memory. Note that bdelay also influences memory encoding time, since faster attentional deployment will result in more rapid evidence accumulation from a target.

3.4. Linking behavior to model parameters: attentional latency and accuracy difference

The eSTST model hypothesizes a link between the attentional latency (i.e. bdelay) and the relative accuracy of reporting two sequential targets. When attention has a small latency, say in the case of a highly salient stimulus, the strength of the perceptual representation of T1 grows more rapidly and achieves a higher peak. This strong representation of T1 increases the chance that it will be encoded into memory and also causes interference with the representation of the following T2 (Wyble et al., 2011). Conversely when attention has a larger latency, the T1 representation accumulates more slowly such that there is less overall activation, which reduces T1 accuracy, and reduces interference with T2. The representation of T2, on the other hand, is relatively less affected...
by attentional latency, because T1 pre-activates attention at its location, which carries forward to the T2.

Thus, the model predicts that differences in attentional latency for different kinds of targets will be reflected in the difference between T1 and T2 accuracy. To summarize this predicted relationship between T1 and T2 we will calculate the accuracy difference (AD) scores (T1 accuracy minus T2 accuracy). Thus the model would predict that target types that trigger attention more quickly would have a difference greater than 0 (i.e. T1 more often reported accurately than T2) while a slower deployment of attention would produce a difference less than 0 (i.e. T1 less often reported accurately than T2).

Contrary to attentional latency, memory encoding latency (which is driven by the typeweight parameter) has relatively little impact on the T1-T2 difference, because the speed of memory encoding has only a minimal effect on whether targets will or will not be encoded. Fig. 6a depicts the model’s prediction of how the AD measure is affected by changes in these two parameters. The graph illustrates that the vast majority of color gradation falls on the horizontal axis, showing that the AD is strongly dictated by attention latency but weakly affected by encoding speed.

3.5. T1-T2 accuracy difference (AD) results

In experiment 1 there was a significant difference in AD scores (T1 accuracy – T2 accuracy) between target types, \( F(1,18) = 28.09, p < 0.001 \) (Fig. 7a). In the SC-SC condition, there was a 0.18 (SE = 0.04) average difference between T1 and T2 accuracy whereas the Cat-Cat condition showed a -0.08 (SE = 0.02) difference. This difference suggests faster attentional deployment to singleton color targets than categorically defined targets according to simulations of the eSTST model.

In experiment 2 the AD scores between target types were significantly different as well (\( M = 0.03, SE = 0.06 \) for non-singleton color and \( M = -0.12, SE = 0.02 \) for categorical), \( F(1,17) = 5.56, p = 0.03 \) (Fig. 7a) which suggests a small attentional latency difference that was not observable in the N2pc latencies. Importantly, the AD score for SC-SC targets was substantially and significantly larger than it was for NSC-NSC targets (0.18 vs 0.03; \( F(1,34) = 4.71, p = 0.04 \)). These results converge with the N2pc latency findings to show that the difference in attention latency between non-singleton color and categorical targets is smaller than that of singleton color and categorical targets.

3.6. Linking behavior to model parameters: memory encoding latency and swap errors

Another behavioral metric of two sequential targets is the likelihood of reporting them in the wrong order, which happens with a probability that is affected by multiple parameters, such as the onset asynchrony of the two targets (Caldwell-Harris & Morris, 2008; Chun & Potter, 1995), their spatial proximity (Wyble & Swan, 2015) and also the type of target. These swap errors are
thought to result from the relative time at which the encoding of each target is completed, such that if T2 encoding is completed quickly, it might enter working memory prior to T1 (Olivers, Hilkenmeier, & Scharlau, 2011; Wyble et al., 2009) or be bundled together into the same representation (Bowman & Wyble, 2007; Hommel & Akyürek, 2005). It could also be that as these stimuli cannot be coherently combined, their swapped order is the product of the visual systems attempt to integrate them into one temporal episode (Akyürek et al., 2012). In eSTST simulations, when T1 and T2 both take longer to encode, the likelihood of them being stored in the wrong order is higher. This is because the initial SOA between the targets has comparatively less influence on which target is encoded first when encoding into memory takes longer.

In these simulations, the proportion of swap errors is affected by both the attentional latency (i.e. bdelay) and memory encoding latency (i.e. typeweight), since both of these parameters affect the total encoding time. Fig. 6b shows that in eSTST simulations, whereas the AD was primarily affected by attentional latency, the proportion of swap rates is strongly influenced by both parameters. Thus, considered in relation to AD, the proportion of swap errors provides a behavioral measure that indicates memory encoding latency.

3.7. Swap rate errors results

In experiment 1, the first and second targets of the SC-SC condition were swapped ($M = 0.07$, $SE = 0.02$) significantly less often than Cat-Cat targets ($M = 0.23$, $SE = 0.03$; $F(1,18) = 25.29$, $p < 0.001$; Fig. 7b). There was also a significant difference in swap rates between conditions in experiment 2, $F(1,17) = 29.37$, $p < 0.001$. NSC-NS targets had a swap rate of 0.12 ($SE = 0.02$) whereas Cat-Cat targets had, again, a swap rate of 0.23 ($SE = 0.03$) (Fig. 7b). Comparing singleton color and non-singleton color swap rates (0.07 vs 0.12) across experiments revealed no significant difference, $F(1,34) = 1.91, p = 0.18$.

These behavioral results provide convergent support for the accompanying EEG data by revealing evidence of a difference in memory encoding latency for both experiments 1 and 2. Thus, even though there is only weak evidence of an attentional latency difference between categorical and non-singleton color targets, there is strong evidence of an encoding latency difference.

3.8. Experiment 3

One possible confound in the two previous studies was that categorical targets were always digits, in addition to being of a different category to letters. This difference could have caused the slower P3 onset for the Cat condition. This experiment attempted to replicate the EEG results of experiments 1 and 2 using a simpler paradigm with only 1 target per trial, all target-types within each subject, and with reversed target/distractor categories for the Cat condition.

3.9. Participants

Sixteen undergraduate participants were used for this study. All participants signed informed consent forms prior to participation. Fifteen participants passed trial rejection criteria and were used in analysis.

3.10. Stimuli & apparatus

The same stimuli and equipment were used as in experiments 1 and 2.

### 3.11. Procedure

As in the previous experiments, on every trial participants were presented with two RSVP streams on either side of fixation. In this study however there was only ever one target per trial. This experiment had two blocks: the SC-Cat block and the NSC-Cat block. In the SC-Cat block participants were told that targets were either digits of a target color (SC) or black letters (Cat). Distractors were black digits. The color of the target digits were chosen randomly out of the possible 5 colors (see previous method section for detail) and was constant throughout the entirety of the experiment. In this sense the SC-Cat block was slightly different from experiment 1 because while the color of the targets were constant and were pop out, they were not necessarily red for every participant. This is an important change as it ensures that the latency effects seen are due to the color-singleton nature of the trial and not specific to red, as has been seen in previous work (Fortier-Gauthier, Dell’Acqua, & Jolicœur, 2013). Cat and SC trials were randomly mixed within block. In the NSC-Cat block participants were told that targets were either digits of a target color (NSC) or letters of any color (Cat). The target color used in the NS-Cat block was the same as that used in the SC-Cat block. In this block the distractors were digits of the remaining four colors. The same reporting procedure was used at the end of each trial. The order of the blocks was counterbalanced across participants. After accuracy and artifact rejection, the average number of trials per condition were 54 (SC), 62 (Cat), 51 (NSC) and 59 (Cat).

### 4. Results

#### 4.1. Behavioral results

In order to have participants complete enough trials of each target type in a single testing session and to maximize the number of accurate trials, only the single target conditions from Experiments 1 & 2 were used in Experiment 3. Therefore the AD scores and swap rates are unavailable. However the single target accuracies per condition are displayed in Table 1. There was significant difference found in target accuracy between conditions, $F(3,14) = 9.21$, $p < 0.01$.

#### 4.2. N2pc latency

The same analysis technique was used to measure both the N2pc and P3 latency as was described in the previous experiments. As was found in experiment 1, there was a significant difference in the SC-Cat block between the N2pc onset to singleton color targets ($M = 176 ms, SE = 10$) compared to categorical targets ($M = 222 ms, SE = 18$), $F(1,14) = 5.47, p = 0.03$ (Fig. 8). Just as in experiment 2, no significant difference was found in the NSC-Cat block between non-singleton color targets ($M = 236 ms, SE = 9$) and categorical targets ($M = 227 ms, SE = 4$), $F(1,14) = 0.73, p = 0.41$. Experiment 3 also allowed us to compare the N2pc onset time to categorical targets across blocks ($M = 222 ms VS M = 227 ms$) in a within subject analysis which revealed no significant difference $F(1,14) = 0.07, p = 0.80$. The lack of a difference supports the use of categorical targets as a reliable baseline by which to compare the singleton color and non-singleton color targets in the previous experiments.

#### Table 1

<table>
<thead>
<tr>
<th></th>
<th>SC</th>
<th>Cat</th>
<th>NSC</th>
<th>Cat</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 Accuracy</td>
<td>0.92 (0.01)</td>
<td>0.95 (0.01)</td>
<td>0.81 (0.03)</td>
<td>0.89 (0.03)</td>
</tr>
</tbody>
</table>
4.3. P3 latency

In the SC-Cat block, there was a significant difference between P3 onset to singleton color targets ($M = 306, SE = 12$) and categorical targets ($M = 385, SE = 7$), $F(1,14) = 43.54, p < 0.001$. In the NSC-Cat block there was also a significant difference between non-singleton color targets ($M = 336, SE = 4$) and categorical targets ($M = 398, SE = 9$), $F(1,14) = 45.60, p < 0.001$. These results are consistent with experiments 1 and 2. Comparing across blocks we also found a significant difference between the P3 onset for singleton color compared to non-singleton color targets ($M = 307$ ms vs $M = 336$ ms), $F(1,14) = 6.15, p = 0.03$.

5. General discussion

The processing of a visual stimulus from a percept into a memory trace involves a series of cognitive operations that are difficult to dissociate with measures of RT or single-target accuracy alone. In this paper, we use convergent electrophysiological and behavioral measures to detect differences in the time course of attention and subsequent encoding into memory for targets with different signifying criteria. For EEG, the N2pc and P3 components provide measures of these processes, which highlights the utility of EEG in dissociating distinct stages of processing. Measuring these latencies using behavior is more difficult so we developed a new method using two sequential targets and examined differences in the ability to report them and the likelihood of reporting them in the correct temporal order. The eSTST model of sequential target processing (Wyble et al., 2009) provides a formalized way of mapping these behavioral variables onto attentional latency and the speed of memory encoding. This convergence between behavior and neurophysiology is important because findings that rely on EEG results in the absence of corresponding behavioral evidence invoke assumptions about what the potentials represent and such assumptions may not hold across experiments. Thus, measuring the effect simultaneously with both behavior and EEG is not only reassuring as to the robustness of the results, but is also ultimately essential for validating electrophysiological indices of cognitive processes.

5.1. Understanding the behavioral and EEG results

The latencies of the N2pc and P3 components of the EEG, which are typically assumed to reflect attention and memory encoding respectively, were used in these experiments to measure the time at which these processing stages began for different target types. Experiment 1 revealed a difference of 40 ms in N2pc latency between the singleton color and categorical targets and a 77 ms difference in the latency of P3 components. These findings were replicated in experiment 3 which found a 46 and 79 ms difference in N2pc and P3 onset respectively between singleton color and categorical targets. The EEG results of experiment 2 revealed no difference in the N2pc latency between categorical and non-singleton color marked targets, but a clear difference in the time of the P3 onset (59 ms), with non-singleton color being faster than categorical. These results were also replicated in experiment 3 which found a 63 ms difference in P3 latency between non-singleton color and categorical targets. The fact that the P3 latencies differ while the N2pc latencies do not suggests there are differences in processing speed for different types of targets despite similar attention latencies.

Behavioral data, as interpreted through the eSTST model (Wyble et al., 2009), provided partially convergent support for these findings. The model simulations indicate that differences in the time of attentional latency are reflected in the AD score (T1 accuracy – T2 accuracy) for two targets presented in rapid succession at the same spatial location. According to the model, if attentional latency is relatively slow, the second target should be reported more often than the first target and vice versa. This was the exact pattern seen in the categorical condition of experiment 1 where T2 had a substantially higher accuracy than T1. The opposite pattern was seen for the singleton color targets, suggesting a much shorter attentional latency. These results thus mirrored the substantially earlier N2pc for the singleton color targets versus categorical ones. In experiment 2 the behavioral results provided more modest support...
for the EEG findings since there was a small but significant difference in the AD scores that was not reflected in the N2pcs. One possibility is that the behavioral measure was able to detect attentional latency differences that were too small to detect with EEG measures. While these two different correlates do not exactly agree with one another, they do support the conclusion that the difference between attentional latency to singleton color and categorical targets is greater than that between non-singleton color and categorical targets. This discrepancy in results highlights the importance of using multiple types of measurement since using either just behavior or just EEG would not have told the complete story. Similar differences between behavioral and EEG measurements have been found in previous research (Smigiesiwc, Hasan, & Verleger, 2017). These efforts to link behavioral and neural correlates are essential for understanding the underlying mechanisms.

The other behavioral measure from two sequential targets is the likelihood of them being reported in the wrong order. The eSTST model suggests that this metric reflects the relative memory encoding time, such that slower encoding into memory produces comparatively more swaps than does faster encoding. For this measure, both experiments revealed a highly significant difference between target types, with categorical targets being swapped more often than both singleton color and non-singleton color targets. These results again converge with the EEG results, which revealed similar corresponding differences in the P3 onset latency.

5.2. Attentional latency differences

The difference in attentional latency between singleton color and categorical targets was not surprising as previous research has found similarly shorter latencies for singleton color targets (Brisson, Robitaille, & Jolicour, 2007; Töllner, Zehetleitner, Gramann, & Müller, 2011), but we had also expected a clear difference in the attentional latency for non-singleton and categorical targets that was not observed. This prediction rested on the idea that complex shapes such as letters or digits would be detected at later stages of processing than simple colors. Furthermore, in our experiments the participants did not know which specific digit(s) would be presented on a given trial while the target color in the non-singleton color condition was always consistent which should have given a further advantage to the attentional latency for color-defined targets.

Having found instead that non-singleton color and categories triggered attention with almost identical latencies according to the N2pc, and only modestly different latencies according to the behavior, these results thus contribute directly to the growing body of research which suggests that attention to a category can be a highly efficient attentional set, which allows categorically specified target sets to be detected from an RSVP of images (Potter, 1976); to trigger N2pcs (Nako, Wu, Smith, & Eimer, 2014), to direct eye movements (Alexander & Zelinsky, 2011; Maxfield, Stalder, & Zelinsky, 2014; Yang & Zelinsky, 2009), to trigger spatial attention (Wyble, Potter & Bowman, 2009), produce attentional capture effects (Wyble, Folk, & Potter, 2013) and trigger efficient enhancement or suppression depending on task demands (Hickey & Peelen, 2015). The present results contribute a first direct comparison of latencies for color and category within a single experiment, using a common attentional set (i.e. subjects were simultaneously looking for the both the color and category targets).

We note that the characters used in the present study are highly familiar, and participants who are fluent speakers of English presumably have at least 10 years of exposure to the categorical distinction between letters and digits. It has been proposed that the binding of features described by Feature Integration Theory is necessary for “on-demand” conjunctions with no previously learned importance, such as finding the red square among green squares and red circles (Vanrullen, 2009). On the other hand, highly over-learned categorical boundaries for highly familiar stimuli have been shown to produce extremely efficient attentional selection (Schneider & Shiffrin, 1977).

5.3. Understanding the transition from attention to memory encoding

Another important finding from experiments 2 and 3 was the fact that there were clear differences in encoding speed between categorical and non-singleton color targets, as measured by the P3 onset latency, that were not accompanied by a correspondingly clear attentional latency differences as measured by the N2pc. Thus, non-singleton colors and categories triggered attention at almost the same latency, but there were clear differences in the latency of encoding into memory in both the EEG and the behavioral results. Note that the more rapid encoding for color-defined targets is unlikely to be due to differences in familiarity of the information to be remembered, since the information in both conditions was highly familiar (letters and digits). In fact, the set of digits in the categorical target set was smaller than the corresponding set of letters in the color-marked set, which one might have expected to increase encoding speed for the categorical targets.

One potential interpretation of these results is that despite the fact that color-defined targets could not recruit attention more rapidly, the relative simplicity of the color based target signifier was able to more rapidly engage the circuits responsible for transferring information from a sensory representation to a working memory representation. These results place important constraints on the search for mechanisms of attention and memory by suggesting that there are factors governing the speed of memory encoding that are not associated with corresponding changes in the speed of attentional deployment. Furthermore, the similarity of attentional latency between non-singleton color and categorical conditions implies that perceptual experience rewrites the perceptual hierarchy of the visual system to such a high degree that familiar categorical distinctions can trigger attention almost as rapidly as simpler features like color. Previous work has demonstrated behavioral (Wyble, Potter & Bowman 2009; Wyble et al., 2013) and neural evidence (Eimer, 1996; Nako et al., 2014; Thorpe, Fize, & Marlot, 1998) for the rapid deployment of attention by categorical and conceptual content, but these are the first experiments to compare the onset latency of the neural correlate of attention directly between such conditions using a single task set.

6. Conclusion

This research demonstrates that we can separately measure the speed of attention and encoding into memory to different kinds of targets. Moreover, it provides convergent measures through the use of a computational model that maps behavioral responses to these internal cognitive mechanisms. The level of temporal granularity afforded by this technique allows us to discern differences between three target types at two different stages of processing. Unsurprisingly, singleton color targets triggered attention and encoding into memory earlier than categorical targets. However, non-singleton color targets showed no advantage in attentional deployment speed over categorical targets in the ERP data and only a small amount in the corresponding behavioral metric. Despite this result, non-singleton color targets were nevertheless encoded into memory more rapidly. These findings suggest that the attentional benefits to singleton color targets are largely due to the fact that they are singletons, rather than their status as being marked by simple color features. The results also revealed an intriguing discrepancy between attention and encoding latencies.
The use of a computational model is critical here as a way to relate behavior to internal mechanisms that would otherwise be difficult to dissociate. These results also suggest that future work could make use of the predicted relationship between the difference in target accuracies and swaps for two sequential targets to dissociate attention from memory encoding without the need for EEG recording.

Acknowledgments

The Authors wish to thank Gregory Wade, Joseph Stucynski, Michael Hess and Andrew Maceyko for their help with data collection. This work was supported by NSF grant BCS-1331073.

Appendix

This section presents the same analyses conducted for experiments 1 & 2, this time on single and double target conditions separately. To be consistent, the same subsample of subjects used in the main analysis was used here.

Single Target Condition, N2pc analysis. There was no significant difference between the N2pc latency of singleton color targets ($M = 164$ ms, $SE = 7$) and categorical targets ($M = 206$ ms, $SE = 38$), $F(1,18) = 1.09, p = 0.31$. In experiment 2 there was also no difference between the N2pc latency of non-singleton color ($M = 220$ ms, $SE = 23$) and categorical targets ($M = 217$ ms, $SE = 8$), $F(1,17) = 0.01, p = 0.92$ (Fig. i).

Fig. i. N2pc difference wave (P7/P8) and P3 ERP (Pz) from single target conditions in experiments 1 & 2.

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Single Target Condition, P3 analysis. There was a significant difference between the P3 latency of singleton color targets (M = 290 ms, SE = 10) and categorical targets (M = 378 ms, SE = 14), F(1,18) = 42.99, p < 0.001. There was also a significant difference in experiment 2 between the P3 latencies of non-singleton color (M = 337 ms, SE = 12) and categorical targets (M = 394, SE = 11), F(1,17) = 26.15, p < 0.001 (Fig. i).

Double Target Condition, N2pc analysis. In experiment 1 there was a significant difference between singleton color (M = 167 ms, SE = 10) and categorical (M = 204 ms, SE = 6) N2pcs, F(1,18) = 10.80, p < 0.01. In experiment 2 there was no significant difference between the N2pc elicited by non-singleton color targets (M = 210, SE = 33) and that elicited by categorical targets (M = 210, SE = 28), F(1,17) < 0.01, p = 0.99 (Fig. ii).

Double Target Condition, P3 analysis. In experiment 1 there was a significant difference in P3 latency between singleton color (M = 299 ms, SE = 6) and categorical targets (M = 369 ms, SE = 10), F(1,18) = 47.46, p < 0.001. There was a significant difference in experiment 2 between non-singleton color (M = 337 ms, SE = 9) and categorical targets (M = 397 ms, SE = 25), F(1,17) = 5.06, p = 0.04 (Fig. iii).


underlying the left-hemifield advantage in rapid serial visual presentation. *Journal of Cognitive Neuroscience, 21*(3), 474–488.


