

**Category-based guidance of spatial attention
during visual search for feature conjunctions**

Rebecca Nako, Anna Grubert, & Martin Eimer*

*Corresponding author

Department of Psychological Sciences, Birkbeck College, University of London,
Malet Street, London WC1E 7HX, UK

Phone: 0044 20 76316358

Fax: 0044 20 76316312

Email: m.eimer@bbk.ac.uk

Short title: Category-based attentional control

Abstract

The question whether alphanumerical category is involved in the control of attentional target selection during visual search remains a contentious issue. We tested whether category-based attentional mechanisms would guide the allocation of attention under conditions where targets were defined by a combination of alphanumerical category and a basic visual feature, and search displays could contain both targets and partially matching distractor objects. The N2pc component was employed as an electrophysiological marker of attentional object selection in tasks where target objects were defined by a conjunction of color and category (Experiment 1) or shape and category (Experiment 2). Some search displays contained the target or a nontarget object that matched either the target color/shape or its category among three non-matching distractors. In other displays, the target and a partially matching nontarget object appeared together. N2pc components were elicited not only by targets and by color- or shape-matching nontargets, but also by category-matching nontarget objects, even on trials where a target was present in the same display. On these trials, the summed N2pc components to the two types of partially matching nontargets were initially equal in size to the target N2pc, suggesting that attention was allocated simultaneously and independently to all objects with target-matching features during the early phase of attentional processing. Results demonstrate that alphanumerical category is a genuine guiding feature that can operate in parallel with color or shape information to control the deployment of attention during visual search.

Keywords: selective attention, visual search, category-based attentional control, event-related brain potentials, feature-based attention, object-based attention

Introduction

The visual world often contains multiple objects and events that compete for perceptual processing and for access to the cognitive mechanisms that are responsible for their identification and for the selection of appropriate responses. Mechanisms of selective attention resolve this competition in favor of those objects that are relevant for current task goals. In visual search tasks, where observers have to find particular target objects among multiple distractors, the allocation of attention can be guided by representations of target-defining features (attentional templates) in working memory (e.g., Duncan & Humphreys, 1989; Wolfe & Horowitz, 2004; Olivers et al., 2011). Such attentional templates are set up prior to the arrival of visual search displays, and facilitate the visual processing of template-matching visual objects in a spatially selective fashion (e.g., Desimone & Duncan, 1995; Eimer, 2014, 2015). When search targets are defined by a specific feature (e.g., the color red), search templates will bias attention towards objects with this particular feature, even when these template-matching objects are task-irrelevant and have to be ignored (task-set contingent attentional capture; see Folk et al., 1992; Folk & Anderson, 2010; Eimer & Kiss, 2008).

The question of which stimulus attributes can guide attention effectively during visual search is still controversial. There is agreement that basic physical stimulus features like color, motion, orientation, and size can be represented in attentional templates when they are task-relevant, and that these templates can control the deployment of attention in visual search tasks. However, the role of other visual properties for the guidance of attention in visual search is less clear. In particular, there is as yet no consensus whether the category membership of a target object can be employed as a guiding attribute for visual search. In their influential review article, Wolfe and Horowitz (2004) concluded that the role of alphanumeric category in the guidance of search performance is doubtful, and that information about the semantic category of visual stimuli can probably not be used for the goal-directed control of visual search. Studies investigating the role of object categories for the control of attention have often focused on questions such as how the typicality of an object with respect to its category affects its selection as a target object during visual search (e.g., Castelhana, Pollatsek, & Cave, 2008; Maxfield, Stalder, & Zelinsky, 2014), or how shared category-defining features make items within the same category more similar to

each other, thereby improving search efficiency (Alexander & Zelinsky, 2011; see also Alexander & Zelinsky, 2012). The observation that search for category-defined targets is slower than search for a specific exemplar within this category, but faster than random search (Yang & Zelinsky 2009) suggests that information about object categories can guide search to some degree, but perhaps less efficiently than information about basic visual target features. In line with this apparent superiority of attentional templates for basic visual stimulus features, experiments using eye tracking (Malcolm & Henderson, 2009) or event-related brain potentials (ERPs; Nako, Smith, & Eimer, 2015) have shown that the selection of real-world target objects is less efficient when target identity is specified by word cues than when selection can be guided by a representation of visual target properties.

These observations suggest that although object categories may be involved in the control of target selection processes during visual search, the ability of category information to guide attention is limited, and certainly inferior to the role played by basic visual stimulus features during the template-guided control of search processes. However, this conclusion was called into question by the results of recent studies from our lab where electrophysiological measures were used to compare the time course of attentional object selection during feature-based and category-based visual search (Wu et al., 2013; Nako, Wu, & Eimer, 2014). In these experiments, search displays contained alphanumeric characters, and search targets were defined either at the item level (e.g., letter *C*) or categorically¹ (e.g., any letter). These target definitions were specified either at the start of each trial by precues (Wu et al., 2013) or prior to each block by experimental instructions (Nako et al., 2014). To determine how rapidly targets were selected during item-based and category-based search, we measured the N2pc component as a marker of the allocation of attention to target objects (Luck & Hillyard, 1994; Eimer, 1996). The N2pc is an enhanced negativity at occipitotemporal electrodes contralateral to the side where a target appears among distractors in a search display. This component is generated in retinotopic extrastriate ventral visual cortex (Hopf et al., 2000), and reflects the attentional selection of candidate target objects during visual search. When search targets are defined by simple visual

¹ For simplicity, we will use the terms ‘category’ and ‘alphanumeric category’ interchangeably to both refer to digit/letter categorizations in the rest of this article. Whenever a different type of category is discussed, this will be stated explicitly.

features such as color or shape, N2pc components emerge around 180-200 ms after stimulus onset (e.g., Luck & Hillyard, 1994; Kiss, Jolicoeur, Dell'Acqua, & Eimer, 2008; Grubert & Eimer, 2013), demonstrating that attentional templates for such features can guide attention rapidly and efficiently to the location of search targets.

In our studies of feature-based and category-based attentional selection processes (Wu et al., 2013; Nako et al., 2014a), N2pc components were elicited not only by targets that were defined at the item level, but also by category-defined targets. This suggests that when the deployment of attention has to be guided by search templates for object categories, target objects can still be selected rapidly, at relatively early stages during the processing of visual input. Importantly, when observers searched for a particular item, nontarget objects that matched the category of the current target (e.g., the letter A during search for the letter P) also triggered N2pc components (Nako et al., 2014a). Although this “foil” N2pc was smaller than the N2pc to targets, it was already reliably present during the 180-200 ms post-stimulus interval. This observation suggests that when observers search for a particular alphanumeric item, the category of this item is activated as part of an attentional template, and produces rapid spatially selective modulations in the visual processing of category-matching objects (see also Nako et al., 2014b, for the presence of similar foil N2pcs during item-based search for real-world objects).

In contrast to previous assertions that the role of alphanumeric category in the guidance of visual search is doubtful (Wolfe & Horowitz, 2004), these N2pc results suggest that category-based search templates can affect attentional selection processes rapidly, within approximately 200 ms after stimulus onset. If this is the case, alphanumeric category may have to be included among the features that are able to guide the deployment of spatial attention in an effective fashion. There are different ways in which this type of category-based attentional guidance could be implemented. One possibility is that the discrimination between letters and digits is based on a (potentially complex) set of visual features that in conjunction uniquely specify the category of alphanumeric characters (see Yang & Zelinsky, 2009, for a feature-based account of category guidance during search for real-world objects). In this case, the allocation of attention to letters versus digits would be guided by a combination of these diagnostic visual features. Alternatively, it is possible that alphanumeric category is already extracted in parallel at a pre-attentive level (e.g., Duncan, 1980). If this was correct, the guidance of attentional

selectivity during letter-digit search might be based on such information about the category membership of different objects in the visual field. We will return to this issue in the General Discussion.

In all previous N2pc studies that provided evidence for the guidance of attentional selection processes in visual search by category (Wu et al., 2013; Nako et al., 2014a, 2014b), category-defined target objects were always accompanied by multiple distractor objects that belonged to a different task-irrelevant category (e.g., one target letter among digits during letter search, or one kitchen object among items of clothing during search for kitchen utensils). In other words, target objects were category singletons in the sense that they were the only category-matching item in the search displays. Even though the presence of N2pc components to these category-defined targets demonstrates that category-based attentional guidance can operate rapidly under these circumstances, it is not yet known whether this is also the case when category-matching items are accompanied by other candidate target objects in the same search display. Because top-down attentional guidance processes are most relevant in search tasks where multiple potential target objects compete for selection, it is important to find out whether category-based guidance processes are still available under such conditions.

The most frequently studied case where attentional control processes are required to resolve the competition between multiple candidate target objects is conjunction search. Here, a target defined by a specific combination of features from different dimensions (e.g., a red circle) can appear together with distractor objects that match one but not all target-defining features in the same displays (e.g., red squares and blue circles). The Guided Search model (Wolfe, 1994, 2007) assumes that in such tasks, signals from all currently task-relevant dimensions will contribute jointly to the guidance of attention towards the most likely target objects. However, only low-level visual attributes (color, motion, orientation, or size) are assumed to be able to participate in such joint attentional guidance processes, whereas object category is not (Wolfe & Horowitz, 2004). The goal of the present study was to find out whether this hypothesis is correct. This can be tested in search tasks where targets are defined by the conjunction of their alphanumeric category and another basic visual feature. For example, when participants search for red digits that can be accompanied by red letters or by digits in a different nontarget color, is the allocation of attention

exclusively controlled by color or does alphanumerical category contribute to attentional guidance?

The task design employed in the present experiments was analogous to the design of a recent N2pc study where targets were defined by a specific combination of color and shape (Eimer & Grubert, 2014a). Search displays always contained four objects. In no-competition trials, only one object with target-matching features was present, and this could be the target or a nontarget object that matched either the target color (e.g., a blue circle) or the target shape (e.g., a green square). In competition trials, the target appeared together with a partially matching nontarget object. To use the N2pc as a marker of the attentional selection of an object with target-matching features on competition trials, this component has to be measured independently from any parallel attentional processing of the other target-matching object in the same display. Because the N2pc is elicited contralaterally to candidate target object in the left or right visual field, no N2pc is triggered when such objects appear on the vertical meridian (e.g., Woodman & Luck, 2003; Hickey, McDonald, & Theeuwes, 2006; Eimer, Kiss, & Nicholas, 2011; Eimer & Grubert, 2014b). For this reason, all search displays contained two objects on the horizontal midline (to the left and right of fixation) and two objects on the vertical meridian (above and below fixation). On competition trials, one object with target features (either the target or a partially matching nontarget) appeared on the vertical meridian and the other on the horizontal meridian, and N2pc components therefore exclusively reflected the allocation of attention to the horizontal target-matching object. On no-competition trials, N2pc components were elicited not only by target objects but also by color-matching and shape-matching nontargets. Importantly, both types of partially matching nontargets also triggered reliable N2pc components in competition trials where they appeared together with a target object on the vertical midline. Furthermore, the sum of these two N2pc components was identical in size to the N2pc to target objects during the early phase of the N2pc (from 180 ms until around 230 ms post-stimulus).

These N2pc results suggest that color-based and shape-based attentional guidance processes initially control the deployment of attention independently and in parallel. During this early phase of spatially selective processing, attention is deployed simultaneously to all objects with target-matching features, even when the target object itself is present in the same display. An alternative serial selection model (e.g., Wolfe, 2007) would assume that

attention is directed to targets on most competition trials, and to a partially matching nontarget on a minority of these trials. If this was the case, the summed contribution of the N2pc to partially matching nontargets should have been much smaller than the target N2pc throughout the whole N2pc time window. The presence of additive N2pc effects of color-matching and shape-matching nontargets that equaled the early N2pc to target objects was not in line with this prediction, and suggested instead that the initial stage of feature-guided attentional selectivity can operate in parallel for multiple objects.

To find out whether alphanumerical category can guide the allocation of attention even when another visual feature is simultaneously task-relevant and when multiple items with target-matching attributes can be present in the same search display, we ran two experiments that used the same procedures as our previous color/shape conjunction search study (Eimer & Grubert, 2014a), except that one of the two target-defining attributes was now alphanumerical category (letter versus digit). Because sixteen participants were included in this previous study, the same sample size was used in the current experiments, to allow for direct comparison between the N2pc results obtained in these two studies. In Experiment 1, search displays contained colored digits and letters, and targets were defined by a specific color/category combination (e.g., green digits, as illustrated in Figure 1). On different trials that appeared in random sequence within each block, displays could contain one, two, or no items with target-matching features. On no-competition trials, a target object (Figure 1A and 1B, green digits) or a nontarget object that matched the target color (Figure 1C and 1D) or the target category (Figure 1E and 1F) appeared together with three distractor objects without target-matching features. On competition trials (Figure 1G – 1J), a target object was presented together with a color-matching or category-matching nontarget and two nonmatching distractors. One feature-matching item always appeared on the horizontal meridian and the other on the vertical meridian on these competition trials. On distractor-only trials, displays contained four nonmatching items (Figure 1K).

If alphanumerical category can control the deployment of attention during conjunction search in the same way as basic visual features such as color and shape, the time course of attentional selection processes in Experiment 1, as reflected by N2pc components to targets and partially matching nontargets, should be similar to the pattern observed in our earlier color/shape conjunction search study (Eimer & Grubert, 2014a). On no-competition trials, N2pc components should be elicited not only in response to targets

but also for color-matching nontargets and, importantly, for category-matching nontargets (e.g., a blue digit during search for green digits). On competition trials, where a partially matching nontarget appears together with a target object in the same display, N2pc components should not only be observed in response to lateral targets, but also for search displays where a lateral partially matching nontarget is accompanied by a target on the vertical midline. Critically, N2pc components should not only be elicited by color-matching nontargets that appear together with a vertical target (as shown in our previous study; Eimer & Grubert, 2014a), but also by category-matching nontargets. If color-based and category-based attentional control processes operate independently and in parallel at different locations in the visual field during the early phase of attentional target selection, the sum of the two N2pc components to color-matching and category-matching nontargets should initially equal the N2pc to target objects on competition trials.

The alternative possibility is that information about alphanumeric category cannot be employed to guide attention during color/category conjunction search. In this case, early attentional selection processes, as reflected by the N2pc component, will be exclusively controlled by color. N2pc components should therefore be only elicited by targets and color-matching nontargets, but not by category-matching nontarget objects. If category-based attentional guidance is unavailable, any discrimination between digits and letters can only take place after the color-based deployment of attention. In this case, targets and color-matching nontarget objects should trigger identical N2pc components, and ERP differences between these two types of objects should only emerge at longer post-stimulus latencies.

Experiment 1

Methods

Participants

Nineteen paid volunteers with normal or corrected to normal vision participated in the experiment. One participant was excluded due to poor task performance (accuracy below 62%), and two due to an excessive number of eye movements, resulting in the

rejection of more than 50% of all trials. The remaining sixteen participants were aged between 21 and 42 years ($M = 29.7$, $SD = 6.23$), 12 were female, and 4 were left handed.

Stimuli, Design, and Procedure

Stimuli were presented against a black background on a 24-inch LCD monitor with a resolution of 1280 x 1024 pixels and a 100 Hz refresh rate. Stimuli were presented using Matlab (Mathworks, Inc.) and the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/). Participants were seated at a distance of approximately 100 cm from the screen. They were asked to maintain fixation on a central grey fixation dot which was present throughout each block. On each trial, a search display was presented for 150 ms, and was followed by an intertrial interval of 1650 ms. All search displays contained four colored alphanumerical characters (size of each item: $0.6^\circ \times 0.6^\circ$). Two items were always presented on the horizontal meridian (to the left and right of fixation), and the other two on the vertical meridian (above and below fixation), at an eccentricity of 1.9° from fixation (see Figure 1). Stimuli were letters (A, G, P, Q, R, U) or digits (2, 4, 5, 6, 7, 8). These specific items were chosen to balance letters and digits for low-level features (curvature, intersections, number of pixels per item). Item colors were green (CIE x/y coordinates: .262/.572), blue (.185/.188), cyan (.212/.347), and yellow (.342/.477). All colors were equiluminant (9.8 cd/m^2).

Participants' task was to search for a target that was defined by a specific combination of color and alphanumerical category (e.g., a green digit), and to report its presence or absence on each trial by pressing one of two vertically aligned purpose-built response keys with their left or right index finger. The assignment of target-present and target-absent responses to the top and bottom key, or vice versa, was counterbalanced across participants. After eight of the 16 experimental blocks, the hand-to-key mapping was swapped for all participants. Target identity was counterbalanced across participants. Each of the eight possible combinations of color (green, blue, cyan, yellow) and category (letter, digit) served as target for two participants, and target identity remained constant throughout the experiment for each participant.

Different types of search displays appeared in random order within each experimental block. On no-competition trials (Figure 1, A-F), a single item with target-matching features appeared among three non-matching distractors. This target-matching item could either be the target (target-only trials; Figure 1A and 1B), a nontarget item that

matched the target color but not its category (color-matching nontarget – colMNT, e.g., green letter; Figure 1C and 1D) or a nontarget that matched the target category but not its color (category-matching nontarget – catMNT, e.g., yellow digit; Figure 1E and 1F). On half of all no-competition trials, the target or the partially matching non-target appeared on the horizontal meridian, and on the other half on the vertical meridian. In competition trials (Figure 1G through 1J), the target object appeared together with a color-matching or with a category-matching nontarget in the same display. A target on the horizontal meridian could be accompanied by a color-matching nontarget (T&colMNT; Figure 1G) or by a category-matching nontarget (T&catMNT; Figure 1I) on the vertical meridian. A target on the vertical meridian could appear together with a horizontal nontarget that matched either the target color (colMNT&T; Figure 1H) or the target category (catMNT&T; Figure 1J). Finally, there were also distractor-only trials, where four nontarget items without target-matching features were presented (Figure 1K). On all trials, non-matching distractor items were selected randomly, with two constraints. No physically identical items were allowed to be present in the same search display, and all displays always contained three different colors, to avoid the presence of color singletons.

The experiment comprised 16 experimental blocks with 96 trials. In each block, there were four no-competition trials for each combination of trial type (target, color-matching nontarget, category-matching nontarget) and location of matching item (left, right, top, bottom), resulting in 48 no-competition trials for each block. There were two competition trials for each combination of trial type (target with color-matching nontarget, target with category-matching nontarget), horizontal matching item (target, non-target), horizontal location of matching item (left, right), and vertical location of matching item (top, bottom), resulting in a total of 32 competition trials per block. To equate the number of target-present and absent-trials, each block included 16 distractor-only trials. Prior to the first experimental block, participants completed a practice block.

EEG Recording and Data Analysis

EEG was DC-recorded from 23 scalp electrodes at standard positions of the extended 10/20 system (500 Hz sampling rate; 40 Hz low-pass filter) against a left-earlobe reference, and re-referenced offline to averaged earlobes. The continuous EEG was segmented from 100 ms before to 400 ms after onset of the search arrays, and was averaged relative to the

100 ms pre-stimulus baseline. Trials with artifacts (horizontal EOG exceeding $\pm 25 \mu\text{V}$, vertical EOG exceeding $\pm 40 \mu\text{V}$, all other channels exceeding $\pm 80 \mu\text{V}$) were removed prior to analysis. This led to an exclusion of less than 20% of all trials for each participant. Separate averaged waveforms were computed for each type of competition and no-competition trials with either a target or a partially matching non-target in either the left or right hemifield. N2pc amplitudes were quantified on the basis of ERP mean amplitudes obtained between 180 and 280 ms after search array onset at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were compared between trial types on the basis of difference waveforms, obtained by subtracting ipsilateral from contralateral ERPs at PO7/8, using the jackknife-based analysis method described by Miller, Patterson, & Ulrich (1998). Sixteen subsamples of grand-averaged difference waves were computed, each excluding a different participant from the original sample. Onset latencies were determined as the point in time when each of these subsample waveforms reached an absolute threshold of $-1\mu\text{V}$. Onset latency differences between trial types were substantiated by means of *t*-tests with *t* values corrected according to the formula described by Miller et al. (1998) and indicated as t_c . All *t*-tests were two-tailed and *p*-values were Bonferroni-corrected where appropriate.

Results

Behavioral Performance

Figure 2 shows mean correct reaction times (RTs; top panel) and error rates (bottom panel), separately for target-present and target-absent trials. For target-present RTs, there was a main effect of display type (target-only, target with colMNT, target with catMNT), $F(2,30) = 10.5$, $p < .001$, $\eta^2 = .412$. RTs to targets that were accompanied by a color-matching nontarget were delayed relative to RTs on trials with a category-matching nontarget and RTs on target-only trials (522 ms versus 512 ms and 514 ms, respectively; both $t(15) > 3.3$; both $p < .01$). There was no RT difference between target-only trials and trials where the target appeared together with a category-matching nontarget, $t(15) < 1$. Response errors occurred on 5% of all target-present trials, and error rates did not differ between display types,

$F(2,30) = 2.8, p = .077, \eta^2 = .157.$ ²

For target-absent displays, a main effect of display type (distractor-only, colMNT, catMNT) on RTs, $F(2,30) = 48.1, p < .001, \eta^2 = .762$, was due to the fact that target-absent responses were faster for distractor-only displays (486 ms) relative to displays with a color-matching nontarget (555 ms; $t(15) = 8.97, p < .001$) or a category-matching nontarget (513 ms; $t(15) = 5.13, p < .001$). The RT delay produced by the presence of a color-matching nontarget was reliably larger than the delay observed for target-absent displays that included a category-matching nontarget, $t(15) = 7.36, p < .001$. There was also a main effect of display type on accuracy rates on target-absent trials, $F(2,30) = 14.8, p < .001, \eta^2 = .496$. Participants incorrectly reported the presence of the target on 7% and 3% of all trials with a color-matching or category-matching object, respectively, but only on 1% of all distractor-only trials.

N2pc Components on No-competition Trials

Figure 3 (top panel) shows grand-averaged ERPs on no-competition trials where displays only contained one fully or partially target-matching object. ERPs triggered in the 350 ms interval after search array onset are shown separately for electrodes PO7/8 ipsilateral and contralateral to the side of the target (left panel), or to a color-matching or category-matching nontarget object (middle and right panels). N2pc components were largest for targets, but were also present for both types of partially matching nontargets. This is illustrated in Figure 3 (bottom panel), which shows N2pc difference waveforms computed by subtracting ipsilateral from contralateral ERPs, separately for all three display types. A repeated measures ANOVA was conducted on ERP mean amplitudes obtained in the 180 - 280 ms post-stimulus interval with the factors display type (target, colMNT, catMNT) and laterality (electrode ipsilateral versus contralateral to relevant stimulus). A main effect of laterality, $F(1,15) = 46.9, p < .001, \eta^2 = .796$, reflecting the presence of reliable

² The tendency for lower error rates on target-present trials with a partially matching nontarget relative to target-only trials (Figure 2, bottom panel) might suggest the presence of a speed-accuracy tradeoff on these trials. To test this, inverse efficiency scores were computed on the basis of both RTs and error rates for target-present trials. The main effect of display type remained significant for inverse efficiency, $F(2,30) = 4.2, p = .025, \eta^2 = .217$, and follow-up analyses confirmed that the presence of a color-matching nontarget impaired performance relative to the other two display types, both $t(15) > 2.66$; both $p < .02$.

N2pc components, was accompanied by a significant interaction between display type and laterality, $F(2,30) = 30.1$, $p < .001$, $\eta^2 = .667$, demonstrating that the N2pc differed in size between the three types of search displays. Follow-up t -tests confirmed that the target N2pc was larger than the N2pc to color-matching nontargets, $t(15) = 5.1$, $p < .001$, and category-matching nontargets, $t(15) = 7.15$, $p < .001$. Color-matching nontargets elicited a larger N2pc than category-matching nontargets, $t(15) = 2.71$, $p = .016$. However, direct comparisons between contra- and ipsilateral ERPs at PO7/8 confirmed that reliable N2pc components were present for all three display types (target-only: $t(15) = 7.68$, $p < .001$; colMNT: $t(15) = 5.95$, $p < .001$; catMNT: $t(15) = 5.50$, $p < .001$).

N2pc Components on Competition Trials

Figure 4 shows ERPs measured on competition trials where the target and a partially matching nontarget object were present in the same search display. ERPs are shown separately for trials where a horizontal target was accompanied by a color- or category-matching nontarget on the vertical meridian (top panels), and trials where a horizontal color-matching or category-matching nontarget was presented together with a vertical target (middle panels). The corresponding contralateral-ipsilateral N2pc difference waveforms for horizontal targets (averaged across displays with a vertical color-matching or category-matching nontarget), color-matching nontargets, and category-matching nontargets are shown in Figure 4 (bottom panel). Targets triggered larger N2pc components than color- or category-matching nontarget objects. However, these partially matching nontargets also appeared to elicit an N2pc, in spite of the fact that they were accompanied by a vertical target object in the same display. Analyses of N2pc mean amplitudes triggered by horizontal target objects revealed a significant main effect of laterality, $F(1,15) = 78.5$, $p < .001$, $\eta^2 = .840$, that was not modulated by whether these targets were accompanied by a color-matching or category-matching nontarget on the vertical meridian, $F(1,15) = 1.9$, $p = .188$, $\eta^2 = .115$. The corresponding analysis of N2pc components to horizontal partially matching nontargets also revealed a significant main effect of laterality, $F(1,15) = 24.0$, $p < .001$, $\eta^2 = .616$, confirming that these objects elicited N2pc components even though a target was simultaneously present in the same display. N2pc components to color-matching nontargets were numerically larger than the N2pc to category-matching nontargets (see Figure 4, bottom panel), but this difference only approached significance, $F(1,15) = 3.4$, $p =$

.085, $\eta^2 = .186$. Follow-up comparisons of contralateral and ipsilateral ERP waveforms showed that N2pc components were reliably present both for color-matching nontargets, $t(15) = 4.12, p = .001$, and category-matching nontargets, $t(15) = 2.47, p = .026$.

The N2pc difference waveforms in Figure 4 (bottom panel) also include the sum of the two N2pc components to horizontal color-matching and category-matching nontarget objects that appeared together with a target on the vertical meridian. During the early phase of the N2pc, the N2pc to target objects was similar in size to the summed contribution of the N2pc components to color-matching and category-matching nontarget objects. To assess this formally, the N2pc difference waveform to horizontal targets was compared to the summed N2pc waveforms to horizontal color- and category-matching nontargets. There was no reliable onset latency difference between these two N2pc waveforms, $t_c(15) < 1$, confirming that the summed N2pc to color-matching and category-matching nontargets started at the same time as the N2pc to target objects. The point in time when target N2pc amplitude started to become larger than the sum of the two N2pc components to partially matching nontargets was assessed via a series of paired t-tests that were conducted for each post-stimulus sampling point (for similar analyses, see Blair & Karniski, 1993; Jacques, Schiltz & Goffaux, 2014). The onset of an N2pc amplitude difference between targets and summed partially matching nontargets was defined as the point in time when this difference remained reliable for at least five successive sampling points. This analysis showed that the target N2pc started to become larger than the summed contribution of the N2pc to the two types of partially matching nontargets at a post-stimulus latency of 216 ms. To provide additional evidence that during the early phase of the N2pc, the summed N2pc components to partially matching nontargets were equal in size to the target N2pc, the N2pc measurement window (180 -280 ms post-stimulus) was divided into two successive 50 ms time intervals (180 – 230 ms and 230-280 ms post-stimulus). During the early N2pc time interval, there was no reliable difference in N2pc mean amplitudes between targets and summed partially matching nontargets, $t(15) = 1.08, p = .297$. During the later time interval, the target N2pc was significantly larger than the sum of the two N2pc components to color- and category-matching nontargets, $t(15) = 4.1, p = .001$.

Discussion of Experiment 1

When targets were defined by a conjunction of color and alphanumeric category, partially target-matching nontarget objects were able to attract attention, as reflected by reliable N2pc components, even when they were accompanied by a target in the same display. Critically, this was the case not only for nontargets that matched the target color, but also for category-matching nontargets. On no-competition trials where a target or partially matching nontarget was presented together with three distractors, N2pc components were elicited by lateral targets as well as in response to displays that contained a color-matching or category-matching nontarget on the left or right side (Figure 3). The observation that category-matching nontargets triggered N2pc components on no-competition trials demonstrates that category-based guidance signals were involved in controlling the allocation of attention during search for color/category conjunctions, independently of signals provided by color channels. The fact that target-absent RTs were significantly delayed by the presence of both color-matching and category-matching nontargets relative to distractor-only trials (Figure 2) further supports this conclusion.

The pattern of N2pc results on competition trials provides direct evidence for the hypothesis that color-based and category-based attentional control processes operate independently and in parallel during the early phase of attentional object selection. On these trials, horizontal color-matching and category-matching nontargets both triggered N2pc components, in spite of the fact that a vertical target object was presented in the same display. The presence of reliable N2pc components for category-matching nontargets on competition trials shows that category-based guidance signals did initiate a rapid allocation of spatial attention to category-matching objects, irrespective of whether these objects also matched the target color. In addition, the sum of the two N2pc components to color-matching and category-matching nontargets on competition trials was initially identical to the N2pc elicited in response to target objects (Figure 4). This observation suggests that attention was initially deployed in parallel to all objects that matched one of the two target-defining attributes. The early phase of the N2pc reflects the additive contribution of these feature-specific attentional guidance processes which operate independently for color and alphanumeric category.

This temporal pattern of N2pc components to targets and partially matching nontargets observed in Experiment 1 was very similar to the results of our previous N2pc study of color/shape conjunction search (Eimer & Grubert, 2014a). They suggest that guidance signals from feature channels that analyze color and alphanumeric category control the rapid deployment of spatial attention independently, and in an additive fashion. The subsequent emergence of a superadditive N2pc to target objects on competition trials is likely to reflect the point in time when attentional guidance begins to operate across feature dimensions. This will be further considered in the General Discussion.

Even though both color-matching and category-matching nontargets elicited reliable N2pc components in Experiment 1, these components were substantially larger for color-matching objects. This dominant role of color in the attentional control of conjunction search was also apparent in our previous study (Eimer & Grubert, 2014a), where the N2pc to color-matching nontargets was consistently larger than the N2pc to shape-matching nontargets. While color and alphanumeric category both contributed in parallel to attentional guidance processes in Experiment 1, the contribution of color was obviously more prominent, and the relative effects of category comparatively small. Experiment 2 was conducted to test whether even stronger category-based guidance effects would be observed when alphanumeric category is combined with another target-defining feature that is less dominant than color. In this experiment, participants searched for category/shape conjunction targets.

Experiment 2

Experiment 2 used the same procedures as Experiment 1, except that color was now replaced by shape as one of the two target-defining features. Search displays contained the same letters and digits as in Experiment 1, but these items were now presented within four different outline shapes (see Figure 5). Targets were defined by a specific combination of shape and alphanumeric category (e.g., digits that appear within squares). All stimuli were presented in white against a dark background. The shapes used in Experiment 2 were the same as in our earlier N2pc study of color/shape conjunction search (Eimer & Grubert, 2014a). In this study, N2pc components to nontarget objects with a target-matching shape

were smaller than N2pcs to color-matching nontargets, suggesting that shape is less effective than color in guiding attention during visual search. However, shape is regarded as a “probable” guiding feature during visual search (Wolfe & Horowitz, 2004), and should therefore be used to control the allocation of attention to candidate target objects in Experiment 2. The critical question was whether analogous to Experiment 1, category-based guidance processes would be activated simultaneously with shape-based processes. The role of alphanumeric category for attentional control might even be more pronounced than in Experiment 1 if the other target-defining feature (shape) is a less effective guiding attribute than color. In this case, N2pc amplitudes to category-matching nontargets should be larger than in the first experiment on no-competition and on competition trials, and possibly similar in size to the N2pc elicited by shape-matching nontargets. Furthermore, the sum of the two N2pc components to partially matching nontargets should again be identical to the early phase of the target N2pc on competition trials, in line with the hypothesis that attention is initially deployed in parallel and independently to different target-matching features.

Methods

Participants

Sixteen paid volunteers, aged between 21 and 41 years ($M = 28.9$, $SD = 5.82$) participated in Experiment 2. 10 were female, 2 were left handed, and all had normal or corrected to normal vision

Stimuli, Design, Procedure, and Analyses

Experimental procedures were identical to Experiment 1, except that different stimuli were employed. Search displays now included four alphanumeric characters that each appeared within an outline shape (see Figure 5). The letters and digits were the same as in Experiment 1 (A, G, P, Q, R, U and 2, 4, 5, 6, 7, 8), and had the same size ($0.6^\circ \times 0.6^\circ$). In contrast to Experiment 1, the letters/digits and the surrounding shapes all appeared in white (approximate luminance of all stimuli: 6.5 cd/m^2). Outline shapes were circles, squares, hexagons or gates (size of each shape item: $1.1^\circ \times 1.1^\circ$). As in Experiment 1, two

items were always presented on the horizontal meridian, and the other two on the vertical meridian, at an eccentricity of 1.9° from fixation.

Participants' task was to search for a target that was defined by a specific combination of shape and alphanumeric category (e.g., a digit in a square), and to report its presence or absence on each trial by pressing one of two vertically aligned response keys with their left or right index finger. Target identity was counterbalanced across participants. Different groups of four participants searched for a letter or a digit within either a square or a circle. Target identity remained constant throughout the experiment for each participant. Hexagons and gates never served as target shapes.

The different search display types (as illustrated in Figure 5) were equivalent to Experiment 1, except that shape now replaced color as one of the two target-defining features. Targets were defined by a particular shape/category combination. Instead of color-matching nontargets, there were now shape-matching nontarget (shapeMNT) objects. The probabilities of no-competition and competition trials, and the rules for the selection of partially matching and non-matching distractor items in each search display were the same as in Experiment 1. EEG recording and data analysis were identical to Experiment 1. The ratio of trials excluded due to artifacts was below 22% for each participant.

Results

Behavioral Performance

Figure 6 shows mean correct RTs (top panel) and error rates (bottom panel), separately for target-present and target-absent trials. For target-present RTs, a main effect of display type (target-only, target with shapeMNT, target with catMNT) was present, $F(2,30) = 12.5$, $p < .001$, $\eta^2 = .455$. When targets were accompanied by a shape-matching or category-matching nontarget, RTs were delayed relative to target-only trials (624 ms and 627 ms versus 604 ms; both $t(15) > 4.4$; both $p < .002$). There was no reliable RT difference between trials where targets appeared together with a shape-matching or category-matching nontarget $t(15) < 1$. A similar pattern was present for accuracy. A main effect of display type, $F(2,30) = 7.8$, $p = .002$, $\eta^2 = .342$, was due to the fact that error rates were higher when targets were accompanied by a shape-matching or category-matching

nontarget relative to target-only trials (6.5% and 9% versus 5%; both $t(15) > 2.92$; both $p < .011$). Accuracy on target-present trials with category-matching and shape-matching nontargets did not differ reliably, $t(15) < 2.05$, $p > .05$.

For target-absent displays, there was also a main effect of display type on RTs, $F(2,30) = 64.0$, $p < .001$, $\eta^2 = .810$, as target-absent responses were faster for distractor-only displays (592 ms) relative to displays with a shape-matching or category-matching nontarget (668 ms for both display types; both; $t(15) > 10.1$, both $p < .001$). There was no difference in target-absent RTs between displays with shape-matching and category-matching nontargets, $t(15) < 1$. A main effect of display type on accuracy rates on target-absent trials, $F(2,30) = 12.7$, $p < .001$, $\eta^2 = .459$, reflected more incorrect target-present response to displays that included a shape-matching or category-matching object, relative to distractor-only trials (5% and 2% versus 1%, both $t(15) > 3.5$, both $p < .01$). These errors were more frequent in the presence of a shape-matching object relative to trials with a category-matching object, $t(15) = 2.76$, $p = .015$.

N2pc Components on No-competition Trials

Figure 7 (top panel) shows grand-averaged ERPs elicited at PO7/8 on no-competition trials at electrodes contralateral and ipsilateral to a fully or partially target-matching object, separately for displays that contained the target, a shape-matching nontarget, or a category-matching nontarget. As in Experiment 1, N2pc components were largest for targets, but sizeable N2pc components were also elicited by shape-matching and category-matching nontargets. Figure 7 (bottom panel) shows contralateral-ipsilateral N2pc difference waveforms for all three display types, and suggests that N2pc components of similar size were elicited by shape-matching and category-matching nontargets on no-competition trials. A repeated measures ANOVA conducted on ERP mean amplitudes in the 180 - 280 ms post-stimulus interval with the factors display type (target, shapeMNT, catMNT) and laterality (electrode ipsilateral versus contralateral to relevant stimulus) revealed a main effect of laterality, $F(1,15) = 33.5$, $p < .001$, $\eta^2 = .691$, reflecting the presence of reliable N2pc components. There was also an interaction between display type and laterality, $F(2,30) = 15.7$, $p < .001$, $\eta^2 = .512$. Follow-up t -tests confirmed that the target N2pc was larger than the N2pc to shape-matching nontargets, $t(15) = 6.43$, $p < .001$, and to category-matching nontargets, $t(15) = 4.24$, $p = .001$. There was no N2pc amplitude

difference between these two types of partially matching nontargets, $t(15) < 1$. Direct comparisons between contralateral and ipsilateral ERPs confirmed the presence of reliable N2pc components for all three display types (target-only: $t(15) = 6.35$, $p < .001$; shapeMNT: $t(15) = 3.68$, $p = .002$; catMNT: $t(15) = 4.40$, $p = .001$).

N2pc Components on Competition Trials

Figure 8 shows ERPs measured on competition trials, separately for trials where a horizontal target was accompanied by a shape- or category-matching nontarget on the vertical meridian (top panels), and trials where a horizontal shape-matching or category-matching nontarget was presented together with a vertical target (middle panels). Targets triggered larger N2pc components than shape- or category-matching nontarget objects. However, these two types of partially matching nontargets also elicited sizable N2pc components on competition trials. This is illustrated in Figure 8 (bottom panel), which shows contralateral-ipsilateral N2pc difference waveforms for horizontal targets (averaged across trials with vertical shape-matching and category-matching nontargets), and for horizontal shape- and category-matching nontargets. N2pc components of similar size were elicited by shape-matching and category-matching nontargets on competition trials. There was a main effect of laterality, $F(1,15) = 41.2$, $p < .001$, $\eta^2 = .733$, for mean amplitudes of N2pc components triggered by horizontal target objects, but no interaction between laterality and display type (target with shapeMNT or catMNT; $F(1,15) = 1.5$, $p = .240$, $\eta^2 = .09$), demonstrating that target N2pcs were not affected by the nature of the partially target-matching item in the same display. The analysis of N2pc components to horizontal partially matching nontargets revealed a significant main effect of laterality, $F(1,15) = 10.7$, $p = .005$, $\eta^2 = .687$, confirming that these objects elicited N2pc components on competition trials. N2pc amplitudes to shape-matching and category-matching nontargets did not differ, $F(1,15) = 0.6$, $p = .451$, $\eta^2 = .09$. Follow-up analyses confirmed the presence of reliable N2pc components not only for shape-matching nontargets, $t(15) = 4.37$, $p = .001$, but also for category-matching nontargets, $t(15) = 5.42$, $p < .001$.

In Figure 8 (bottom panel), N2pc difference waveforms for targets and partially matching nontargets are shown together with the sum of the two N2pc components elicited by shape-matching and category-matching nontarget objects. The summed N2pc component to these two types of partially matching nontargets started at the same time

and was initially equal in size to the N2pc to target objects. There was no onset latency difference between these two N2pc difference waveforms, $t_c(15) < 1$.³ As in Experiment 1, a comparison of N2pc amplitude values between targets and summed partially matching nontargets with paired t -tests was conducted successively for each post-stimulus sampling point. This analysis showed that target N2pc components started to become larger than the sum of the two N2pc components to partially matching nontargets at a post-stimulus latency of 210 ms. To confirm that the summed N2pc components to partially matching nontargets and the target N2pc were initially equal in size, the two N2pc difference waveforms were again compared within two successive time windows (180 – 230 ms and 230-280 ms post-stimulus). During the early N2pc time interval, there was no N2pc amplitude difference between targets and summed partially matching nontargets, $t(15) = .696$, $p = .497$. During the later time interval, the target N2pc was reliably larger than the summed N2pc components to shape- and category-matching nontargets, $t(15) = 2.96$, $p = .01$.

Discussion of Experiment 2

The results of Experiment 2 provide additional evidence for the role of alphanumeric category in the guidance of spatial attention during conjunction search. When targets were defined by a category/shape combination, both shape-matching and category-matching nontargets elicited reliable N2pc components of similar size in no-competition trials, suggesting that category and shape were equally able to engage attentional guidance mechanisms. In competition trials, shape- and category-matching nontarget objects also triggered significant N2pcs, even though a vertical target was present in the same display. As in Experiment 1, the summed contribution of these two N2pc components was equal in size to the target N2pc during the early phase of spatially selective attentional processing, in line with the hypothesis that attention is initially allocated independently and in parallel to target-defining features at different positions in a search

³ Although the N2pc difference waveforms in Figure 8 (bottom panel) suggest that the N2pc to shape-matching nontargets might emerge earlier than the N2pc to category-matching nontargets, a jackknife-based onset latency comparison found no reliable latency difference between these two types of nontarget objects, $t_c(15) = 1.65$, $p = .120$.

display. The amplitudes of N2pc components to category-matching nontargets were generally larger in Experiment 2 relative to Experiment 1. This is most likely a result of the fact that color is a powerful selection feature, and will therefore tend to dominate simultaneous attentional guidance processes by another feature during conjunction search. Because shape is less efficient than color, shape-based and category-based guidance processes were equally involved in the parallel allocation of attention to possible target objects in Experiment 2, as reflected by N2pc components of similar size to shape-matching and category-matching nontarget objects on competition trials. The behavioral results in Experiment 2 also suggested that shape and category contributed equally to attentional guidance. Performance costs of similar size were observed for search displays that contained a shape-matching or a category-matching nontarget relative to displays without a partially target-matching object. This suggests that both types of partially matching nontargets attracted attention, which interfered with the decision to report the presence or absence of a target object.

General Discussion

Previous electrophysiological studies (Wu et al., 2013; Nako et al., 2014a, 2014b) have shown that reliable N2pc components are elicited during the selection of search targets that are defined by their category, demonstrating that category-based attentional control processes can operate at relatively early visual-perceptual processing stages. Because a category-defined target always appeared together with distractor objects that belonged to a different task-irrelevant category in these earlier studies, this type of rapid category-based attentional guidance may only be available in search displays where target objects are unique items (singletons) with respect to their category. The goal of the present study was to investigate whether alphanumerical category would still be involved in the guidance of attention in conjunction search tasks where targets are defined by a combination of alphanumerical category and color (Experiment 1) or shape (Experiment 2), and where targets and partially matching nontarget objects could appear in the same search display. In both experiments, reliable N2pc components were triggered not only by targets and color-matching or shape-matching nontargets, but also by nontarget objects that

matched the target-defining category (letter/digit). Importantly, this was the case also when displays included the target on the vertical midline, suggesting that attention was allocated simultaneously and independently to target-matching features. The observation that during the initial phase of the N2pc, the summed contributions of the two N2pc components to category-matching and color- or shape-matching nontargets were equal in size to the target N2pc provides additional evidence for this hypothesis.

The results observed in this study suggest that attentional guidance mechanisms during search for targets that are defined by a combination of features initially operate in a parallel feature-based fashion, and that alphanumerical category can be employed as one of the attributes that controls these early parallel selection processes. The relative importance of particular features during attentional guidance may differ across feature dimensions. Color seems to be a more effective selection attribute than either shape (e.g., Eimer & Grubert, 2014a) or alphanumerical category (Experiment 1 of the current study), and thus tends to dominate parallel feature-based attentional selection processes. In contrast, as suggested by the results of Experiment 2, shape and alphanumerical category appear to be similar in their ability to guide the allocation of attention during visual search. Overall, our findings suggest that there may be no fundamental difference between basic visual features such as color or shape and more complex attributes such as the alphanumerical category of objects in their accessibility to attentional control mechanisms. Both can be employed simultaneously to guide the deployment of attention to candidate target objects during visual search.

The fact that in both experiments, the summed N2pc components to partially matching nontargets on competition trials initially equaled the target N2pc is consistent with a parallel selection mechanism. This finding is more difficult to reconcile with the alternative hypothesis that attention was always first allocated to a single object with target-matching features on these trials. If attention had been directed to targets on the majority of competition trials and to the partially matching nontarget on a minority of these trials, the summed N2pcs to horizontal partially matching nontargets should have been smaller than the N2pc to horizontal targets throughout the N2pc time window, reflecting the smaller proportion of trials where an N2pc was triggered by partially target-matching

objects.⁴ While the early phase of the N2pc was equal in size for targets and summed partially matching nontargets on competition trials, the target N2pc started to become larger than the summed contribution of the two partially matching nontargets at about 210 – 220 ms after search display onset. The emergence of a superadditive target N2pc, which was also observed in our previous study of color/shape conjunction search (Eimer & Grubert, 2014a), could mark the point in time when attentional guidance mechanisms no longer operate in a strictly independent feature-based fashion, and information about target-matching features begins to be integrated across different feature dimensions. At this point, top-down control processes begin to facilitate the focal attentional processing of target objects above and beyond the spatial bias that was previously triggered in parallel by independent feature-based guidance. One possibility is that during this second phase in the attentional selection of conjunctively defined targets, attention is withdrawn from objects that match some but not all target-defining features but is maintained at the location of target objects (see Kiss, Grubert, & Eimer, 2013, for N2pc evidence for such a two-stage selection scenario from spatial cueing experiments).

It has previously been claimed that the case of alphanumeric category as a guiding feature during visual search is doubtful (Wolfe & Horowitz, 2004; but see Cunningham & Wolfe, 2014, for a role of object categories during later target identification processes in hybrid visual and memory search). The present N2pc results show that category-based guidance signals can affect early attentional object selection processes, and can act in parallel with color or shape during this early phase of attentional selectivity. This goes beyond previous demonstrations that category-defined targets trigger N2pc components in search tasks where category is the only selection attribute and all other search display items belong to a different irrelevant category (e.g., Wu et al., 2013; Nako et al., 2014a) by demonstrating that category-based guidance remains available during more demanding

⁴ Because N2pc components are computed by comparing contralateral and ipsilateral ERP waveforms, they can only be measured in response to horizontal candidate target objects. Analogous to previous N2pc experiments that investigated multiple-object selection processes by employing search displays where these objects appeared on the horizontal and vertical meridian (e.g., Woodman & Luck, 2003; Hickey et al., 2006; Eimer et al., 2011; Eimer & Grubert, 2014b), the current study assumes that there are no systematic differences in the allocation of attention between target-matching objects that are presented to the left or right of fixation and objects that appear above or below fixation.

conjunction search tasks. The current findings therefore make a strong case for awarding alphanumeric category the status of a genuine guiding feature for visual search, alongside other less controversial feature dimensions such as color, orientation, or size. Behavioral evidence also suggests that alphanumeric category can be used as an effective selection criterion during visual search. Search performance is better when targets and distractors belong to different categories (e.g., letters among digits) than when they are drawn from the same category, and this type of category-based search can produce flat search functions (Egeth, Jonides, & Wall, 1972). This suggests that alphanumeric category can be extracted rapidly for all items in a search array at a stage that precedes their focal attentional processing (e.g., Duncan, 1980). Although category effects in visual search have been linked to low-level feature differences between items that belong to different categories (e.g., White, 1977; Krueger, 1984), they remain reliable when the physical similarity of letters and digits is matched (e.g., Dixon & Shedden, 1987), suggesting that they may indeed reflect the efficiency of category-guided attentional target selection mechanisms during search for alphanumeric targets.

How could information about alphanumeric category control the allocation of spatial attention during visual search at the neural level? The guidance of attention by attentional templates for particular target-defining features is assumed to be based on preparatory sustained enhancements of neural activity within visual cortical areas that are sensitive to these features (“baseline shifts”; see Driver & Frith, 2000). Such sustained activity modulations that are set up during the preparation for search will result in a facilitation of neural responses to target features once search displays are presented (see Eimer, 2014, 2015 for a more detailed discussion). The initial parallel allocation of attention to objects with target-matching features, as reflected by the early phase of the N2pc component in the present study, may be based on the same feature-based attention mechanisms that have previously been shown to operate in a spatially global fashion at multiple locations in the visual field (e.g., Martinez-Trujillo & Treue, 2004; Serences & Boynton, 2007). If such spatially global feature-based attentional modulations are triggered simultaneously for different target-defining features, neural activity in retinotopic visual cortex can be biased in favor of candidate target objects at multiple locations in the visual field.

This account provides a plausible scenario for attentional guidance by basic visual

features like color and shape that are represented by distinct populations of visual neurons. However, the control of attention by alphanumeric category may be more difficult to explain on the basis of similar mechanisms, given the absence of dedicated hard-wired visual detectors of letters versus digits in visual cortex. Individual letters or digits are perceptually analyzed in dedicated visual areas such as the anterior left fusiform gyrus (e.g., James et al., 2005), and the outcome of these analyses may be used to guide attention towards objects with sets of visual features that are diagnostic for the currently task-relevant category. In this case, the allocation of attention towards targets that are defined by their alphanumeric category would essentially be based on a potentially complex conjunction of visual features (see Yang & Zelinsky, 2009, for a similar model of attentional guidance by the category of real-world visual objects). Categorization itself will take place at a subsequent stage that follows the attentional selection of potential target objects (but see Zelinsky, Peng, Berg, & Samaras, 2013, for evidence that the same features are involved in attentional guidance and object identification during category-based search for real-world objects). Alternatively, alphanumeric category may already be extracted during the parallel analysis of visual input (e.g., Duncan, 1980), and the outcome of this process may then be relayed to prefrontal areas involved in category-based object discriminations (e.g., Freedman et al., 2001; Miller et al., 2003). According to this hypothesis, alphanumeric category is detected pre-attentively through the activation of direct pathways between temporal visual object recognition areas and ventrolateral prefrontal cortex (see Kravitz et al., 2013, for a review of such links between temporal and prefrontal cortex). In this scenario, category-based attentional guidance would take place at a subsequent stage, based on recurrent feedback signals from prefrontal to posterior visual areas that trigger the allocation of attention to objects that match the currently task-relevant category (see also Hochstein & Ahissar, 2002, for similar ideas). The results of the current study are consistent with both of these two alternative models. The observation that N2pc components to category-matching nontarget objects emerged rapidly, within 200 ms after search display onset (see also Nako et al., 2015, for similar findings during search for real-world target objects that were specified by word cues) may seem more in line with a feature-based account of category guidance that operates locally within visual cortex than with the hypothesis that this type of attentional guidance is based on long-range recurrent interactions between posterior visual and prefrontal areas. However, it is not inconceivable

that the parallel pre-attentive detection of alphanumerical identity can be completed and the subsequent allocation of attention to objects that match the currently task-relevant category be initiated within such a short post-stimulus time window.

In summary, the current study has provided new electrophysiological evidence for the role of alphanumerical category in the control of spatial attention during visual search. When search targets are defined by a conjunction of color and category or shape and category, attention is deployed rapidly to objects that match the current target category. During the early phase of attentional processing, this type of category-based guidance operates independently and in parallel with the selection of basic visual features such as color or shape.

Acknowledgement

This work was supported by grant ES/K006142/1 from the Economic and Social Research Council (ESRC), UK, and by the BIAL Foundation (#224/12). The authors would like to thank Sue Nicholas for technical support and Greg Zelinsky, Justin Maxfield, Todd Horowitz, and an anonymous referee for their comments.

References

- Alexander, R. G., & Zelinsky, G. J. (2011). Visual similarity effects in categorical search. *Journal of Vision, 11*, 1-15.
- Alexander, R. G., & Zelinsky, G. J. (2012). Effects of part-based similarity on visual search: The Frankenbear experiment. *Vision Research, 54*, 20-30.
- Blair, R. C., & Karniski, W. (1993). An alternative method for significance testing of waveform difference potentials. *Psychophysiology, 30*, 518-524.
- Castelhano, M. S., Pollatsek, A., & Cave, K. (2008). Typicality aids search for an unspecified target, but only in identification and not in attentional guidance. *Psychonomic Bulletin & Review, 15*, 795-801.
- Cunningham, C. A., & Wolfe, J. M. (2014). The role of object categories in hybrid visual and memory search. *Journal of Experimental Psychology: General, 143*, 1585–1599.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193-222.
- Dixon, P., & Shedden, J. M. (1987). Conceptual and physical differences in the category effect. *Perception, & Psychophysics, 42*, 457-464.
- Driver, J., & Frith, C. (2000). Shifting baselines in attention research. *Nature Reviews Neuroscience, 1*, 147-148.
- Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review, 87*, 272-300.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433-458.
- Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive Psychology, 3*, 674-698.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 99*, 225-234.
- Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences, 18*, 526-535.
- Eimer, M. (2015). EPS Mid-Career Award 2014: The control of attention in visual search - Cognitive and neural mechanisms. *The Quarterly Journal of Experimental Psychology, 68*, 2437-2463.

- Eimer, M., & Grubert, A. (2014a). The gradual emergence of spatially selective target processing in visual search: From feature-specific to object-based attentional control. *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 1819-1831.
- Eimer, M., & Grubert, A. (2014b). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*, 193-198.
- Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, *20*, 1423-1433.
- Eimer, M., Kiss, M., & Nicholas, S. (2011). What top-down task sets do for us: An ERP study on the benefits of advance preparation in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1758-1766.
- Folk, C. L., & Anderson, B. A. (2010). Target-uncertainty effects in attentional capture: Color-singleton set or multiple attentional control settings? *Psychonomic Bulletin & Review*, *17*, 421-426.
- Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030-1044.
- Freedman, D. J., Riesenhuber, M., Poggio, T., & Miller, E. K. (2001). Categorical representation of visual stimuli in the primate prefrontal cortex. *Science*, *291*, 312-316.
- Grubert, A., & Eimer, M. (2013). Qualitative differences in the guidance of attention during single-color and multiple-color visual search: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1433-1442.
- Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience*, *18*, 604-613.
- Hochstein, S., & Ahissar, M. (2002). View from the top: hierarchies and reverse hierarchies in the visual system. *Neuron*, *36*, 791-804.
- Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze, H.-J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10*, 1233-1241.

- Jacques, C., Schiltz, C., & Goffaux, V. (2014). Face perception is tuned to horizontal orientation in the N170 time window. *Journal of Vision, 14*, 1-18.
- James, K. H., James, T. W., Jobard, G., Wong, A. C., & Gauthier, I. (2005). Letter processing in the visual system: Different activation patterns for single letters and strings. *Cognitive, Affective, & Behavioral Neuroscience, 5*, 452-466.
- Kiss, M., Grubert, A., & Eimer, M. (2013). Top-down task sets for combined features: Behavioral and electrophysiological evidence for two stages in attentional object selection. *Attention, Perception, & Psychophysics, 75*, 216-22.
- Kiss, M., Jolicoeur, P., Dell'Acqua, R., & Eimer, M. (2008). Attentional capture by visual singletons is mediated by top-down task set: New evidence from the N2pc component. *Psychophysiology, 45*, 1013-1024.
- Kravitz, D. J., Saleem, K. S., Baker, C. I., Ungerleider, L. G., & Mishkin, M. (2013). The ventral visual pathway: An expanded neural framework for the processing of object quality. *Trends in Cognitive Sciences, 17*, 26-49.
- Krueger, L. E. (1984). The category effect in visual search depends on physical rather than conceptual differences. *Perception, & Psychophysics, 35*, 558-564.
- Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 1000-1014.
- Malcolm, G. L., & Henderson, J. M. (2009). The effects of target template specificity on visual search in real-world scenes: Evidence from eye movements. *Journal of Vision, 9*, 1-13.
- Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology, 14*, 744-751.
- Maxfield, J. T., Stalder, W. D., Zelinsky, G. J. (2014) Effects of target typicality on categorical search. *Journal of Vision, 14*, 1-11.
- McDonald, J. J., Green, J. J., Jannati, A., & Di Lollo, V. (2013). On the electrophysiological evidence for the capture of visual attention. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 849-860.
- Miller, E. K., Nieder, A., Freedman, D. J., & Wallis, J. D. (2003). Neural correlates of categories and concepts. *Current Opinion in Neurobiology, 13*, 198-203.
- Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35*, 99-115.

- Nako, R., Smith, T. J., & Eimer, M. (2015). Activation of new attentional templates for real-world objects in visual search. *Journal of Cognitive Neuroscience*, *27*, 902-912.
- Nako, R., Wu, R., & Eimer, M. (2014a). Rapid guidance of visual search by object categories. *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 50-60.
- Nako, R., Wu, R., Smith, T. J., & Eimer, M. (2014b). Item and category-based attentional control during search for real-world objects: Can you find the pants among the pans? *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 1283.
- Olivers, C. N. L., Peters, J., Houtkamp, R. & Roelfsema, P.R. (2011). Different states in visual working memory: when it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*, 327-334.
- Serences, J. T., & Boynton, G. M. (2007). Feature-based attentional modulations in the absence of direct visual stimulation. *Neuron*, *55*, 301-312.
- White, M. J. (1977). Identification and categorization in visual search. *Memory & Cognition*, *5*, 648-657.
- Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, *1*, 202-238.
- Wolfe, J. M. (2007). Guided Search 4.0: Current Progress with a model of visual search. In W. Gray (Ed.), *Integrated Models of Cognitive Systems* (pp. 99-119). New York: Oxford.
- Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, *5*, 495-501.
- Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 121-138.
- Wu, R., Scerif, G., Aslin, R. N., Smith, T. J., Nako, R., & Eimer, M. (2013). Searching for something familiar or novel: Top-down attentional selection of specific items or object categories. *Journal of Cognitive Neuroscience*, *25*, 719-729.
- Yang, H., & Zelinsky, G. J. (2009). Visual search is guided to categorically defined targets. *Vision Research*, *49*, 2095-2103.
- Zelinsky, G. J., Peng, Y., Berg, A. C., & Samaras, D. (2013). Modeling guidance and recognition in categorical search: Bridging human and computer object detection. *Journal of Vision*, *13*, 30.

Figure Legends

Figure 1. Illustration of the different search display types used in Experiment 1 where targets were defined by a color/category combination. In the examples shown here, green digits serve as targets. On no-competition trials (panels A-F), the target or a partially matching nontarget object were accompanied by three distractor objects without target-matching features. Panels A and B show displays where the target appeared on the horizontal or vertical meridian. In panels C-F, a color-matching nontarget (a green letter) or a category-matching nontarget (a digit in a nontarget color) were present on the horizontal or vertical meridian. On competition trials (panels G-J), the target and a partially matching nontarget object appeared in the same display. A horizontal or vertical target could be accompanied by a vertical or horizontal color-matching nontarget (panels G and H) or by a vertical or horizontal category-matching nontarget (panels I and J). On distractor-only trials (panel K), displays contained four objects without target-matching features. This Figure is reproduced in color in the online version of this article.

Figure 2. Mean correct response times (RTs, top panel) and error rates (bottom panel) on target-present and target-absent trials in Experiment 1, shown separately for target-only and distractor-only displays, and for displays that contained a color-matching nontarget (colMNT) or a category-matching nontarget (catMNT) with or without a target in the same display. Error bars represent 95% confidence intervals of the means.

Figure 3. N2pc results on no-competition trials in Experiment 1. Top panel: Grand-average ERPs measured in the 350 ms interval after search display onset at posterior electrodes PO7/8 contralateral and ipsilateral to the location of a target, a color-matching nontarget, or a category-matching nontarget on the horizontal meridian. Bottom panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for horizontal target displays (solid black line), and for displays with a horizontal color-matching or category-matching nontarget (blue dashed and red dotted lines). Reproduced in color in the online version of this article.

Figure 4. N2pc results on competition trials in Experiment 1. Top and middle panels: Grand-average ERPs measured in the 350 ms interval after search display onset at posterior electrodes PO7/8 contralateral and ipsilateral to a horizontal target or partially matching nontarget. ERPs are shown separately for displays with a horizontal target and a vertical color-matching nontarget (T&colMNT), a horizontal target and a vertical category-matching nontarget (T&catMNT), a horizontal color-matching nontarget and a vertical target (colMNT&T), and a horizontal category-matching nontarget and a vertical target (catMNT&T). Bottom panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. Difference waves are shown for displays with horizontal targets (averaged across displays with a vertical color-matching and category-matching nontarget, solid black line), for displays with horizontal color-matching or category-matching nontarget (blue dashed and red dotted lines), and for the sum of the N2pc components to color- and category-matching nontargets (blue and red dashed line). Reproduced in color in the online version of this article.

Figure 5. Illustration of the different search display types used in Experiment 2 where targets were defined by a shape/category combination. In the examples shown here, digits in a square serve as targets. Panels A-F show no-competition trials where a target or a partially matching nontarget object was accompanied by three distractor objects without target-matching features. Panels G-F show competition trials where the target and a partially matching nontarget object appeared in the same display. Panel K shows distractor-only trials.

Figure 6. Mean correct response times (RTs, top panel) and error rates (bottom panel) on target-present and target-absent trials in Experiment 2, shown separately for target-only and distractor-only displays, and for displays that contained a shape-matching nontarget (shapeMNT) or a category-matching nontarget (catMNT) with or without a target in the same display. Error bars represent 95% confidence intervals of the means.

Figure 7. N2pc results on no-competition trials in Experiment 2. Top panel: Grand-average ERPs measured in the 350 ms interval after search display onset at posterior electrodes PO7/8 contralateral and ipsilateral to the location of a target, a shape-matching nontarget,

or a category-matching nontarget on the horizontal meridian. Bottom panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for horizontal target displays (solid black line), and for displays with a horizontal shape-matching or category-matching nontarget (blue dashed and red dotted lines). Reproduced in color in the online version of this article.

Figure 8. N2pc results on competition trials in Experiment 2. Top and middle panels: Grand-average ERPs measured in the 350 ms interval after search display onset at posterior electrodes PO7/8 contralateral and ipsilateral to a horizontal target or partially matching nontarget. ERPs are shown separately for displays with a horizontal target and a vertical shape-matching nontarget (T&shapeMNT), a horizontal target and a vertical category-matching nontarget (T&catMNT), a horizontal shape-matching nontarget and a vertical target (shapeMNT&T), and a horizontal category-matching nontarget and a vertical target (catMNT&T). Bottom panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. Difference waves are shown for displays with horizontal targets (averaged across displays with vertical shape- or category-matching nontargets, solid black line), for displays with horizontal shape-matching or category-matching nontarget (blue dashed and red dotted lines), and for the sum of the N2pc components to shape- and category-matching nontargets (blue and red dashed line). Reproduced in color in the online version of this article.