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## Searching for something familiar or novel: ERP correlates of top-down attentional selection for specific items or categories

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### Abstract

Visual search is often guided by top-down attentional templates that specify target-defining features. But search can also occur at the level of object categories. We measured the N2pc component, a marker of attentional target selection, in two visual search experiments where targets were defined either categorically (e.g., any letter), or at the item level (e.g., the letter C) by a prime stimulus. In both experiments, an N2pc was elicited during category search, in both familiar and novel contexts (Experiment 1) and with symbolic primes (Experiment 2), indicating that even when targets are only defined at the category level, they are selected at early sensory-perceptual stages. However, the N2pc emerged earlier and was larger during item-based search compared to category-based search, demonstrating the superiority of attentional guidance by item-specific templates. We discuss the implications of these findings for attentional control and category learning.

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In most visual search tasks (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980), the goal is clearly specified by the experimenter (e.g., look for the letter L among an array of T's). A hallmark of these tasks is top-down attentional selection: in order to find the target, one must activate a visual representation that specifies the goal of the search process. The guidance of visual search is assumed to be under the control of attentional templates – representations that are stored in visual working memory and specify physical properties of a relevant target object (e.g., Desimone & Duncan, 1995; Olivers, Peters, Houtkamp, & Roelfsema, 2011). Attentional templates can represent target-defining elementary visual features such as color, orientation, or shape, or exemplar target objects such as apples, cats, or teddy bears. Once activated, these templates bias processing in visual cortical areas in a top-down fashion in favor of visual features and objects that match the current target-defining attributes.

The role of attentional templates held in working memory for the control of visual search has recently become an important topic in attention research. From studies of item search involving identically matching targets, either at the level of exemplars or indexical features such as shape or color, there is considerable debate about whether it is possible to search for more than one feature or item at any time (i.e., to maintain one versus multiple attentional templates; e.g., Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, in press; Irons, Folk, & Remington, 2012; Olivers et al., 2011), and about whether simply maintaining a representation in working memory is sufficient to bias the allocation of attention during

visual search (e.g., Carlisle, Arita, Pardo, & Woodman, 2011; Carlisle & Woodman, 2011; Olivers, Meijer, & Theeuwes, 2006).

Another equally important question concerns the content of the representations that are involved in attentional guidance: Are they always feature-based or exemplar-based attentional templates, or can attention also be guided towards object *categories*? In the natural environment, search targets are often underspecified. When you look for an apple, you can form an attentional template for a prototypical apple to guide this search, but non-prototypical exemplars require a category match, such as a kiwi when looking for fruit. If your goal is to find an item that belongs to a perceptually heterogeneous category (e.g., anything edible), search cannot be based on simply matching physical features of incoming visual input with a pre-existing top-down attentional template. In spite of this difficulty, there is behavioral evidence that visual search for targets among distractors can remain efficient even under conditions where targets are categorically defined (e.g., numbers among letters; Egeth, Jonides, & Wall, 1972). This might in principle be achieved by activating multiple templates simultaneously, each matching one exemplar of the target category. However, if recent evidence is correct that only one attentional template can be active at any given moment (e.g., Houtkamp & Roelfsema, 2009; see also Olivers et al., 2011, for discussion), visual search for categorically defined target objects that do not match along perceptual features of specific items should be less efficient than search for feature-defined targets, because the former cannot be guided by feature-based attentional templates. Indeed, evidence from eye movements during search for complex target objects (e.g., teddy bears) suggests that categorical search is slower than search for a specific exemplar of the category, but still quicker than random search (Yang & Zelinsky, 2009). Furthermore, search efficiency improves with feature information about the target (Malcolm & Henderson, 2009), increasing dissimilarity between category exemplars and distractors (Alexander & Zelinsky, 2011) as well as similarity between distractors (Alexander & Zelinsky, 2012).

Another important aspect of category-based attentional selectivity in the natural environment is that categories may be acquired in the course of perceptual learning (see Goldstone, 1998). The literature on learning new categories largely focuses on categorization based on feature dimensions (e.g., morphed cats and dogs; Freedman, Riesenhuber, & Poggio, 2001), rather than conceptual categories (i.e., across both perceptually similar items, such as vehicles, and dissimilar items such as fruit). If the category is conceptual (e.g., “fruit”), and participants are not given explicit information about each category member (i.e., that the target items contain exotic fruits), they can guide the top-down selection of category-matching targets from non-targets on the basis of both visual dimensions and previously acquired information about category membership.

Here we report the results of two experiments that directly compared behavioral and electrophysiological correlates of item-based and category-based attentional selection. In both experiments, search arrays were preceded by prime stimuli that specified either the identity or the category (letter or digit) of an upcoming target. Experiment 1 employed letter/digit primes in two contexts: one in which the categorical membership of objects was highly familiar (letters versus digits), and another in which category membership was novel (Chinese characters) and had to be learned during task performance. Experiment 2 investigated only the familiar context, but now used symbolic rather than concrete prime stimuli. Is item-based attentional selection faster and more efficient than category-based selection even for highly familiar categories? (How) do item-based and category-based selection processes operate in tandem?

To answer these questions, we measured the N2pc component as an established event-related brain potential (ERP) marker of attentional target selection (e.g., Eimer, 1996; Luck,

Chelazzi, Hillyard, & Desimone, 1997; Luck & Hillyard, 1994). The N2pc represents an enhanced negativity at occipito-temporal electrodes contralateral to the hemifield of a visual candidate target object, typically emerges around 200 ms post-stimulus, is generated in retinotopic occipito-temporal cortex (Hopf et al. 2000), and is associated with the allocation of spatial attention to visual objects rather than preparatory visual-spatial orienting (Brignani, Lepsien, & Nobre, 2010; Leblanc, Prime, & Jolicoeur, 2008; Seiss, Kiss, & Eimer, 2009). Thus far, virtually all N2pc studies of top-down controlled attentional target selection have investigated conditions where search templates specify target features or feature conjunctions (e.g., color, size, shape, or orientation). In fact, the term “attentional template” itself implies that target selection is guided by feature-based matching processes. The aim of our study was to compare and contrast this type of precise feature-based attentional selectivity with the selection of visual targets when they are defined categorically. We asked whether attention can be controlled by a top-down task goal that defines target membership as a category with physically dissimilar exemplars, thus ruling out item-specific template matching. We also asked whether category-based selection is just as fast and efficient as target-selection based on the physical features of an item, or whether there are substantial costs associated with attentional selection based on category membership. Finally, we studied whether category-based attentional selection is more efficient when these categories are familiar and well-practiced, relative to novel categories that have to be newly acquired.

N2pc components were measured in response to targets in two primed search tasks: one based on target selection defined by physical features, and the other defined by category membership. On each trial, a prime display informed participants that an upcoming search target was defined either by its identity or its category, but did not predict target presence or absence in the search array. The prime display was followed by a four-item search display that contained a target on some but not all trials. In the familiar condition in Experiment 1, items and categories were familiar (i.e., numbers and letters). In the novel condition in Experiment 1, they were unfamiliar (i.e., Chinese characters). There were two types of prime displays: Primes containing two identical stimuli instructed participants to search for a target that physically matched this specific item. For example, if an identity prime specified the letter C or the Chinese symbol 四, target-present responses were required when the subsequent search display contained this item (see Figure 1). For trials with Identity primes, search could be guided by a feature-specific attentional template (e.g., targets that share all of the features with the prime – an item match). By contrast, Category primes contained two non-identical items of the same category (e.g., the letters C and E). These primes informed participants that this category was now search-relevant, and that target-present responses were required when search displays contained a category-matching item (e.g., any letter), regardless of whether this item was identical to one of the items shown in the prime display. Following Category primes, search could not be guided by exemplar-specific features, but had to be based on knowledge about category membership. In the familiar condition, participants could activate target selection by their pre-existing knowledge about letters and digits. In the novel condition, category knowledge had to be acquired by observing the co-occurrence of the primes, which were always from the same category. Experiment 2 implemented the same methods as the familiar condition in Experiment 1, except that category search was elicited by symbolic cues (i.e., line drawings of a book or abacus for letter and digit search).

Figure 1 (bottom panel) shows all of the different combinations of prime and search array types for both Experiments 1 and 2. On trials where an Identity prime is followed by a search array that includes a matching target stimulus (Id-Id), target selection should be efficient, because it can be guided by a precise physical match with an attentional template that specifies target identity. Therefore, an early and large N2pc component should be

observed. Because physical target properties can be specified irrespective of category knowledge, presuming accurate encoding and sufficient working memory, this N2pc component should be present for both the familiar and novel conditions. On trials where Category primes are followed by search displays that contain a category-matching but not a physically matching target (Cat-Cat), target selection cannot be based on an item-specific match. One important question is whether an N2pc component would still be elicited by targets on these trials, because this would show that even category-based attentional target selection modulates relatively early stages of visual-perceptual processing. Another question is whether the N2pc on Cat-Cat trials would be delayed and attenuated relative to Id-Id trials. This would demonstrate the benefits of selective attentional processing guided by an exemplar over category-guided target selection. A third question is whether N2pc components on Cat-Cat trials would only be found in the familiar condition where attentional selection could be based on pre-existing category knowledge, or whether it would also be present in the novel condition, where this knowledge had to be newly acquired.

We also analyzed ERPs in two other trial conditions shown in Figure 1, to obtain insights about interactions between identity-guided and category-guided attentional target selection. Trials where an Identity prime is followed by search arrays that contain a category-matching but not an identity-matching item (Id-Cat) required a target-absent response. The presence of an N2pc to these category-matching items would suggest that activation of a feature-specific attentional template automatically activates a corresponding categorical representation. On trials where a Category prime is followed by a category-matching target that is also a physical match with one of the primes (Cat-Id), target selection can in principle be guided by item-specific or categorical top-down task goals. If selection was exclusively driven by category membership, the N2pc observed on these trials should be very similar to the N2pc measured on Cat-Cat trials. However, if it was driven primarily by item-specific attentional templates, the N2pc on Cat-Id trials might be similar to the N2pc observed on Id-Id trials.

## Experiment 1

### Methods

**Participants**—Twelve paid volunteers participated in this experiment. One participant was excluded due to equipment failure. All remaining 11 participants ( $M=25.45$  years,  $SD=3.45$ , range: 21–34 years, 5 males) had normal or corrected vision. All participants in the final sample had no previous knowledge of the meanings of Chinese characters.

**Stimuli, Design, and Procedure**—Stimuli were presented on a 24-inch LCD monitor with a 75 Hz refresh rate at a resolution of 640×480. Search arrays consisted of four different items drawn from one of the four sets (letters, digits, Chinese numbers, Chinese non-numbers, each including five items, as shown in Figure 1). The four array elements were arranged at equidistant positions around a central fixation dot at a radial distance of 2.01° visual angle as measured from the fixation to the center of each stimulus.

Each item subtended  $1.72^\circ \times 1.72^\circ$  at a viewing distance of 100 cm. All stimuli (letters, numbers, and Chinese characters) were black and presented on a gray background (RGB: 96,96,96). They were presented in random order and with equal probability across trials. On each trial, targets were specified by a preceding prime array presented for 200 ms and containing two items. Identity primes (two identical items) instructed participants to select the physically identical target item (if present) in the next search array. Category primes (two different items belonging to the same category) instructed participants to select a category-matching target in the next search array. Following the priming array and an empty interval of 800ms, the search array was presented for 200 ms. The location of the target (when present) was randomly assigned on each trial. Targets were always accompanied by

three different distracters from the other category. For example, if the target was a letter, it was presented with three digits (Figure 1). The intertrial interval was 1600 ms. A central fixation point was continuously present, and participants were instructed to maintain fixation.

Participants' task was to report whether a target was present or absent in the search array by pressing one of two horizontally arranged response keys (present: left key; absent: right key) with their right hand. Target-present responses were required on three types of trials (see Figure 1). On Identity Prime, Identity Match trials [Id-Id], the prime stimulus reappeared in the search array. On Category Prime, Identity Match [Cat-Id] trials, one of the two prime stimuli reappeared in the search array. On Category Prime, Category Match [Cat-Cat] trials, one item in the search array matched the category but not the identity of the prime stimuli. Target-absent responses were required on the other three types of trials. On Identity Prime, Category Match [Id-Cat] trials, a stimulus that matched the category of the prime stimulus but not its identity was present in the search array. Finally, on both types of No-match trials, Identity or Category Primes were followed by search arrays that contained four items in the other non-matching category. Each block contained 76 trials: 16 trials each were Id-Id, Cat-Id, Cat-Cat, and Id-Cat trials, and 12 were No-Match trials. Thus, 48 trials per block required a target-present response and 28 trials a target-absent response.

There were two experimental sessions that were conducted on separate days within the same week. In the first session, participants completed four blocks of the familiar condition, followed by eight blocks of the novel condition. In the second session, eight blocks of the novel condition preceded four blocks of the familiar condition. There were twice as many blocks in the novel condition compared to the familiar condition to maximize the number of correct novel Cat-Cat trials, where target-present responses required learning of category memberships for the novel stimuli.

**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 to  $500$  ms relative to the onset of the search array. Trials with artifacts (Horiz-EOG exceeding  $\pm 25$   $\mu$ V, Vert-EOG exceeding  $\pm 60$   $\mu$ V, all other channels exceeding  $\pm 80$   $\mu$ V) were removed prior to analysis. Averaged waveforms for trials with correct responses (target-present responses on Id-Id, Cat-Id, and Cat-Cat trials; target-absent responses on Id-Cat trials) were computed for each of these trial types, separately for the familiar and novel conditions. The final sample consisted of 76.8% and 59.5% of all trials in the familiar and novel conditions, respectively. N2pc amplitudes were quantified on the basis of ERP mean amplitudes obtained between 220 and 320ms after search array onset at lateral posterior electrodes PO7 and PO8. Jackknife-based analyses were used to determine and compare N2pc onset latencies across trial types (using the method described by Miller, Patterson, & Ulrich, 1998). N2pc onset was defined relative to an absolute amplitude criterion of  $-7\mu$ V from 180 ms after the onset of the search array.

## Results

**Behavioral results (Familiar condition)**—The left panels of Figure 2 show the mean accuracy and reaction times (RTs) on correct trials for all different trial types in the familiar condition. Main effects of trial type were present for accuracy,  $F(4,40)=14.04$ ,  $p<.001$ ,  $\eta^2=.58$ , and RT,  $F(4,40)=59.37$ ,  $p<.001$ ,  $\eta^2=.86$ . Subsequent Bonferroni-corrected comparisons were focused on target-present responses. Target detection performance on Id-Id trials was better than on Cat-Cat trials, both for accuracy ( $p<.001$ ) and RT ( $p<.001$ ). Performance was better on Cat-Id relative to Cat-Cat trials, for accuracy ( $p<.001$ ) as well as RT ( $p<.001$ ). RTs

were faster on Id-Id compared to Cat-Id trials ( $p < .001$ ), but accuracy did not differ between these two trial types ( $p = .176$ ).

**Behavioral results (Novel condition)**—The middle panels of Figure 2 show mean accuracy and RTs for correct trials in the novel condition of Experiment 1. Data were collapsed across the sixteen novel blocks, since there was no overall difference in performance between the first and second sessions across all trial types for either accuracy,  $F(4,80) = .20$ ,  $p = .94$ ,  $\eta^2 = .01$ , or RT,  $F(4,80) = .13$ ,  $p = .97$ ,  $\eta^2 < .01$ . Main effects of trial type were present for accuracy,  $F(4,40) = 30.10$ ,  $p < .001$ ,  $\eta^2 = .75$ , and RT,  $F(4,40) = 10.13$ ,  $p < .001$ ,  $\eta^2 = .50$ . Target detection performance on Id-Id trials was better than on Cat-Cat trials, and this difference was reliable for accuracy ( $p < .001$ ), and a trend for RT ( $p = .081$ ). Performance on Cat-Id trials was better than on Cat-Cat trials, both for accuracy ( $p = .001$ ), and RT ( $p = .001$ ). Accuracy was better on Id-Id compared to Cat-Id trials ( $p < .001$ ), but RT did not differ between these two trial types ( $p = 1.00$ ).

To determine participants' sensitivity to category in the novel task,  $d'$  was computed on the basis of their accuracy on Cat-Cat trials (target-present trials where targets did not physically match the prime) and on trials where a Category prime was followed by a target-absent search display (Cat-No Match). Target-present responses on Cat-No Match trials were classified as false alarms.  $D$ -prime scores ( $M = .23$ ,  $SE = .05$ ) were significantly above chance,  $t(10) = 4.88$ ,  $p = .001$ , demonstrating that participants acquired some category knowledge in the novel condition.

**ERP results**—Figures 3 and 4 show ERPs triggered in the 500 ms after search array onset at electrodes PO7/8, for target-present trials (Id-Id, Cat-Id, Cat-Cat), and for Id-Cat trials that contained a category-matching item. Solid and dashed lines show ERPs contralateral and ipsilateral to the target or category-matching stimulus. Both figures also include difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for the four trial types. In the familiar condition, a large N2pc component was triggered on Id-Id trials. The N2pc was smaller on Cat-Id and Cat-Cat trials, and appeared to be absent on Id-Cat trials. A similar pattern of results was present in the novel condition.

**Familiar condition:** A repeated measures ANOVA for the factors trial type (Id-Id, Id-Cat, Cat-Id, Cat-Cat) and laterality (electrode contralateral vs. ipsilateral to the target or category-matching item) revealed a main effect of laterality,  $F(1,10) = 27.00$ ,  $p < .001$ ,  $\eta^2 = .73$ , and an interaction between trial type and laterality,  $F(3,30) = 10.61$ ,  $p < .001$ ,  $\eta^2 = .52$ . With a Bonferroni-corrected  $p$ -value threshold of .013, one-tailed  $t$ -tests comparing contralateral and ipsilateral ERP mean amplitudes demonstrated that N2pc components were present in the Id-Id trials,  $t(10) = 4.27$ ,  $p = .001$ , Cat-Id trials,  $t(10) = 3.97$ ,  $p = .002$ , and Cat-Cat trials,  $t(10) = 2.85$ ,  $p = .009$ . In contrast, there was no N2pc on Id-Cat trials,  $t(10) = .46$ . Bonferroni-corrected comparisons revealed that N2pc amplitudes were larger on Id-Id relative to both Cat-Cat and Cat-Id trials, both  $p = .014$ , while there was no difference between Cat-Id and Cat-Cat trials,  $p = .24$ . The N2pc emerged earlier on Id-Id trials relative to Cat-Id trials (223 ms versus 255 ms),  $t(10) = 3.10$ ,  $p = .011$ . There was no reliable difference in N2pc onset latencies between Cat-Id and Cat-Cat trials.

**Novel condition:** There was no N2pc amplitude difference between the first and second session of the novel condition,  $F < 1$ , and the data from the two sessions were therefore collapsed. There was a main effect of laterality,  $F(1,10) = 30.93$ ,  $p < .001$ ,  $\eta^2 = .76$ , and an interaction between trial type and laterality,  $F(3,30) = 26.17$ ,  $p < .001$ ,  $\eta^2 = .72$ . With a Bonferroni-corrected  $p$ -value of .013, as in the familiar condition, reliable N2pc components were present in Id-Id trials,  $t(10) = 5.55$ ,  $p < .001$ , Cat-Id trials,  $t(10) = 5.57$ ,  $p < .001$ , and Cat-Cat trials,  $t(10) = 2.91$ ,  $p = .008$ . There was again no N2pc on Id-Cat trials,  $t(10) = -.25$ .

Bonferroni-corrected comparisons revealed that the N2pc amplitude was larger on Id-Id relative to Cat-Cat trials,  $p < .005$ , and on Cat-Id relative to Cat-Cat trials,  $p = .023$ . The N2pc emerged earlier on Id-Id trials relative to Cat-Id trials (215 ms versus 242 ms),  $t_c(10) = 2.87$ ,  $p = .017$ . There was no difference in N2pc onset latencies between Cat-Id and Cat-Cat trials.

## Experiment 2

In Experiment 1, the N2pc in the Cat-Cat condition was smaller than in the Id-Id condition, but was still reliably present, which suggests that early visual-perceptual stages of attentional target selection are under the control of category-defined top-down task goals. However, prime displays always contained two items that could also appear as targets in the subsequent search arrays. Thus, in the Cat-Cat condition, it is possible that participants primarily searched for the two specific items that were part of the category prime, and only searched for other objects in the target category when neither of these two items was found in the search array. This interpretation is in line with the observation that relative to Cat-Cat trials, performance was better on Cat-Id trials, where category-matching targets also matched physically with a preceding Category prime. To rule out this possibility, Experiment 2 employed symbolic category primes that did not share any features with their associated category members. In contrast to Experiment 1, all primes now contained a single object (identity primes: the target letter/digit; symbolic primes: a schematic book for letter search, and an abacus for digit search, see Figure 1). Only the familiar search task (letter/digit search) was included in Experiment 2.

## Methods

**Participants**—Fourteen paid volunteers participated in this experiment. Three participants were excluded due to excessive eye blinks (63% of trials rejected). All remaining 11 participants ( $M = 28.09$  years,  $SD = 4.76$ , range: 24–37 years, 5 males) had normal or corrected vision.

**Stimuli, Design, and Procedure**—Experiment 2 used the same methods as the familiar condition in Experiment 1, with the following exceptions. Symbolic primes were now used for category search (a line drawing of a book for letter search, and a line drawing of an abacus for digit search; see Figure 1). As a result, there were no longer any Cat-Id trials because the symbolic primes did not match any of the letters or digits in the search arrays. Stimulus set sizes were larger than in Experiment 1, and now differed between stimulus categories (6 digits versus 12 letters, see Figure 1). Experiment 2 also used a more canonical font for the letters and digits than in Experiment 1 (Figure 1). This change was introduced to compensate for the increase in target set size, in particular in the letter task, which produced a substantial decrease in performance during a pilot study that employed the stimulus set used in Experiment 1. In all other respects, procedures and analyses were the same as in Experiment 1.

## Results

**Behavioral results**—The right panels of Figure 2 show mean accuracy and reaction times (RTs) on correct trials for all different trial types, collapsed across trials where digits or letters were targets. Analyses of accuracy and RT data included the factors trial type (Id-Id, Id-Cat, Cat-Cat, No Match) and search target (digit versus letter). There were main effects of trial type for accuracy,  $F(3,30) = 6.21$ ,  $p = .002$ ,  $\eta^2 = .38$ , as well as for RT,  $F(3,30) = 37.50$ ,  $p < .001$ ,  $\eta^2 = .79$ . Bonferroni-corrected follow-up analyses revealed that accuracy was higher on Id-Cat trials compared to Cat-Cat ( $p = .002$ ) and No Match trials ( $p = .042$ ), whereas there was no reliable accuracy difference between Id-Id and Cat-Cat trials. Analogous comparisons confirmed that RTs were faster on Id-Id as compared to Cat-Cat trials ( $p < .001$ ). There were

no significant main effects of search target on either accuracy or RT, demonstrating that overall task performance did not differ between the letter search and digit search, and the different set sizes had no effect. No reliable interaction between trial type and search target was observed for accuracy. For the RT data, there was a significant interaction,  $F(3,30)=9.90$ ,  $p<.001$ ,  $\eta^2=.50$ , which was driven by a trend for faster responses to numbers versus letters in Cat-Cat trials, and a trend in the opposite direction in No Match trials.

**ERP results**—The final sample after artifact rejection included 72.3% of all trials. Figure 5 shows ERPs triggered in the 500 ms after search array onset at electrodes PO7/8, for target-present trials (Id-Id and Cat-Cat), and for Id-Cat trials that contained a category-matching item. Solid and dashed lines show ERPs contralateral and ipsilateral to the target- or category-matching item. ERPs were collapsed across trials where participants searched for digit targets or for letter targets. As in Experiment 1, a large N2pc component was triggered on Id-Id trials. The N2pc was smaller on Cat-Cat trials, and appeared to be absent on Id-Cat trials.

A repeated measures ANOVA for the factors trial type (Id-Id, Id-Cat, Cat-Cat) and laterality revealed a main effect of laterality,  $F(1,10)=28.97$ ,  $p<.001$ ,  $\eta^2=.74$ , and an interaction between trial type and laterality,  $F(3,30)=41.87$ ,  $p<.001$ ,  $\eta^2=.81$ . With a Bonferroni-corrected p-value of .017, reliable N2pc components were present on Id-Id trials,  $t(10)=6.71$ ,  $p<.001$ , one-tailed, and Cat-Cat trials,  $t(10)=3.02$ ,  $p=.007$ , one-tailed. In contrast, the small N2pc observed on Id-Cat trials only approached significance,  $t(10)=2.15$ ,  $p=.029$ , one-tailed. Bonferroni-corrected comparisons revealed that the N2pc amplitude was larger on Id-Id relative to Cat-Cat trials,  $p<.001$ . The N2pc emerged earlier on Id-Id trials relative to Cat-Cat trials (178 ms versus 248 ms),  $t_c(10)=2.45$ ,  $p=.03$ . Importantly, N2pc amplitudes on Cat-Cat trials did not differ reliably between trials where the symbolic book prime instructed participants to search for letters ( $M = -.96$ ,  $SE = .35$ ) and trials where the abacus prime was presented and participants searched for digits ( $M = -.62$ ,  $SE = .27$ ;  $t(10)=.97$ ,  $p=.365$ ).

## Discussion

We compared item-based and category-based attentional target selection in visual search by measuring behavioral performance and N2pc components to search targets that were defined at the item or category level. In Experiment 1, participants had to detect targets in a familiar or novel context. As expected, target selection was very efficient when it was based on a physical match with an item-specific attentional template. On trials where Identity primes were followed by a search array that contained a matching target (Id-Id trials), RTs were fast, and N2pc components were larger and emerged earlier than on all other trial types. Because this kind of feature-guided attentional target selection is independent of previous knowledge about stimulus categories, it was expected to be similarly effective in familiar and in novel contexts, and results confirmed that this was indeed the case.

When compared to Id-Id trials, there were considerable costs for target selection performance on Cat-Cat trials (Category prime followed by physically non-matching category target), and the N2pc to targets on these trials was strongly attenuated and delayed. This demonstrates that relative to item-based selection, the speed and efficiency of attentional target selection is considerably reduced when it can only be guided by advance information about target category. However, and importantly, although N2pc amplitudes were attenuated on Cat-Cat trials, the N2pc was still reliably present. This was the case not only in the familiar condition, but also in the novel condition. The fact that the N2pc component was triggered at all during category-based target selection is important, because it suggests that top-down modulations of early visual-perceptual processing stages during



target selection are not restricted to conditions where selection relies on item-based attentional template matching, but are also elicited during category-based target selection.

Behavioral evidence of attentional guidance by categorically defined targets has relied on categories that are highly familiar to participants prior to the experiment, e.g. letters, numbers, or teddy bears (Egeth et al., 1972; Yang & Zelinsky, 2009; Alexander & Zelinsky, 2011). The fact that an N2pc also emerged for categorically guided search for the novel condition of Experiment 1, where category knowledge had to be acquired during the early trials as participants became familiar with the stimuli, is even more remarkable, as target selection should be more difficult when it has to be based on new information about category membership. It is important to note that the N2pc data were based exclusively on trials where targets were successfully detected, and the percentage of detected targets on Cat-Cat trials was much lower in the novel as compared to the familiar condition (see Figure 2), thus demonstrating the expected superiority of existing as compared to newly acquired category knowledge. Nevertheless, the current results show that whenever it is available, and even if it has only just been acquired, category knowledge can guide attentional selectivity at early stages of visual processing. No N2pc was triggered by category-matching items on Id-Cat trials where participants were searching for a physical match, demonstrating that activating an item-specific attentional template during visual search does not automatically result in an additional activation of the matching category.

Due to the specific nature of the category primes used in Experiment 1 (two different members of the target category), the results obtained in this experiment could still primarily reflect item-based attentional guidance rather than genuine category-based target selection. However, essentially the same pattern of behavioural and electrophysiological results was observed in Experiment 2, where these primes were replaced by symbolic category primes that had no featural similarity with the individual tokens included within category. The fact that a reliable N2pc component was observed with these symbolic cues on Cat-Cat trials provides strong evidence for the hypothesis that category-based attentional guidance can affect relatively early stages of visual-perceptual processing in a spatially selective fashion. It is also worth noting that the N2pc on Cat-Cat trials did not differ between target digits and target letters in Experiment 2, in spite of the fact that memory set size was twice as large for letters (twelve candidate target letters versus six possible target digits). In fact, N2pc amplitudes were numerically but not reliably larger for letter targets. If target selection was at least partially due to item-based attentional templates, one might expect it to be more efficient during digit search than during letter search. The observation that there was no link between memory set size and target N2pc amplitudes does not support this prediction. However, target category and memory set size were not independently varied in Experiment 2, which means that the absence of differential set size effects on the N2pc cannot provide conclusive evidence that item-based attentional templates were not involved in target selection on Cat-Cat trials. This specific question deserves further investigation.

This study goes beyond recent evidence suggesting that search can be guided by multiple feature-specific templates (e.g., Irons et al., 2012; Beck et al., 2012) by demonstrating a reliable N2pc for category-based visual search when target categories included up to 12 different items, which is well beyond working memory capacity (Vogel & Machizawa, 2004). It seems that category search can be fast even when there is no obvious single representative set of visual properties that could be part of a feature-based search template. But if target selection is not based on visual feature matching, which alternative mechanism might be responsible for the successful selection of category-defined targets? In other words, what is the nature of attentional task goals for stimulus categories, and how are these employed during visual search? If category membership is critical for the guidance of target selection when target set size is large, search should be much more effective when targets

and distracters always belong to different categories (as in the current study) than during within-category search (e.g., search for one of several predefined target letters among other non-target distractor letters). Furthermore, although our findings indicate that the N2pc can be obtained without an identical match between a prime and target, it is possible that attentional templates allowing category-based selection could be established by extracting commonalities of visual features across target exemplars. A combined approach that manipulates visual similarity across exemplars within and between categories, and a computational model of feature similarity and category membership (following Alexander & Zelinsky, 2011, 2012), could determine the visual and non-visual parameters contributing to category-based top-down selection. Nevertheless, compared to other categorical search experiments (e.g. Alexander & Zelinsky, 2011), the letters and numbers used in this study seriously restricted the range of visual parameters that could be used by such a model to distinguish the categories, suggesting that the extraction of these may not be sufficient for the task.

In summary, our study provides new evidence that category-guided visual search with perceptually dissimilar items can be relatively fast and efficient, although not as efficient as search controlled by item-specific attentional templates. The observation that activating a top-down task goal for a specific object category (digits versus letters) modulated visual processing in extrastriate visual cortex in a spatially selective fashion within 250 ms after stimulus onset is theoretically relevant, because it provides important temporal and anatomical-functional constraints for future models of category-based attentional guidance. While the exact nature of the mechanisms and representations that are involved in this type of attentional control will need to be identified in future research, our findings demonstrate that they can be activated very rapidly, and are able to selectively affect neural processing at relatively low levels of the visual hierarchy.

Our demonstration that the N2pc component is a marker of category-based attentional target selection in both familiar and novel contexts may also provide intriguing prospects for researchers who wish to determine what participants have learned about particular categories, because it can index whether they are deploying an attentional set that is independent of the physical characteristics of the targets. This may prove especially useful in a developmental context. The presence or absence of an N2pc, or an equivalent infant component that has yet to be discovered, to feature-defined or category-defined targets may be a useful marker of selection efficiency and attentional learning (see Amso & Johnson, 2006). Our findings with expert adult learners provide the foundation for exploring the fundamental issue of how optimal attentional selection and learning interact in naïve learners (infants and children; Amso & Johnson, 2006; Wu & Kirkham, 2010). Given that the relationship between attention and learning is reciprocal -- learning is enabled and facilitated by attentional selection, and attentional selection builds on previously learned knowledge -- investigating this relationship will provide insight into the emergence and use of efficient and flexible cognitive strategies.

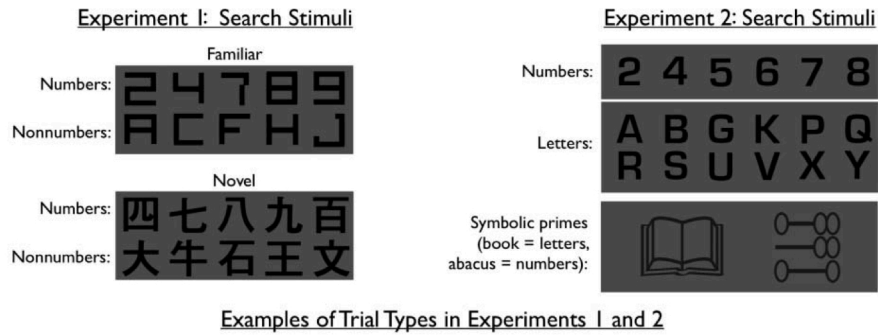
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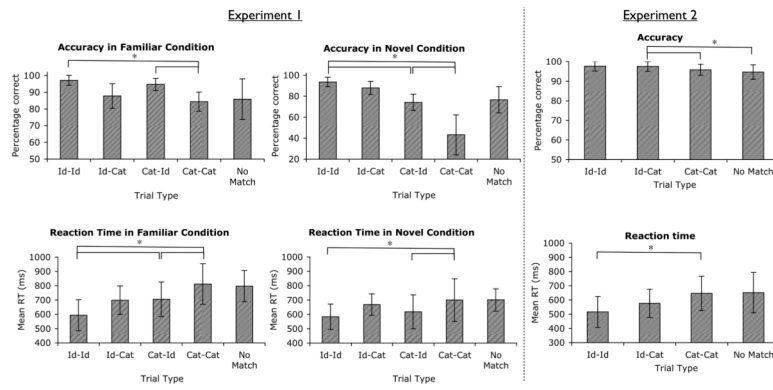
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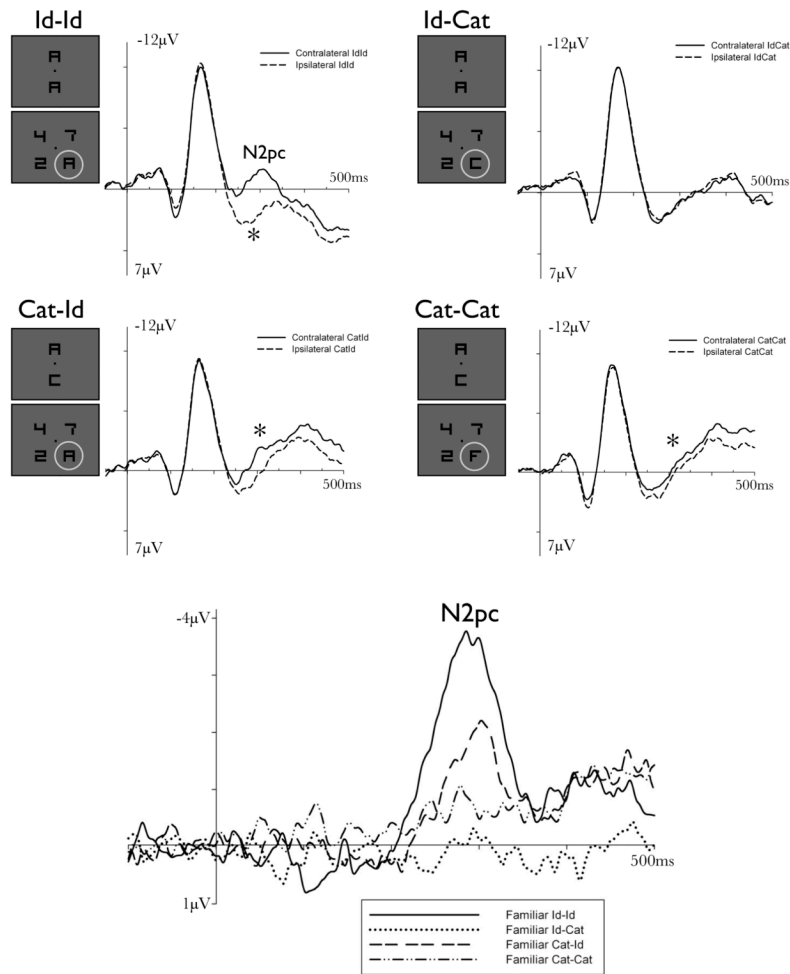
		Identity prime, Identity match	Identity prime, Category match	Category prime, Identity match	Category prime, Category match	Identity prime, No match	Category prime, No match
Experiment 1	Prime	C C	C C	C F	C F	C C	C F
	Search array	4 7 2 C	4 7 2 F	4 7 2 C	4 7 2 A	4 7 2 B	4 7 2 B
Experiment 2	Prime	A	A	n/a		A	
	Search array	4 7 2 A	4 7 2 G	n/a	4 7 2 G	4 7 2 B	4 7 2 B

**Figure 1.** Stimuli used in Experiments 1 and 2. The top panel shows familiar stimuli (letters and digits) and novel stimuli (Chinese numbers and non-number characters) used in Experiment 1, and the familiar letters and digits and symbolic primes used in Experiment 2. The bottom panel shows examples of primes and test arrays in the different conditions in both experiments.

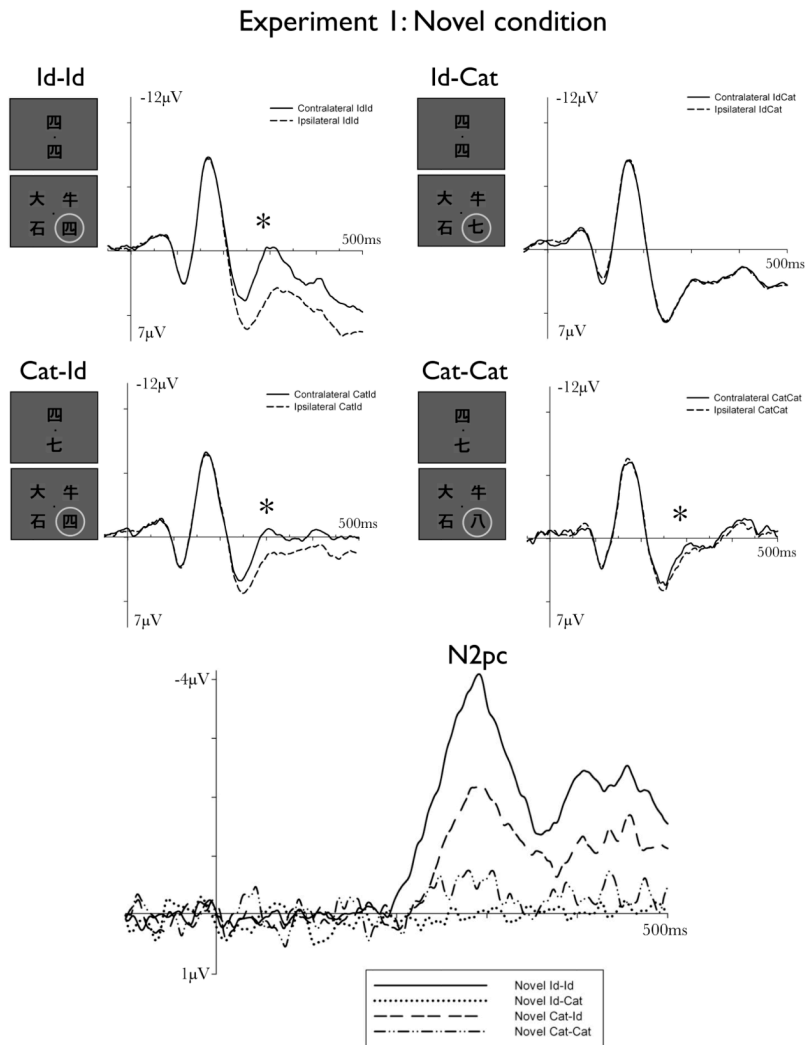


**Figure 2.** Accuracy and reaction times for the five familiar trial types in Experiment 1 averaged across eight blocks (left panel), and for the five novel trial types in Experiment 1 averaged across 16 blocks (middle panel). The right panel shows the accuracy and reaction times for the four trial types in Experiment 2 across eight blocks. Error bars represent standard deviation.

Experiment I: Familiar condition



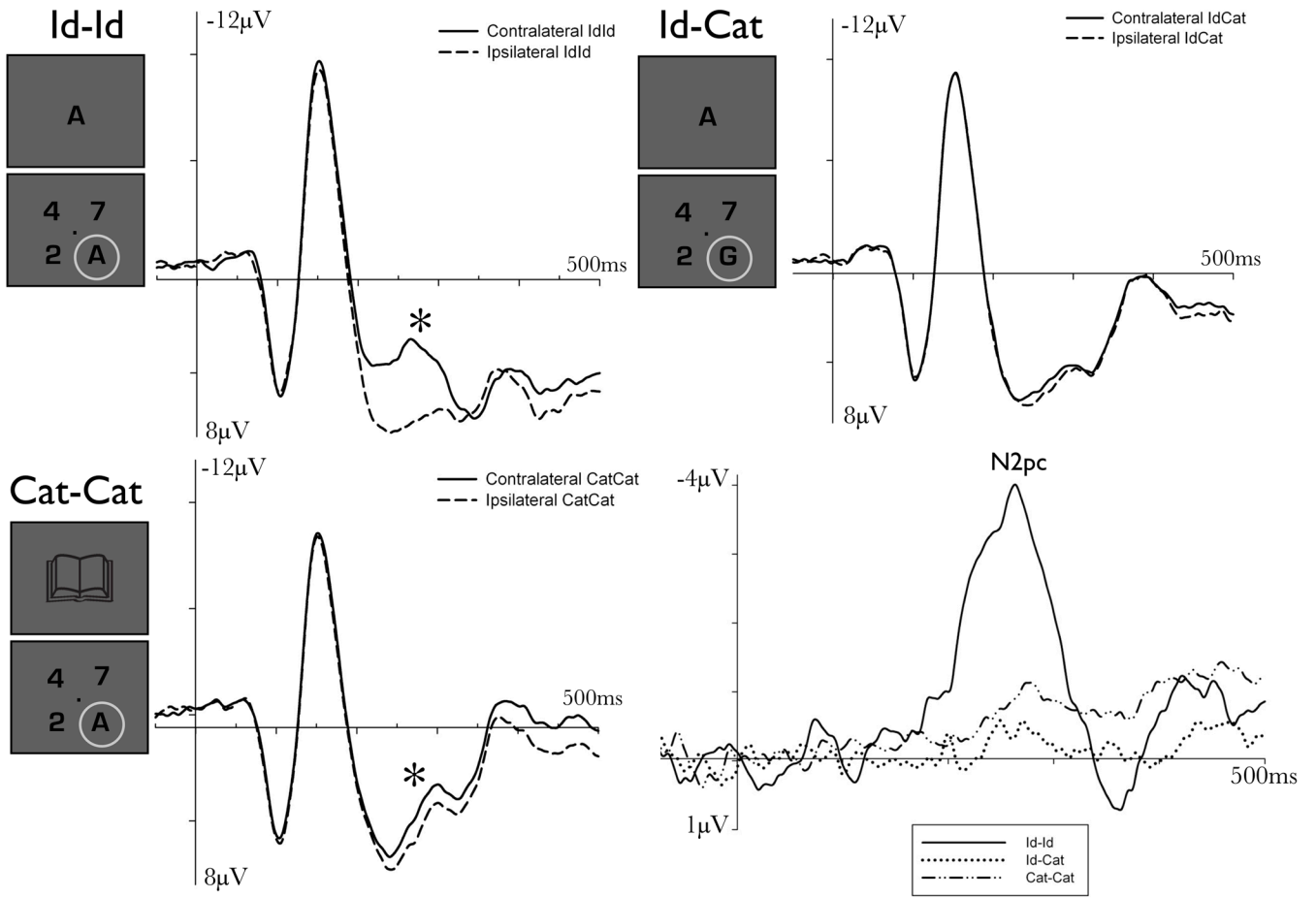
**Figure 3.** ERPs and difference waves for the four familiar trial types in Experiment 1 (Identical prime-Identity match [Id-Id], Identical prime-Category match [Id-Cat], Category prime-Identity match [Cat-Id], Category prime-Category match [Cat-Cat]) averaged across eight blocks.



**Figure 4.** ERPs and difference waves for the four novel trial types in Experiment 1 (Identical prime-Identity match [Id-Id], Identical prime-Category match [Id-Cat], Category prime-Identity match [Cat-Id], Category prime-Category match [Cat-Cat]) averaged across 16 blocks.



### Experiment 2



**Figure 5.** ERPs and difference waves for the three trial types in Experiment 2 (Identical prime-Identity match [Id-Id], Identical prime-Category match [Id-Cat], Category prime-Category match [Cat-Cat]) averaged across eight blocks.