Atten Percept Psychophys (2016) 78:749–760
DOI 10.3758/s13414-015-1039-6

A neural signature of rapid category-based target selection as a function of intra-item perceptual similarity, despite inter-item dissimilarity

Rachel Wu[1] · Zoe Pruitt[2] · Megan Runkle[2] · Gaia Scerif[3] · Richard N. Aslin[2]

Published online: 5 January 2016

Abstract Previous work on visual search has suggested that only a single attentional template can be prioritized at any given point in time. Grouping features into objects and objects into categories can facilitate search performance by maximizing the amount of information carried by an attentional template. From infancy to adulthood, earlier studies on perceptual similarity have shown that consistent features increase the likelihood of grouping features into objects (e.g., Quinn & Bhatt, Psychological Science. 20:933–938, 2009) and objects into categories (e.g., shape bias; Landau, Smith, & Jones, Cognitive Development. 3:299–321, 1988). Here we asked whether lower-level, intra-item similarity facilitates higher-level categorization, despite inter-item dissimilarity. Adults participated in four visual search tasks in which targets were defined as either one item (a specific alien) or a category (any alien) with either similar features (e.g., circle belly shape and circle back spikes) or dissimilar features (e.g., circle belly shape and triangle back spikes). Using behavioral and neural measures (i.e., the N2pc event-related potential component, which typically emerges 200 ms poststimulus), we found that intra-item feature similarity facilitated categorization, despite dissimilar features across the category items. Our results demonstrate that feature similarity builds novel categories and activates a task-appropriate abstract categorical search template. In other words, grouping at the lower, item level facilitates grouping at the higher, category level, which allows us to overcome efficiency limitations in visual search.

Keywords Visual search · N2pc · Categorization

✉ Rachel Wu
Rachel.Wu@ucr.edu

[1] Department of Psychology, University of California, Riverside, CA, USA

[2] Brain and Cognitive Sciences, University of Rochester, Rochester, NY, USA

[3] Department of Experimental Psychology, University of Oxford, Oxford, UK

Previous visual search studies have shown that search for one item is more efficient than search for two or more items, as reflected in behavioral (reaction time and accuracy) and electroencephalographic (EEG) measures (the N2pc event-related potential [ERP] component; see Grubert & Eimer, 2013; Nako, Wu, & Eimer, 2014; Nako, Wu, Smith, & Eimer, 2014; Olivers, Peters, Houtkamp, & Roelfsema, 2011). The N2pc is the established ERP marker of attentional target selection, emerging approximately 200 ms after stimulus onset at electrodes contralateral to the hemifield of the target (e.g., Eimer, 1996; Luck & Hillyard, 1994). Using the N2pc to measure early search efficiency, Nako, Wu, and Eimer (2014) presented participants with four-item search arrays containing different letters, one of which sometimes was the target. Participants were asked to search for one letter target (e.g., the letter A), two letter targets, or three letter targets among other letter distractors. The N2pc amplitude became attenuated (as did behavioral measures) as the number of potential targets increased. More efficient search for one than for two or more items supports an account that limits attentional prioritization to only one target template at a time (Olivers et al., 2011). Attentional templates are working memory representations based on features guiding visual search that are deployed early in the information-processing stream.

However, multiple-target search can become more efficient if the set of target items forms a natural or learned category.

Nako, Wu, and Eimer (2014) also showed that search for any letter (i.e., a category target) among number distractors yielded N2pc components that were very similar to those from one-item search (see also Egeth, Jonides, & Wall, 1972, for similar behavioral evidence). In other words, once participants were able to use category knowledge, searching for many items (e.g., 26 letters) became similar to searching for one item, whereas multi-item search in which a category-level template could not be deployed was much less efficient. This finding suggests that categorization, and grouping in general, can overcome the attentional limitation of efficient search for only one item at a time.

In summary, although attentional templates can contain a single, low-level, target-defining feature (e.g., one orientation, shape, or color) or one whole object (see Olivers et al., 2011), findings by Nako, Wu, and Eimer (2014) have shown that attentional templates can also consist of higher-level, abstract features, such as categories composed of multiple objects (see the additional evidence in Wu, Nako, et al., 2015; Wu et al., 2013). Thus, grouping multiple features into one object and multiple objects into one category may be an effective strategy for maximizing the information content of one attentional template and overcoming attentional limitations during search. Indeed, an increasing number of studies have shown that searching for multiple features belonging to one object or for multiple objects belonging to one category is efficient (for a review, see Cunningham & Wolfe, 2014). Thus, efficient grouping strategies (similar to "chunking" strategies; e.g., Gobet et al., 2001) enable adults to maximize attentional search capacities (Treisman, 1982). Although it is clear that objects in known categories (e.g., letters, clothing, or human faces) can be grouped together, what strategies can unify objects from novel categories to facilitate visual search?

Previous work on the effects of perceptual similarity from infancy to adulthood has shown that identical features increase the likelihood of grouping elements into larger units (e.g., Xs vs. Os; Quinn & Bhatt, 2009) and objects into categories (e.g., shape bias; Landau, Smith, & Jones, 1988). Moreover, perceptual similarity among targets has been shown to facilitate visual search among distractors, and even to automatically capture attention in task-irrelevant ways (e.g., Duncan & Humphreys, 1989). If items composed of similar features are detected more efficiently, then a category of items containing matching features should produce more efficient search, even if the matching features are dissimilar across objects (i.e., even if inter-item dissimilarity is high). However, it remains unclear whether low-level intra-item similarity facilitates higher-level categorization, and in turn boosts the efficiency of category-level visual search. Whereas perceptual similarity within objects may facilitate search for specific objects, perceptual dissimilarity between objects may hinder categorization.

Although the result is counterintuitive from the broader perceptual similarity literature, previous behavioral studies with infants and adults on feature correlation predict that intra-item feature similarity should facilitate categorization (e.g., Austerweil & Griffiths, 2011, 2013). Feature correlation studies have shown that objects with correlated features (e.g., bananas tend to be yellow and have a crescent shape) rather than uncorrelated features (e.g., jelly beans come in many colors) enable more robust representations of multipart objects and categories. Having stronger individual object representations due to consistent feature correlations aids categorization of these objects, because the features determining category diagnosticity are more reliable, and thus less corrupted by noise (Austerweil & Griffiths, 2011, 2013; Goldstone, 2000; Younger & Cohen, 1986). Consistent feature correlations lead to narrower generalization based on specific features of existing category members, suggesting a tighter category boundary than that of uncorrelated features. Unfortunately, establishing new feature correlations in a visual search task requires extensive training, which in turn constrains the number of targets that can be used in a given experiment. Furthermore, creating target and distractor stimulus sets that are similar enough to avoid low-level pop-out effects typically precludes true feature correlations (e.g., features on the target are shared by distractors, as in conjunction search). An alternative to creating new feature correlations is to ask whether feature similarity serves to facilitate category-based target search. That is, does intra-item similarity among a set of targets that define a category, despite inter-item dissimilarity, facilitate categorization by highlighting between-category differences?

We had two aims in the present study: (1) to determine whether a category of objects with perceptually similar features, despite dissimilar features across objects, leads to more efficient search both for individual items and for categories (as compared to perceptually dissimilar features within an object), and (2) to determine whether this efficient search is due to the ability to group objects with similar intra-item features into a single, categorical attentional template. Although the first aim can be addressed easily with behavioral measures, the second aim can best be addressed with the N2pc ERP component. This component provides a window into the grouping mechanism underlying better behavioral performance, because it is modulated differentially by the number of categorically relevant and irrelevant search targets. Specifically, the amplitude of the N2pc decreases in a nonlinear manner as the number of related targets increases, and decreases linearly with unrelated targets (e.g., Nako, Wu, & Eimer, 2014; Nako, Wu, Smith, & Eimer, 2014). That is, searching for two or more unrelated items reduces the amplitude of the N2pc linearly, relative to searching for one item. However, if these items are exemplars from the same category, the amplitude of the N2pc does not fall off linearly with the number of items in the category (e.g., search for any letter is similar to search for two specific letters; Nako, Wu, & Eimer, 2014). Once features are grouped into objects and the objects are grouped into a category, the N2pc is present, regardless of the number of items in the category. As a result, the nonlinear fall-off of the N2pc with increasing set size can be diagnostic of a category-level attentional template. Importantly, the N2pc is modulated by grouping exemplars into a category, not by task difficulty (Wu, Nako, et al., 2015).

Previous work has shown that the amplitude of the N2pc is modulated by other factors, such as the number of targets (e.g., Mazza & Caramazza, 2012), distractors semantically related to the target (e.g., Telling, Kumar, Meyer, & Humphreys, 2010), reward salience (e.g., Kiss, Driver, & Eimer, 2009), and low-level pop-out effects (see, e.g., Theeuwes, 2010; this point is heavily debated, however, with the other side arguing that top-down factors are the main contributors to the N2pc component—e.g., Eimer, 2014). In the present study, we controlled for all of these previously identified factors in order to draw conclusions about grouping based on intra-item similarity or dissimilarity. Specifically, only one target (or nontarget) was presented during a trial with a distractor, novel targets were used to avoid semantic processing, and the two categories did not differ in reward salience or bottom-up visual features (i.e., the same features were used across both categories). Although multiple factors are known to influence the amplitude of the N2pc, here we controlled for these previously identified factors by comparing an item set (“category”) whose exemplars shared high intra-item similarity, with a set whose exemplars did not. Intra-item similarity was the only factor that differed between the two item sets. Our hypothesis based on our previous work was that, after controlling for previously identified factors that contribute to the presence of the N2pc, if an N2pc were to occur during search for multiple targets, the items could be grouped into one set that was “categorical,” in the sense that it was more abstract than the perceptual characteristics of the individual exemplars in the set. This hypothesis was primarily based on our previous work showing the presence of the N2pc during category search for a wide range of familiar categories (e.g., letters, numbers, kitchen items, clothing, and faces).

In the present study, we measured behavioral and neural (N2pc) responses in four visual search tasks (2 × 2 design) in which the targets were defined as either one item (a specific alien) or a category (any alien) with similar intra-item features (e.g., a circle belly shape and circle back spikes; Family S, Fig. 1) or dissimilar intra-item features (e.g., a circle belly shape and triangle back spikes; Family D). Critically, the two categories differed only in the feature similarity within one alien, not in the set of actual features presented across categories. On the basis of the feature correlation literature, we predicted that intra-item similarity would facilitate categorization, despite inter-item dissimilarity, producing a large N2pc for Family S, but no N2pc for Family D during category search. On the basis of the perceptual similarity literature, we predicted that similar features could be chunked into one attentional template during exemplar search, and therefore would produce larger N2pc amplitudes than would the items in Family D, with dissimilar features. Finally, on the basis of previous N2pc studies (e.g., Nako, Wu, Smith, & Eimer, 2014; Wu et al., 2013), it is entirely expected that the N2pc amplitude would be larger for exemplar (specific-item) search than for category search, due to the more precise template-matching during exemplar search. However, the critical comparisons were between (rather than within) the two categories that differed only in intra-item similarity.

Method

Participants

Sixteen adults (M = 23.75 years, SD = 4.81, range = 19–33 years; ten females, six males) participated in this study. The data from an additional five participants were excluded from the final analyses due to excessive eye movements (>50 % of trials excluded). These are typical of the inclusion rates and numbers of participants in N2pc EEG studies (e.g., Nako, Wu, & Eimer, 2014). All participants were compensated $25 at the end of the study.

Stimuli

A novel stimulus set of cartoon alien figures, Wusters (www.callalab.com; Fig. 1), was employed to control for perceptual differences between categories and to reduce the amount of previous knowledge employed in the task. Two categories of aliens with identical bodies differed only in the shape comprising the spikes on the back of the alien, as well as the shape displayed on the belly. Eight shapes were used, including a circle, triangle, square, pentagon, hexagon, star, heart, and X. In one category (Family S: Fig. 1, top panel left), each alien had one of the eight shapes both on its belly and as its spikes. For example, if a circle appeared on the belly, that alien’s spikes would also be circles. The dissimilar family (Family D) consisted of a random set of eight belly shape–spike combinations: aliens with a square belly shape and triangle spikes, heart belly shape with hexagon spikes, pentagon belly shape with circle spikes, triangle belly shape with heart spikes, star belly shape with X spikes, X belly shape with square spikes, hexagon belly shape with star spikes, and circle belly shape with pentagon spikes. The images subtended 5.15° × 2.86°.

Subjective ratings of perceptual similarity and dissimilarity Subjective ratings of similarity were obtained from a separate group of 12 participants (M = 20.92 years, SD = 1.93, range = 18–26 years; ten females, two males) to confirm the intra-item

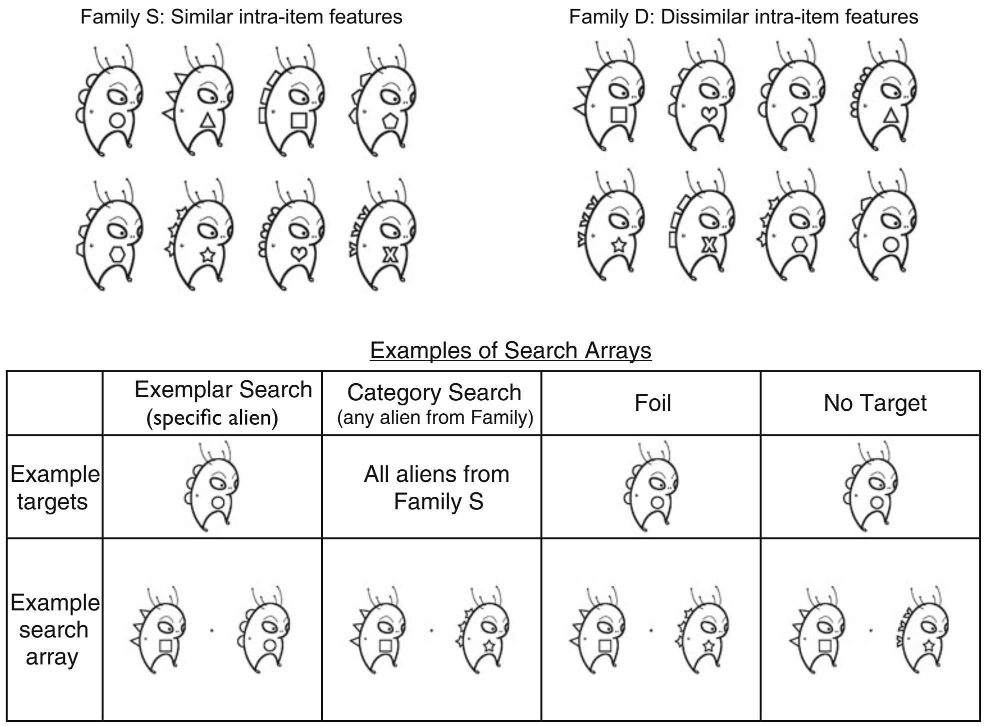

Fig. 1 Items in the "similar" and "dissimilar" categories used as search stimuli are displayed in the top panel, and example search arrays from exemplar, category, foil, and no-target trials are displayed in the bottom panel

similarity and inter-item dissimilarity for Family S as well as the intra-item and inter-item dissimilarity for Family D. For the individual aliens, participants were asked, "How similar is the shape on the alien's belly to the shapes on the alien's back?," and for the pairs of aliens, participants were asked, "How similar are these two aliens?" Participants had to report their similarity judgments on a scale from 1 to 5, with 1 being *not similar at all* and 5 being *extremely similar*. Figure 2 shows the mean ratings for individual aliens (eight aliens per category), as well as for the pairs of aliens. These ratings confirmed our expectations: (1) For Family S, intra-item similarity was high, whereas inter-item similarity was low (Fig. 2, first two bars), and (2) for Family D, both intra-item and inter-item similarity were low (Fig. 2, last two bars). These results indicate that Family S contained aliens with high intra-item similarity and low inter-item similarity, whereas Family D contained aliens with both low intra- and low inter-item similarity.

Design and procedure

In this within-subjects design, each participant completed four tasks: (1) search for a specific alien in Family S (exemplar search), (2) search for a specific alien in Family D (exemplar search), (3) search for any alien in Family S (category search), and (4) search for any alien in Family D (category search). Participants completed 28 blocks of trials in total, with seven continuous blocks of trials being presented for each of the four tasks. Task order was counterbalanced across all participants with two Latin squares, so that half of the participants received two exemplar searches in a row followed by two category searches, and vice versa, whereas the other participants received alternating exemplar and category search blocks. To minimize interference effects per participant, the exemplar targets for both search tasks were pseudorandomized, with the constraint that the exemplars from Families S and D did not have overlapping shapes between them. For example, if a participant searched for an alien with a circle belly shape and circle spikes (an exemplar from Family S), she also searched for an alien with a triangle belly shape and heart spikes from Family D, rather than the alien with the circle belly shape and pentagon spikes. This constraint was implemented to reduce confusion and task difficulty for an already difficult task. For both exemplar search tasks, the same target was displayed at the beginning of every block. Participants were shown the complete inventory of 16 aliens, split by category, at the beginning of the experiment.

There were four trial types across the four search tasks (exemplar S, exemplar D, category S, and category D): exemplar match, category match, foil, and no-target trials (Fig. 1, bottom panel). In each exemplar search task, each of the seven blocks consisted of 28 exemplar match trials (a specific target alien appeared in the search array), 28 foil trials (a nontarget alien from the same category as the target alien), and six no-target trials (only aliens from the other family appeared). In the category search task, 28 category match trials were presented (any alien from the target family

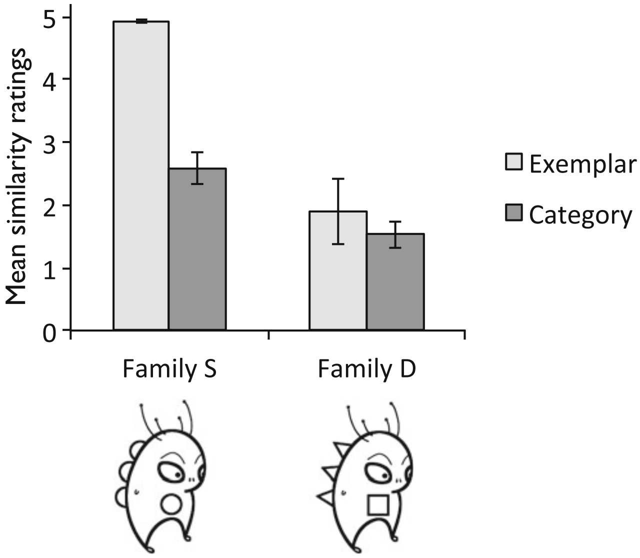

Fig. 2 Graph of similarity ratings for individual aliens and for pairs of aliens in each family. For individual aliens, participants reported the similarity between the back spike and the belly shape. For the pairs of aliens, participants reported how similar the two aliens were. Participants had to report their similarity judgments on a scale from 1 to 5, with 1 being *not similar at all* and 5 being *extremely similar*. These ratings confirm that Family S contained aliens with high intra-item similarity and low inter-item similarity, whereas Family D contained aliens with both low intra- and inter-item similarity. Error bars represent standard deviations

appeared) and 28 no-target trials (only aliens from the other family appeared) in each block. Foil trials were included in the exemplar search task to ensure that participants searched for an exact item, rather than any item with similar or dissimilar features. All foils became targets in the category search task, and therefore were not coded separately in that task.

The participants completed 1,650 trials throughout the experiment. For each trial, a search array displayed for 200 ms contained two black, line-drawn aliens on a white background (Fig. 3; see Eimer, 1996, and Wu, Nako, et al., 2015, for examples of two-item N2pc visual search). The duration was chosen to minimize eye movements, which interfere with the N2pc ERP. Two stimuli were displayed, instead of using a more complex search display with four or more items, because the task was already difficult enough with two-item arrays. The two aliens were displayed on each side of the fixation point (3.44° from center) to elicit the N2pc from contralateral and ipsilateral electrodes. Following the search array, a response screen displayed for 1,600 ms included only a black fixation dot (see Fig. 3). Participants were asked to fixate the dot throughout the entire experiment and indicate target presence or absence with the left and right arrow keys, using the right hand.

EEG recording and data analysis

We DC-recorded the EEG at standard positions of the extended 10–20 system (500-Hz sampling rate, 40-Hz low-pass filter) using 32 electrodes. The EEG was re-referenced offline to the averaged earlobes. The data were split into epochs from –100 to 500 ms relative to the search array onset, with a prestimulus baseline of 100 ms. We used the following criteria for artifact rejection for the entire epoch: horizontal electrooculogram (EOG) exceeding ±25 μV, vertical EOG exceeding ±60 μV, and all other channels exceeding ±80 μV. Including only correct trials, the average percentage of trials retained per participant after artifact rejection was 74 %, a typical amount from previous studies (e.g., Wu, Nako, et al., 2015). Mean N2pc amplitudes were obtained at lateral posterior electrodes PO7 and PO8 between 220 and 340 ms after search array onset (Wu et al., 2013).

Results

Behavioral results

Exemplar versus category match (target-present trials) To investigate accuracy effects for target-present trials (i.e., hits), a 2 (Intra-Item Feature Similarity: Family S vs. D) × 2 (Trial Type: exemplar vs. category match) repeated measures analysis of variance (ANOVA) revealed a main effect of trial type [$F(1, 15) = 215.19$, $p < .001$, $\eta^2 = .94$] and a main effect of intra-item feature similarity [$F(1, 15) = 26.51$, $p < .001$, $\eta^2 = .64$] (Fig. 4). Accuracy was greater for exemplar match trials than for category match trials overall. In addition, accuracy was greater for items with similar than with dissimilar features for both exemplar and category match trials. We found no interaction between these variables for accuracy ($F = 0.05$).

An ANOVA for reaction time (RT) also revealed a main effect of trial type [$F(1, 15) = 50.97$, $p < .001$, $\eta^2 = .77$] and a main effect of intra-item feature similarity [$F(1, 15) = 17.59$, $p < .001$, $\eta^2 = .54$], as well as no interaction ($F = 0.56$). RTs were faster for items with similar intra-item features than for dissimilar features in both exemplar and category match trials, and when searching for one specific item than in category search.

Foil versus no-target (target-absent trials) To investigate accuracy effects for target-absent trials (i.e., correct rejections), a 2 (Intra-Item Feature Similarity: Family S vs. D) × 2 (Trial Type: foil vs. no-target) repeated measures ANOVA revealed only a main effect of trial type [$F(1, 15) = 79.77$, $p < .001$, $\eta^2 = .84$] (Fig. 4), in which accuracy was higher for foil than for no-target trials.

An ANOVA for RT also revealed a main effect of trial type [$F(1, 15) = 128.16$, $p < .001$, $\eta^2 = .90$], in which RTs were faster for foil trials than for no-target trials. We also observed a main effect of intra-item feature similarity [$F(1, 15) = 4.71$, $p = .05$, $\eta^2 = .24$], in which RTs were faster for similar than for dissimilar items for both foil and no-target trials.

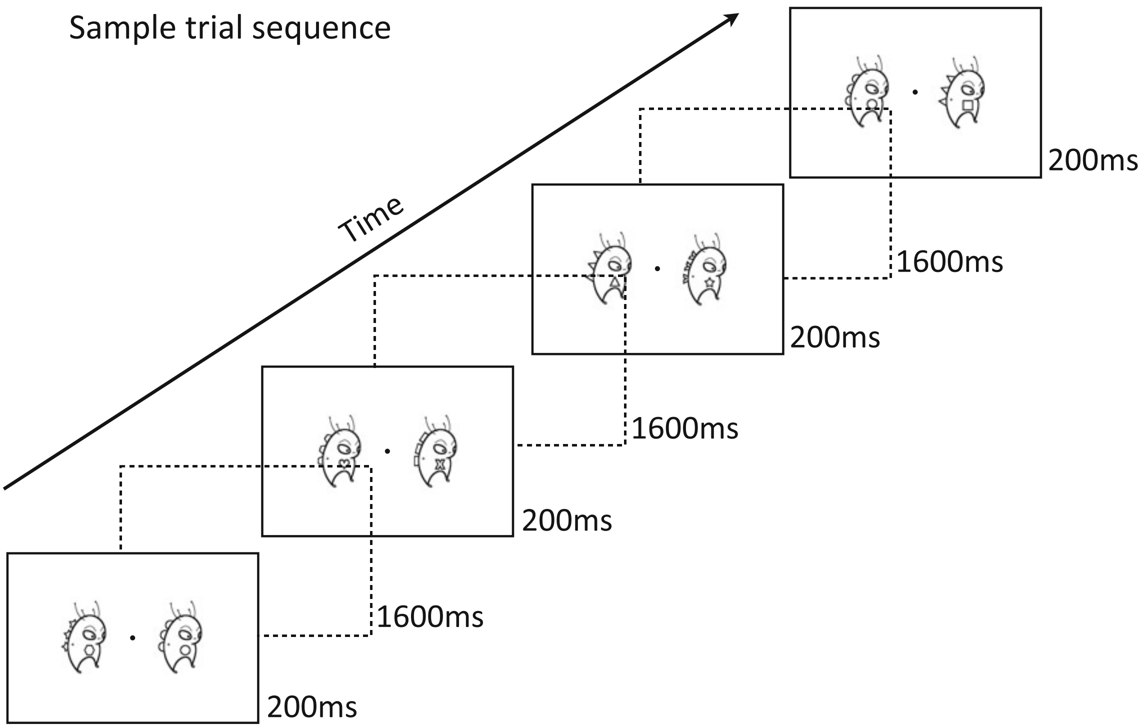

Fig. 3 Sample sequence of trials, displaying an exemplar trial, a no-target trial, a foil trial, and another exemplar trial, respectively. In the category task, the same trials would be labeled as category match, no-target, category match, and category match

Overall, these behavioral results show that both exemplar and category search benefited from intra-item feature similarity (despite inter-item dissimilarity across both categories), and searching for a specific object was easier than searching for a category of objects. The EEG results in the next section determined whether the observed behavioral benefits from intra-item feature similarity were due to establishing a categorical attentional template based on grouping similar features.

EEG results

Planned *t* tests were conducted to assess the presence of the N2pc component in all trial types (exemplar, foil, category) for both similar and dissimilar aliens (adjusted $\alpha = .05/3 = .02$, for conducting three pairwise comparisons for similar aliens, and three comparisons for dissimilar aliens). A significant N2pc component was found for trials in which targets were either an exemplar from Family S [$t(15) = –3.89$, $p = .001$] or an exemplar from Family D [$t(15) = –5.20$, $p < .001$], as we expected on the basis of numerous prior findings at the exemplar search level. Importantly, the N2pc was also significant for any alien (category target) from Family S [$t(15) = –4.78$, $p < .001$] (Figs. 5 and 6), but not for any alien from Family D [$t(15) = 0.72$, $p = .48$]. Finally, foil trials with either similar or dissimilar aliens failed to show a significant N2pc (both *t*s < 1.34, *p*s > .20; Figs. 5 and 6), confirming that these novel items had to be members of the task set to generate an N2pc.

Given our interest in comparing target-present trials (exemplar and category match) between Family S and Family D, and that foil trials for both similar or dissimilar categories did not produce N2pc components, we excluded the foil trials from further analyses. Investigating the difference between similarity conditions for exemplar and category target trials, a 2 (Laterality: contralateral vs. ipsilateral amplitude) × 2 (Task: exemplar vs. category search) × 2 (intra-item similarity vs. dissimilarity) repeated measures ANOVA revealed a main effect of laterality [$F(1, 15) = 27.47$, $p < .001$, $\eta^2 = .65$] and an interaction between laterality and task [$F(1, 15) = 18.00$, $p = .001$, $\eta^2 = .55$], which indicated larger contralateral N2pc components for exemplar than for category match trials. Critically, we also observed a three-way interaction between laterality, task, and intra-item feature similarity [$F(1, 15) = 5.17$, $p = .04$, $\eta^2 = .26$]. There were no other main effects or interactions (*F*s < 3.59).

To investigate the three-way interaction, two pairwise *t* tests were conducted to compare the N2pc components for each trial type, on the basis of feature similarity (adjusted $\alpha = .03$). The N2pc amplitude of category search for items with similar features (i.e., any alien from Family S) was larger than that for Family D [$t(15) = 3.85$, $p = .002$] (Fig. 7). Fourteen out of 16 participants had larger N2pc components for the category search task with high intra-item similarity (Family S), as compared to the category search task, with low intra-item similarity (Family D), which did not produce a significant N2pc on the basis of the analyses presented earlier. The N2pc amplitude for

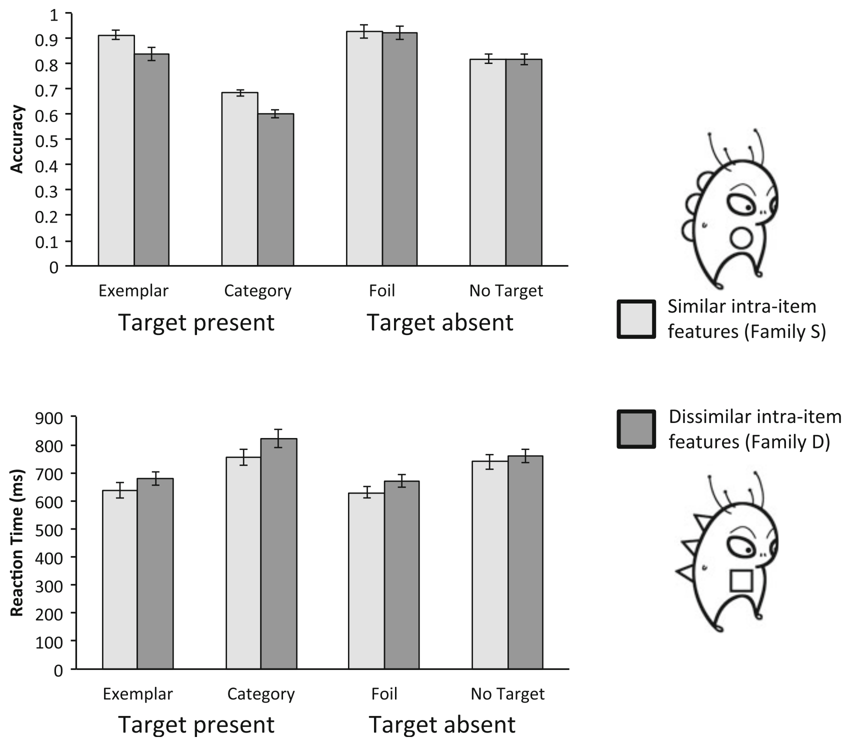

Fig. 4 Accuracy and reaction times for all trial types, for items with similar and dissimilar features. Error bars represent standard errors

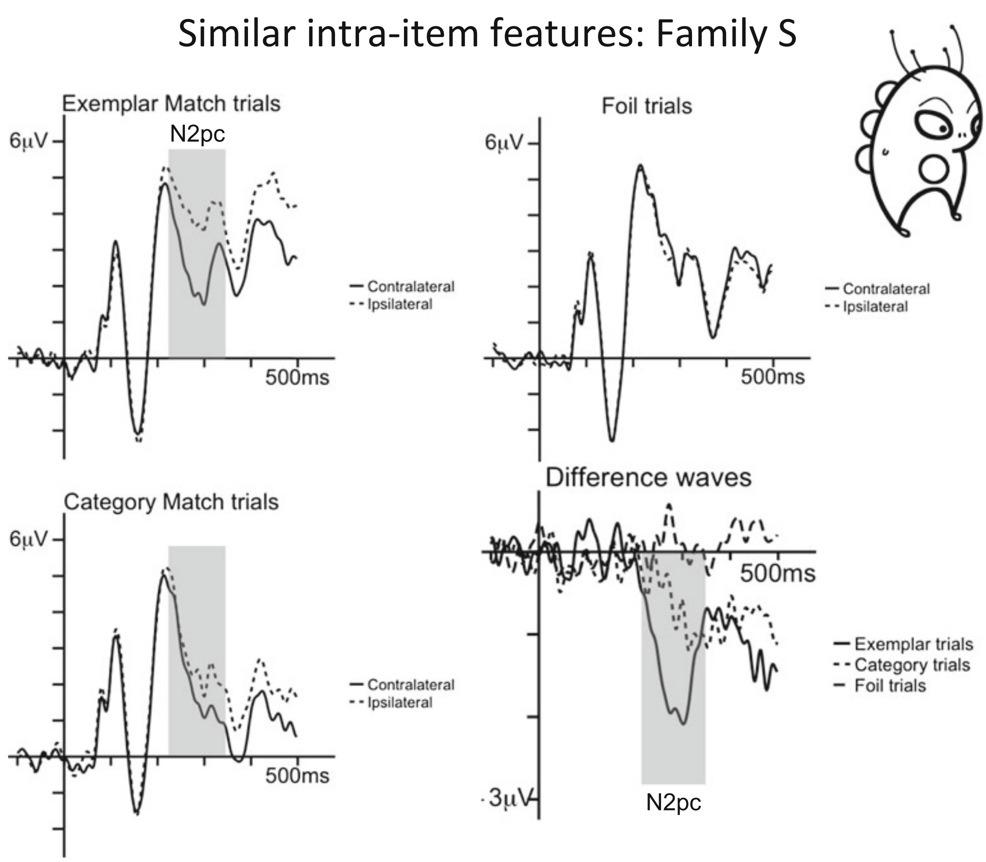

Fig. 5 Grand-averaged ERPs elicited during exemplar, category, and foil trials from Family S at electrodes PO7/8. N2pc difference waveforms (lower right corner) are a subtraction of ipsilateral from contralateral waveforms. Shaded regions represent the N2pc time window

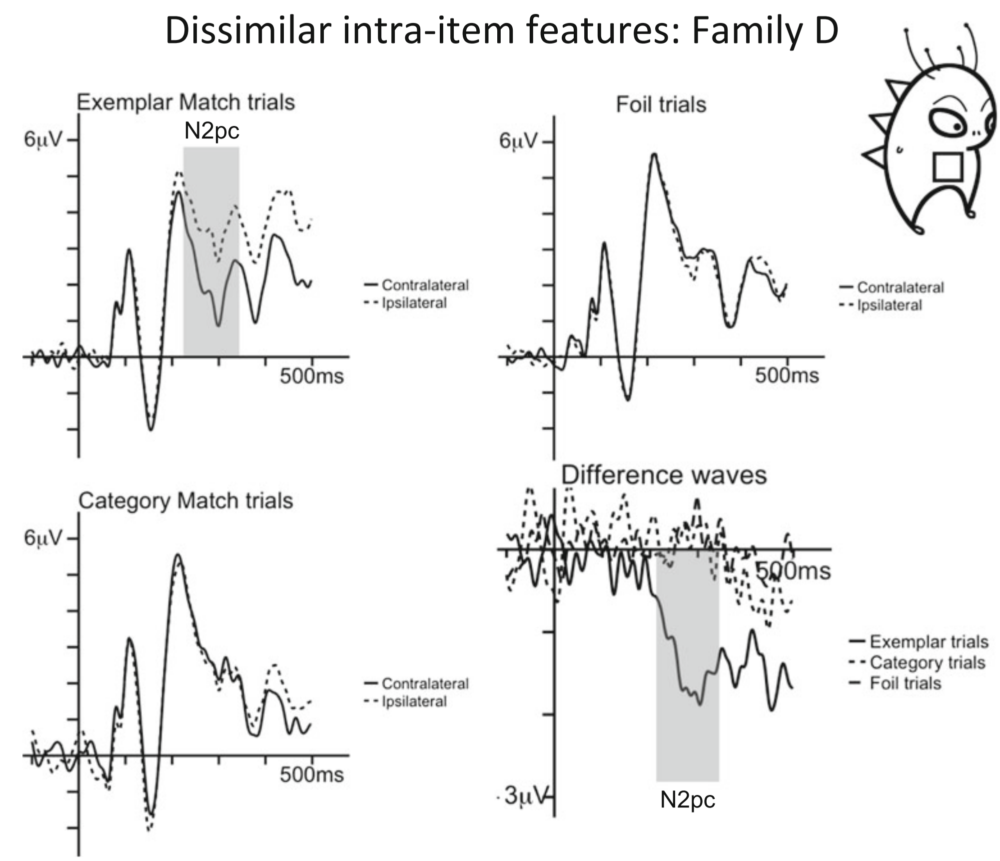

Fig. 6 Grand-averaged ERPs elicited during exemplar, category, and foil trials from Family D at electrodes PO7/8. N2pc difference waveforms (lower right corner) are a subtraction of ipsilateral from contralateral waveforms. Shaded regions represent the N2pc time window

the exemplar match trials did not differ in response to the presence or absence of high intra-item feature similarity [$t(15) = 0.17$, $p = .86$]. Overall, these ERP results show that exemplar search did not benefit from intra-item feature similarity, whereas category search did.

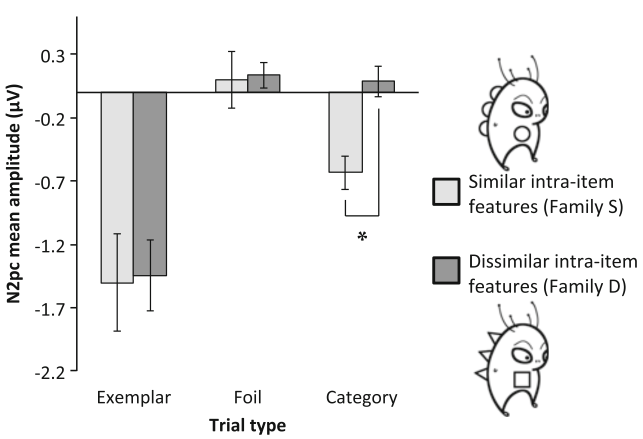

Fig. 7 Mean N2pc amplitudes (grand-averaged) for exemplar, foil, and category trials for both similar and dissimilar items. Error bars represent standard errors, and the asterisk represents a significant difference, $p < .05$

Discussion

To determine how lower-level perceptual grouping facilitates attentional selection of higher-level novel categories, in the present study we investigated whether intra-item similarity facilitates categorization, despite inter-item dissimilarity. Although the perceptual similarity literature (e.g., Duncan & Humphreys, 1989) would likely predict that inter-item dissimilarity hinders categorization, findings from research on consistent feature correlations (e.g., Austerweil & Griffiths, 2011; Younger & Cohen, 1986) suggest that intra-item similarity may facilitate categorization via grouping of the category members. Based on a visual search paradigm, the present study provides support for the feature correlation literature: Intra-item feature similarity not only facilitated exemplar search, but also category search, despite inter-item dissimilarity. Intra-item feature similarity led to higher accuracy and faster RTs in both exemplar and category search tasks than in search for aliens with dissimilar intra-item features.

To measure whether the search efficiency based on behavioral measures was modulated by the grouping of distinct attentional templates into an abstract categorical template, we measured the N2pc, the ERP marker for target selection emerging at approximately 200 ms. The N2pc is modulated by the number of items guiding search, unless the search is for an existing or recently trained category of items. During category search, the N2pc is present regardless of the number of items within the category (Nako, Wu, & Eimer, 2014). We found that the category of items with similar intra-item features (and not the category with dissimilar features) elicited an N2pc, indicating that the ability to group features at the item level facilitated grouping at the category level. These ERP results are noteworthy because we used identical features across both categories; the only difference between categories was whether the features on each alien were paired or shuffled. Importantly, the aliens in the intra-item similarity category were perceptually dissimilar from each other, just like the items from the other category. Although an N2pc-like component may have emerged at a later time window (400 ms) for the intra-item dissimilar category, the SPCN/CDA (a working memory ERP component; Eimer, 2014) is measured on the same electrodes as the N2pc and typically emerges at 400 ms. Therefore, it is difficult to differentiate between a late N2pc component and a typical SPCN/CDA component in our paradigm. Future work should determine whether a “late” N2pc can be interpreted in the same way as a typical N2pc.

On the basis of our N2pc results, the early grouping benefit of similar features was obtained only for category search, and not for exemplar search, suggesting that participants could bind features within one object into one unit, regardless of feature similarity. Although participants considered the eight items in the similar category as a unit, this grouping benefit did not interfere with exemplar search trials. No significant N2pc emerged during foil trials to category-matching nontargets (e.g., circle back and circle belly) when searching for a specific target (e.g., square back and square belly). In other words, category-matching nontargets did not capture attention in an obligatory manner, as they do in well-learned categories (e.g., letters, numbers, clothing; Nako, Wu, & Eimer, 2014; Nako, Wu, Smith, & Eimer, 2014). Rather, feature similarity defined a circumscribed category of objects, and object categories differed from each other on the basis of the presence or absence of feature similarity.

The discrepancy between the behavioral and neural results may be perplexing at first: namely, no difference during exemplar search in neural responses, but a difference in behavioral responses. However, a number of studies have documented discrepancies between neural and behavioral results (Haynes & Rees, 2005; He, Cavanagh, & Intriligator, 1996). Recent N2pc research suggests that behavioral responses are modulated by additional factors that do not affect the N2pc component (Wu, Nako, et al., 2015). In Wu, Nako, et al.’s study, participants had slower RTs when selecting non-native targets (ape faces, with which we tend to have little experience) than with native targets (human faces, with which we have a lifetime of experience). This behavioral effect is entirely consistent with previous behavioral studies on perceptual narrowing, a developmental phenomenon through which we learn about the people and languages in our environment, at the cost of a decreased ability to process non-native images and sounds (cf. Scott et al., 2007). However, Wu, Nako, et al. found that the N2pcs did not differ between native and non-native stimuli, even though the behavioral responses differed significantly. Perhaps, similar to Wu, Nako, et al.’s participants, the participants in the present study exhibited more hesitation to verify the presence of a target when searching for items with intra-item dissimilarity. The N2pc is a fast, involuntary implicit response, and perhaps is immune to voluntary hesitations that are evident in behavior (e.g., guidance/verification phase; see Eimer, 2014). Future work should determine whether participants delay behavioral responses in this task due to an extended verification phase (see Maxfield & Zelinsky, 2012).

To support our claim that grouping multiple exemplar templates into a categorical template underlies our findings, we can rule out attentional capture by feature similarity as an explanation for our ERP results for two main reasons. First, the N2pc components were very comparable in the exemplar trials for both similar and dissimilar aliens. Moreover, no N2pc component emerged for foil trials (i.e., nontarget aliens in the same category as the exemplar target). If lower-level, bottom-up capture were solely responsible for our findings, we would have observed larger N2pc components within the similar category (as compared to the dissimilar category) for both the exemplar and foil trials, as well as for the category trials. Second, the exemplar and category search trials only differed in the top-down task set and explicit instructions, not in the actual stimuli displayed. The exemplar search trials had larger N2pc amplitudes than did the category search trials. If bottom-up capture were the source of our N2pc effects, the N2pc components between the exemplar, foil, and category trials would have been identical.

One unresolved issue in this study is what comprises a categorical template. We propose that in this study it is based on visual features organized by a perceptual rule at the item level. Therefore, it is neither based solely on visual features (e.g., any green object) nor completely rule-based (e.g., things to bring on vacation). Whereas making judgments based on matching features is a perceptual decision, identifying category targets in this study required a rule that bound all of the targets into one category (i.e., any alien with similar features). Participants could not merely rely on a perceptual template, because inter-item similarity was low among category members. Many naturalistic categories also require the use of both visual features and rules (e.g., letters, numbers, clothing), though some may be more perceptually based (e.g., cars) than others (e.g., food; see work on hybrid search: Cunningham & Wolfe, 2014). Although real-world category-level search is much more complex than that targeted in our study, we used a well-controlled single case to better understand how category knowledge can be built easily with novel stimuli. Furthermore, category-learning studies typically use a variety of category types, including both familiar and novel categories based on abstract or perceptual criteria (e.g., simple arbitrary feature combinations, such as tail length and number of fingers on novel "bugs"—Sloutsky, 2010; see also Blair, Watson, & Meier, 2009; Posner & Keele, 1968; Younger & Cohen, 1986). Previous work has shown that searching for homogeneous perceptually based categories that can be identified via diagnostic features (e.g., ape faces vs. other animal faces) deploys perceptual category-level templates by 200 ms (Wu, Nako, et al., 2015). It is not too surprising that searching for a specific item and searching for diagnostic features from a single category template across multiple items elicit similar response patterns. Other studies have shown that familiar abstract categories (e.g., clothing, kitchen items) elicit N2pc components similar to those from perceptually based categories (e.g., Nako, Wu, Smith, & Eimer, 2014). The novel finding in the present study was that the use of newly acquired abstract category templates occurs within the same time window as perceptual templates, even when there are no specific diagnostic perceptual features for a particular category. This finding, along with previous findings, shows that the N2pc ERP component is a robust marker of categorization for both familiar and novel homogeneous (perceptual) and heterogeneous (abstract) categories. Recent work from our lab has extended the present finding to show that the N2pc also emerges within the same time window for very broad heterogeneous categories, such as "healthy versus unhealthy food" (Wu, Pruitt, Cheung, & Zinszer, 2015). Although it is clear from our results that abstract category templates can be used within the same time window as perceptual templates, more research will be required to understand how abstract category templates are constructed, stored, and deployed, relative to perceptual templates.

One limitation of the present study is that we used neural evidence to infer a cognitive process: categorical template deployment. However, our hypotheses were generated on the basis of extensive previous research. We measured a specific, well-documented ERP component that is a known marker of target selection, narrowing down the possible cognitive processes used in the task leading to the differences in the N2pcs generated for the two item sets. In addition, we controlled for the previously mentioned factors (i.e., reward salience, number of presented targets, semantic relatedness between targets and distractors, and pop-out effects) that have been shown to modulate the N2pc, independent of grouping mechanisms. In doing so, we reduced the risk of false alarms, by reducing the number of alternative explanations (Poldrack, 2006). There was one alternative explanation for our findings that we did not explore in this study, due to visual search constraints. We chose to include eight exemplars per category, to equate the numbers of potential targets in each category. However, the actual potential number of targets in the "different" category was 256, as compared to eight aliens in the "similar" category. Of note, previous studies have shown that the actual set size does not modulate the N2pc after perceptual similarity across the exemplars is controlled for (Wu et al., 2013). In addition, two of our unpublished studies showed that even broad categories such as "healthy food" or "upright items" elicit a reliable N2pc in the appropriate time window. Therefore, it is unlikely that the potential number of targets determines the presence or absence of the N2pc, independent of categorization, though it may modulate the amplitude of the N2pc. On the basis of previous studies, our present finding provides strong evidence that under specific circumstances, the N2pc can be a neural signature of rapid category-based selection, and that this can be elicited by intra-item similarity.

The present study adds to a growing body of work investigating how the process of grouping items reduces attention and working memory limitations (see Orhan, Sims, Jacobs, & Knill, 2014, for a review; Austerweil & Griffiths, 2011; Brady, Konkle, & Alvarez, 2009; Orbán, Fiser, Aslin, & Lengyel, 2008; Woodman, Vecera, & Luck, 2003). Grouping can be implemented via statistical regularities (e.g., Brady et al., 2009; Orhan et al., 2014), feature correlation (e.g., Austerweil & Griffiths, 2011; Wu et al., 2013), and Gestalt principles (e.g., Woodman et al., 2003). Moreover, grouping has been observed even in young infants (e.g., Quinn & Bhatt, 2009; Wu, Gopnik, Richardson, & Kirkham, 2011), highlighting the fundamental nature of this mechanism. The novelty of the present findings is that grouping at the lower, item level facilitated grouping at the higher, category level. This grouping benefit allows us to overcome efficiency limitations in visual search. In turn, visual search studies can reveal how items are grouped across various task demands, and search measures can be used as markers of learning and categorization (e.g., Wu et al., 2013).

Future work should further investigate how feature correlation (other than intra-item similarity) and other statistical regularities might facilitate the attentional selection of novel categories (e.g., Wu et al., 2013). A large literature has shown that regularities (correlation, co-occurrence, and transitional probabilities) help infants and adults isolate and group features in both visual and auditory domains (grouping features into objects and words; e.g., Fiser & Aslin, 2001, 2002; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996; Wu et al., 2011). How such knowledge becomes useful for the learner in selecting future information is an important issue in developmental psychology and cognitive science. Investigations into how naïve and mature learners use such regularities to find grouped multipart targets among distractors would allow for a better understanding of how we efficiently learn to attend.

Author note We thank Kristen Meyer, Jared Band, Sandy Xiong, and Eric Partridge for their help with data collection. We also thank Robert Jacobs, George Malcolm, Melissa Võ, Marisa Carrasco, Paul Quinn, Benjamin Zinszer, Rebecca Nako, and the UCR CALLA Lab RAs for useful discussions on the study design, data interpretations, and comments on earlier versions of the manuscript. We also thank Nicholas Turk-Browne and two anonymous reviewers for insightful comments on the manuscript. This research was conducted at the University of Rochester with funding from an NRSA (F32HD070537) from NICHD to R.W., and from an NIH grant (HD-037082) to R.N.A.

References

Austerweil, J. L., & Griffiths, T. L. (2011). A rational model of the effects of distributional information on feature learning. *Cognitive Psychology, 63,* 173–209.

Austerweil, J. L., & Griffiths, T. L. (2013). A nonparametric Bayesian framework for constructing flexible feature representations. *Psychological Review, 120,* 817–851. doi:10.1037/a0034194

Blair, M. R., Watson, M. R., & Meier, K. M. (2009). Errors, efficiency, and the interplay between attention and category learning. *Cognition, 112,* 330–336.

Brady, T. F., Konkle, T., & Alvarez, G. A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General, 138,* 487–502. doi:10.1037/a0016797

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. doi:10.1037/a0036313

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458. doi:10.1037/0033-295X.96.3.433

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. doi:10.1016/0013-4694(96)95711-9

Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences, 18,* 526–535.

Fiser, J., & Aslin, R. N. (2001). Unsupervised statistical learning of higher-order spatial structures from visual scenes. *Psychological Science, 12,* 499–504.

Fiser, J., & Aslin, R. N. (2002). Statistical learning of new visual feature combinations by infants. *Proceedings of the National Academy of Sciences, 99,* 15822–15826.

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C.-H., Jones, G., Oliver, I., & Pine, J. M. (2001). Chunking mechanisms in human learning. *Trends in Cognitive Sciences, 5,* 236–243. doi:10.1016/S1364-6613(00)01662-4

Goldstone, R. L. (2000). Unitization during category learning. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 86–112. doi:10.1037/0096-1523.26.1.86

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.

Haynes, J. D., & Rees, G. (2005). Predicting the orientation of invisible stimuli from activity in human primary visual cortex. *Nature Neuroscience, 8,* 686–691.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383,* 334–337. doi:10.1038/383334a0

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition, 83,* B35–B42.

Kiss, M., Driver, J., & Eimer, M. (2009). Reward priority of visual target singletons modulates event-related potential signatures of attentional selection. *Psychological Science, 20,* 245–251. doi:10.1111/j.1467-9280.2009.02281.x

Landau, B., Smith, L., & Jones, S. (1988). The importance of shape in early lexical learning. *Cognitive Development, 3,* 299–321.

Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology, 31,* 291–308.

Maxfield, J. T., & Zelinsky, G. J. (2012). Searching through the hierarchy: How level of target categorization affects visual search. *Visual Cognition, 20,* 1153–1163.

Mazza, V., & Caramazza, A. (2012). Perceptual grouping and visual enumeration. *PLoS ONE, 7,* e50862. doi:10.1371/journal.pone.0050862

Nako, R., Wu, R., Smith, T. J., & Eimer, M. (2014a). 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,* 1283–1288.

Nako, R., Wu, R., & Eimer, M. (2014b). Rapid guidance of visual search by object categories. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 50–60.

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.

Orbán, G., Fiser, J., Aslin, R. N., & Lengyel, M. (2008). Bayesian learning of visual chunks by human observers. *Proceedings of the National Academy of Sciences, 105,* 2745–2750.

Orhan, A. E., Sims, C. R., Jacobs, R. A., & Knill, D. C. (2014). The adaptive nature of visual working memory. *Current Directions in Psychological Science, 23,* 164–170. doi:10.1177/0963721414529144

Poldrack, R. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences, 10,* 59–63.

Posner, M. I., & Keele, S. W. (1968). On the genesis of abstract ideas. *Journal of Experimental Psychology, 77,* 353–363. doi:10.1037/h0025953

Quinn, P., & Bhatt, R. (2009). Transfer and scaffolding of perceptual grouping occurs across organizing principles in 3- to 7-month-old infants. *Psychological Science, 20,* 933–938.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science, 274,* 1926–1928. doi:10.1126/science.274.5294.1926

Scott, L., Pascalis, O., & Nelson, C. (2007). A domain-general theory of the development of perceptual discrimination. *Current Directions in Psychological Science, 16,* 197–201.

Sloutsky, V. M. (2010). From perceptual categories to concepts: What develops? *Cognitive Science, 34,* 1244–1286.

Telling, A., Kumar, S., Meyer, A., & Humphreys, G. (2010). Electrophysiological evidence of semantic interference in visual search. *Journal of Cognitive Neuroscience, 22,* 2212–2225.

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica, 135,* 77–99. doi:10.1016/j.actpsy.2010.02.006

Treisman, A. (1982). Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 194–214. doi:10.1037/0096-1523.8.2.194

Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review, 10,* 80–87. doi:10.3758/BF03196470

Wu, R., Gopnik, A., Richardson, D. C., & Kirkham, N. Z. (2011). Infants learn about objects from statistics and people. *Developmental Psychology, 47,* 1220–1229.

Wu, R., Nako, R., Band, J., Pizzuto, J., Shadravan, Y., Scerif, G., & Aslin, R. N. (2015a). Rapid selection of non-native stimuli despite perceptual narrowing. *Journal of Cognitive Neuroscience, 27,* 2299–2307.

Wu, R., Pruitt, Z., Cheung, O., & Zinszer, B. (2015). *Increased use of task-irrelevant category templates with increased dieting experience*. Manuscript under review.

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.

Younger, B. A., & Cohen, L. B. (1986). Developmental change in infants' perception of correlations among attributes. *Child Development, 803–815*.