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# Greater sensitivity to nonaccidental than metric shape properties in preschool children

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ABSTRACT

Nonaccidental properties (NAPs) are image properties that are invariant over orientation in depth and allow facile recognition of objects at varied orientations. NAPs are distinguished from metric properties (MPs) that generally vary continuously with changes in orientation in depth. While a number of studies have demonstrated greater sensitivity to NAPs in human adults, pigeons, and macaque IT cells, the few studies that investigated sensitivities in preschool children did not find significantly greater sensitivity to NAPs. However, these studies did not provide a principled measure of the physical image differences for the MP and NAP variations. We assessed sensitivity to NAP vs. MP differences in a nonmatch-to-sample task in which 14 preschool children were instructed to choose which of two shapes was different from a sample shape in a triangular display. Importantly, we scaled the shape differences so that MP and NAP differences were roughly equal (although the MP differences were slightly larger), using the Gabor-Jet model of V1 similarity (Lades & et al., 1993). Mean reaction times (RTs) for every child were shorter when the target shape differed from the sample in a NAP than an MP. The results suggest that preschoolers, like adults, are more sensitive to NAPs, which could explain their ability to rapidly learn new objects, even without observing them from every possible orientation.



## 1. Introduction

Children can quickly learn new objects, even when the objects are presented from a single static view (such as the animal pictures in a typical children's book). What accounts for this ability? When a 3-dimensional object is rotated in depth, its 2-dimensional projections on the retina can vary greatly. Biederman (1987) suggested that in order to achieve robust object recognition despite such image changes, certain shape properties that are view invariant might receive greater weight by the system involved in object recognition. Those view-invariant shape properties have been termed *nonaccidental properties* (NAPs) (Lowe, 1985), e.g., whether an edge is straight or curved or a pair of edges coterminate or not, and are distinguished from metric shape properties (MPs), whose 2-dimensional projections vary continuously as a function of rotation in depth, e.g. degree of curvature, degree of taper.

More generally, Amir, Biederman, and Hayworth (2011) noted that dimensions of shape can be regarded as extending from a *singular* or zero value (e.g., a straight contour with 0 curvature or parallel contours with a 0 angle of convergence) to an infinity of *non-singular* values (e.g., curves and non coterminating pairs of contours). With the exception of accidental viewpoints (as when a curve projects a straight line), as orientation in depth is varied, a singular value remains singular, and a non-singular value will vary but remains non-singular. The difference between singular and nonsingular values will always be nonaccidental but the difference between two nonsingular values will be metric. Lowe (1985) and Biederman (1987) noted that relying on nonaccidental properties can allow a vision system to represent the environment in a less view-dependent manner. Fig. 1 shows several examples of such changes along six different shape dimensions.

In line with Biederman's hypothesis, many studies of adult humans report a greater sensitivity to NAPs relative to MPs (Amir et al., 2012; Kukkonen et al., 1996; Wagemans et al., 2000), even in cultures not extensively exposed to modern artifacts (Biederman, Yue, & Davidoff, 2009). Differences in NAPs confer an enormous gain relative to differences in MPs in matching depth-rotated objects (e.g., Biederman & Bar, 1999; Biederman & Gerhardstein, 1993; Biederman, 2000). NAPs promote perceptual grouping (Feldman, 2007) and categorization (Abecassis et al., 2001) to a greater extent than MPs. Animal studies too, report

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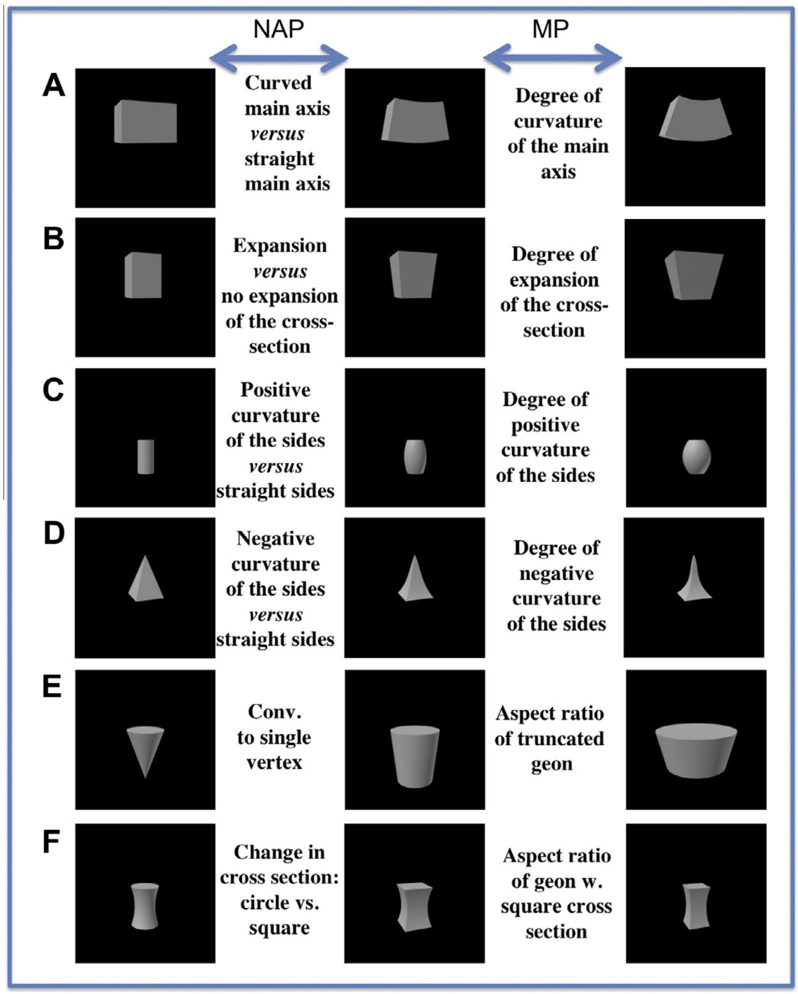


**Fig. 1.** Six sample sets of stimuli (from those used in the present experiment), exemplifying all the dimensions used in the experiment: (A) Main axis curvature, (B) Taper, (C) Positive curvature, (D) Negative curvature, (E) Convergence to a single vertex (vs. aspect ratio of truncated geon), (F) Cross section change (vs. aspect ratio of cross section) In (F), the nonaccidental change from a circular to a square cross section is not the same attribute as the metric change in aspect ratio of the cross section but the latter does provide a metric variation of the cross section. Modified from Fig. 2 in Amir, Biederman, and Hayworth (2012).

greater sensitivity to NAPs in pigeons (Lazareva, Wasserman, & Biederman, 2008) as well as single unit recordings in macaque inferotemporal cortex (Kayaert, Biederman, & Vogels, 2003; Vogels et al., 2001).

Only a handful of studies examined sensitivity to NAPs in younger humans, with somewhat mixed results. On the one hand, Kayaert and Wagemans (2010) reported that infants as young as 3 months are more sensitive to a NAP (convergence to vertex) compared to an MP (aspect ratio). In their study, infants viewed either a triangle or a trapezoid multiple times until they became habituated to the shape. Then the infants were presented, side-by-side, with a shape varying in aspect ratio from the stimulus they were habituated to, and one varying in convergence to vertex (i.e., if the habituated stimulus was a triangle it was a trapezoid, and vice versa). Infants were more likely to look at the shape that varied in convergence to vertex, presumably because they were adapted to (or "bored" with) the habituated shape, and the shape varying in convergence to vertex appeared to differ more from the habituated shape.

On the other hand, three studies of preschool children are sometimes taken as evidence that, unlike adults, preschoolers do not show greater sensitivity to NAPs. In 2011, Ons and Wagemans used a delayed match to sample task with 3–7 year olds. They showed that sensitivity to non-linear shape transformations (that produce changes in NAPs) relative to affine transformations (which preserve NAPs) increase with age. Abecassis et al. (2001) and Sera and Millett (2011) used novel physical objects to test categorization in children and adults. Children and adults were introduced to novel physical objects that were given a name (e.g. "Wug"). They then were presented with objects that differed either in MPs or NAPs from the original object. Adults, but not preschool children, were more likely to call the MP varied objects "Wug," than extend that name to the NAP varied objects. Similar results were obtained when, rather than naming the objects, children were asked which one of the varied shapes is "more like" the original one they have seen.

While these studies suggest children are less sensitive to NAPs relative to adults, they cannot be interpreted to suggest children are not more sensitive to NAPs than MPs. In order to compare relative sensitivities to any shape differences, one needs a principled measure of the relative magnitudes of the *physical* differences. Abecassis et al. (2001) did attempt a scaling by employing, for example, equal differences in curvature and eliciting judgments of similarity from adult observers. However, that geometrical differences produce equal psychological differences is an untested assumption. In general, two centuries of psychophysical scaling, e.g., Weber's and Fechner's Law, suggest that it is rare that geometrical and psychophysical measures are equivalent. If humans are more sensitive to differences in NAPs than MPs, subjective

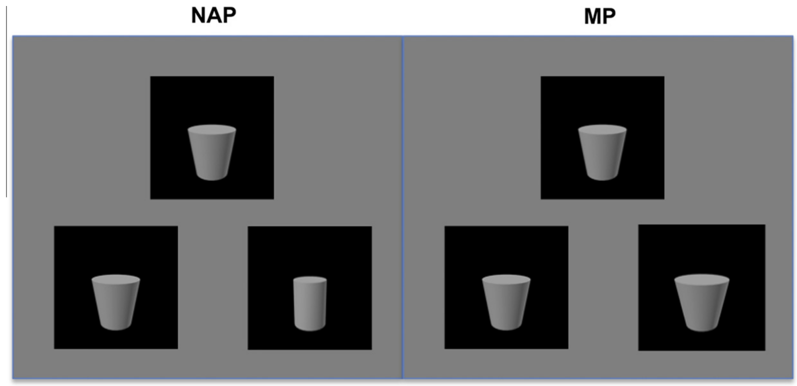


**Fig. 2.** Illustration of a nonmatch-to-sample trial in its two versions: NAP (left) and MP (right). The top shape is the sample and participants chose which one of the two lower stimuli differs from the sample (right, in these examples). The dimension illustrated is Taper (non parallelism).

judgments of equality from adult observers will necessarily null out those differences. That is, the observers will inflate MP differences to be equivalent to NAP differences. An alternative, more principled measure of scaling NAP and MP differences can be derived from the Gabor-Jet model (Lades & et al., 1993), a multi-scale, multi-orientation model of V1 simple cells. The underlying perspective is that V1 codes metric differences with later stage classifiers producing the greater sensitivity to NAP differences. Justification of the Gabor-Jet measure of similarity derives from its almost perfect prediction of humans' sensitivity to MP variations but its marked underestimation of the psychophysical dissimilarity of NAP differences (Yue et al., 2012). Amir and Biederman (2014) measured Gabor differences in the set of objects used in Abecassis et al. (2001) and Sera and Millett (2011) and found that the MP varied objects were much more dissimilar to the object the children first learned than the NAP varied shapes. The greater physical difference, by the Gabor measure, may have countered the potentially greater sensitivity to NAPs in children's categorization choices. Indeed more than 90% of the variance in the children's categorization behavior could be explained by the Gabor-Jet measure of physical similarity.

In order to study children's relative sensitivities to NAPs vs. MPs then, it is necessary to construct a set of shapes in which those differences are equal (or slightly greater for MPs, given that we hypothesize a greater sensitivity to NAPs) using a measure like the Gabor-Jet model. Such a set was used in multiple studies (see sample objects from that set in Fig. 1), and revealed a greater sensitivity to NAPs in adults (Amir, Biederman, & Hayworth, 2012), individuals from cultures with little exposure to modern artifacts (Biederman, Yue, & Davidoff, 2009) and cells in macaque monkeys shape selective cortex (Kayaert, Biederman, & Vogels, 2003). We used that same stimulus set in the present investigation and found that preschool children too, show greater sensitivity to NAPs.

## 2. Methods

We employed a nonmatch-to-sample experiment to assess the sensitivity to NAPs vs. MPs in preschool children. The display was of three geons[1] presented in a triangular array (Fig. 2) with one geon (the sample) on top and two potential matching geons below. Pilot work suggested that the children would find the task easier if the correct target shape was the one *different* from the sample (compatible with the Sesame Street question: "Which one of these is not like the others?"). The shapes on a given trials were all 3D rendered volumes corresponding to different geons. The assessment of NAP vs. MP sensitivity was accomplished by having the target shape differ in either a NAP or an MP from the matching distracter (and sample) shape. The match (or nonmatch)-to-sample task eliminates the criterion effects that arise in a same-different task when subjects have to adopt a criterion as to whether two stimuli are the same or different or whether a label is or is not to be applied to a given stimulus. Such criterion effects can readily lead to significant below-chance same-different performance when stimuli are highly similar. Minimum performance in the match-to-sample task is at chance.

### 2.1. Subjects

14 preschool children, 6 girls, all right handed, with mean age 4.8 years old, range 4.3–5.5, were included in the analysis below. 4 children out of the original 18 who participated were excluded because they either failed to understand the task or had mean RTs that exceeded 5s. The children (and their parent) were rewarded for their participation with a children's t-shirt with the caption "I [picture of brain rather than the typical heart] SC (for the University of Southern California)". Below that was printed "I am a future USC Cognitive Neuroscientist."

### 2.2. Stimuli and design

The stimuli (see examples in Fig. 1) were the same as those used originally in the Kayaert, Biederman, and Vogels' (2003) single unit study, and subsequently in Amir, Biederman, and Hayworth's (2012) study with adults, and Biederman, Yue, and Davidoff's (2009) study of the Himba tribe of Namibia (with minimal exposure to modern artifacts), all of which demonstrated greater sensitivity to NAPs. They were 3D single geons in which a shape dimension, such as the curvature of the axis, was altered from a singular (e.g., straight axis) to two levels of non-singular values (slightly curved axis and very curved axis) resulting in 3 geons per set. We refer to the geon with the intermediate value as the Base geon. Kayaert et al.'s assessment of NAP-MP sensitivity in IT cells was accomplished by comparing the activity to a Base geon, with a small nonsingular value, such as a cylinder with a slightly curved axis, to either a cylinder with a straight axis (singular value, thus a NAP difference) or one with a more highly curved axis (another nonsingular value, thus an MP difference). The match-to-sample task is designed to capture that same variation by having

[1] Geons are a partition of the set of generalized cylinders (GCs). A GC can be described as the volume produced by sweeping a cross section along an axis. A cross section that is a circle will generate a cylinder; a rectangle will produce a brick. The axis might be curved or the cross section might vary in size (so the sides will no longer be parallel) as it moves along the axis, to produce a cone (if a circle cross section expands), a sphere or lemon (if it expands and then contracts), or an hourglass (if it contracts then expands). When the cross section varies in size, it can end as truncated, curved, or at a point—image variations distinguished by NAPs of the contours and vertices. The cross section can be 1D (a line), in which case the geon will be 2D, such as a rectangle or triangle.

the sample always with a small nonsingular value and the target either with a singular value (NAP difference) or a greater nonsingular value (MP difference). The objects subtended 2.5–5° of visual angle in height, and 2–3° in width. Images can be downloaded from http://geon.usc.edu/~ori/VogelsShaded124.html.

Fig. 1 shows an example for each of the dimensions used in the experiment. Each set (row) depicts the manipulation along a single geon dimension, with the Base stimuli (middle) being slightly more dissimilar (by measures of Gabor similarity) from the MP variant (right) than the NAP variant (left). The stimuli were composed of 19 sets for which the following shape dimensions were manipulated: Main Axis Curvature (3 sets): the main axis of the Base shape increased in curvature for the MP, and became straight for the NAP (Fig. 1a). Taper (3 sets): the Base shape had a cross section that expanded continuously along the main axis. The angle of expansion was larger for the MP, and zero for the NAP, resulting in parallel sides (Fig. 1b). Positive Curvature (1 set): the sides of the geon curved outwards along the main axis of the Base shape, with a higher degree of curvature for the MP, and zero curvature, or straight sides, for the NAP (Fig. 1c). Negative Curvature (2 sets): same as positive curvature, but the sides curved inwards instead of outwards (Fig. 1d). Convergence to Vertex (3 sets): the NAP version was a cone with sides converging to a point (an L-vertex); the Base shape appeared truncated with a curved contour separating the sides (so that they did not meet in a single vertex), and the MP version was an elongation of the edge separating the sides (the manipulation preserved the orientation of sides relative to the Base as well as the number of vertices (two) at the bottom of the geon; Fig. 1e). Cross Section (7 sets): the shape of the cross section was changed from Base to NAP (e.g., a circular vs. square cross section) the change from Base to MP was in aspect ratio (Fig. 1f).

### 2.3. Scaling stimulus dissimilarity

To compare the sensitivity to NAP vs. MP shape differences in a principled manner, it is necessary to scale the physical image differences. We selected two measures to reflect similarities as they would be approximated at early stages of visual processing (before presumed NAP classifiers were activated in later stages): (a) pixel energy as a measure of retinal similarity, which was used by Kayaert, Biederman, and Vogels (2003) and (b) Gabor wavelets as a measure of V1's multiscale, multioriented filtering. For compact stimuli, such as the ones in this experiment, these measures are highly correlated (Yue et al., 2012). We made sure the MP differences relative to the Base shape were equal or slightly greater than the NAP differences on both measures. We also made sure that any size differences, if any, between the Base object and its variations were equal or greater for the MP variation. Similar scaling was done in a study demonstrating greater sensitivity to NAPs in infants (Kayaert & Wagemans, 2010).

The Gabor measure of similarity was computed by the Gabor-Jet model, a multiscale, multiorientation model of V1 simple-cell filtering developed by Lades and et al. (1993). The parameters and implementation followed those used by Xu, Yue, Lescroart, Biedeman, & Kim (2009), which can be downloaded at http://geon.usc.edu/GWTgrid_simple.m. Gabor wavelets correlate almost perfectly with psychophysical similarities as assessed by match-to-sample performance when discriminating metrically varying faces or novel blobs (Yue et al., 2012).

### 2.4. Procedure

Children arrived to the lab accompanied by a parent. Once the children grew accustomed to the new environment and the experimenter, they sat at a table with a 15″ Macbook pro laptop, on which the experiment was run. Stimuli were displayed and responses were recorded with Psychophysics Toolbox (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007) running under Matlab (The MathWorks, Natick, MA). Children were presented with a picture of an alien on the screen, and were told that he needed their help to find his way home. Children were instructed to "help the alien" choose the image on the right or left that was different from the image on top. The child was trained on the task using pictures of animals, until the experimenter was convinced that the child understood the task. The match-to-sample array was counterbalanced such that on half the trials the sample stimulus was the Base object, and in the other half either its NAP or MP variant. The target always differed from the sample in either an MP or a NAP and the distractor was always identical to the sample. Participants responded by pressing the 'M' key on the keyboard if the target object was on the right (which it was on half of the trials), and 'Z' if it was on the left. The response keys had blank pink stickers on them.

Feedback was provided in the form of a yellow face appearing at the center of the screen once the child had made the response. The face had a frown if the child chose the wrong object, and a smile if he/she chose the correct one. Pilot work revealed that children were upset (and would not continue in the experiment) when the penalty for errors was emphasized so our feedback was designed to encourage fast, correct responding – the faster the correct responses, the larger the happy face – while the unhappy face indicating an error remained small, irrespective of the speed of response, in order not to discourage the child. Every ten trials the experiment stopped and the alien appeared on the screen. The experimenter said: "The alien is very happy with your help, and he wants to give you a sticker." And the child was then given a sticker of their choice. We attempted to obtain as many trials as each child (or their parent) had patience for, yielding a range of 74–194 trials per child (median 111).

## 3. Results

Overall accuracy (percent correct) was 59.9%, and was essentially equivalent for NAPs and MPs, 60.6% vs. 59.3%, respectively, $t < 1$. Given the relatively small number of trials per participant, when broken down into the six individual dimensions, accuracy did not reliably differ for any of the individual dimensions,[2] ps for all $ts(13) > .10$. However, every one of the 14 preschool participants was slower on MP trials, $M = 2.56$ s, than on NAP trials, $M = 1.91$ s, $t(13) = 4.77$, $p < .001$. Only trials in which the children choose the correct shape were included in the reaction time analysis. One child even stated on an MP trial in which the dimension was main axis curvature "this is harder, because they are both curved."

Fig. 3 shows the RT differences between NAP and MP for the individual dimensions. There either was a non-significant NAP-MP difference in RTs or lower RT for the NAP trials. Longer RTs for MP than NAP trials were found for Main Axis Curvature (MP: $M = 3.38$ s, NAP $M = 1.91$ s, $t(13) = 4.25$, $p < .001$) and Cross Section Change (MP: $M = 2.92$ s, NAP $M = 1.87$, $t(13) = 3.61$, $p < .005$) but not for the other dimensions, although the trend generally was for higher RTs on MP trials (except for the negligible MP advantage for Taper, see Fig. 3).

It would be of interest to compare the data for the individual dimensions for the children from the present study with the adult data from Amir, Biederman, and Hayworth (2012). Unfortunately, with the limited number of trials for the children, (74–194, median 111) as compared to the 2520 trials for each adult (following a

[2] As none of the differences in error rates were close to significance, we thus focus on correct RTs for the rest of the paper. For the sake of completeness here are the error rates for the individual dimensions, MP vs. NAP, respectively: Main Axis Curvature 43.6%, 42.5%; Taper 37.9%, 46.1%; Neg Curv 36.1%, 37.0%; Pos Curv 36.1%, 32.9%; Convergence to Vertex 32.9%, 39.1%; Cross Section 43.3%, 39.9%.

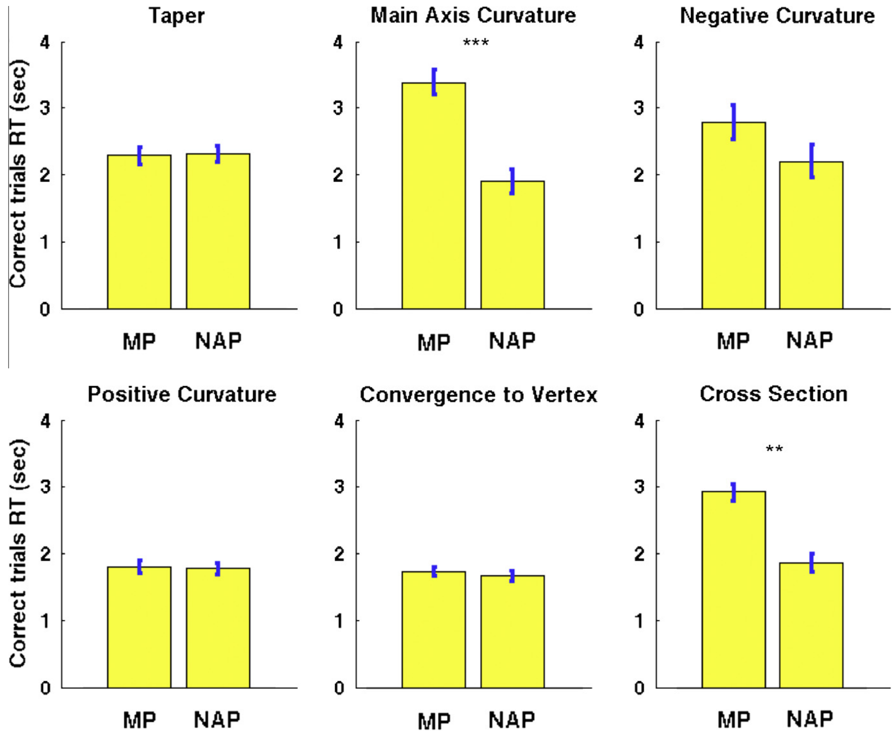


**Fig. 3.** Reaction time in seconds for the MP vs. NAP variations along the six dimensions tested: Taper, Main Axis Curvature, Negative Curvature, Positive Curvature, Convergence to Vertex, and Cross Section Shape. Error bars are the standard errors of the mean with the between subjects variance removed. $^{**}p < .01$, $^{***}p < .001$.

practice run of 84 trials), when broken down into the six individual dimensions, the correlations between adults and children over the dimensions were low and none were close to being significant. For adults, RTs and error rates both showed robust and significant advantages of NAPs over MPs. (Only the RTs were reliable for the children.) There was some similarity in the RTs for the individual dimensions in that both Main Axis Curvature and Cross Section also showed a significant NAP advantage for adults in the error rates whereas these attributes showed the NAP advantage for children only for RTs. (Main axis curvature also showed a NAP advantage for RTs for adults.) A comparison of sensitivity to individual shape attributes in children awaits a more extensive investigation.

## 4. Discussion

We employed a nonmatch-to-sample task in which preschool children were shown a triangular array of geon images (one on top and two on the sides), and were instructed to press a key corresponding to the image (either the right or left one) they thought was different from the top image. Every child responded faster when the target image differed in a nonaccidental property than when it differed in a metric property. Importantly, image differences were scaled so that MP differences were equal to, or slightly greater than NAP differences using the biologically relevant Gabor-Jet model of V1 simple cell filtering as a measure of image similarity.

These results are consistent with previous studies showing greater sensitivity to NAPs in human adults (Amir, Biederman, & Hayworth, 2012; Biederman & Bar, 1999; Biederman, Yue, & Davidoff, 2009; Feldman, 2007; Kukkonen et al., 1996; Wagemans et al., 2000; Biederman & Gerhardstein, 1993; Abecassis et al., 2001; Biederman, 2000; Op de Beeck, Torfs, & Wagemans, 2008), human infants (Kayaert & Wagemans, 2010), pigeons (Lazareva, Wasserman, & Biederman, 2008), and single cell recordings in the macaque (Kayaert, Biederman, & Vogels, 2003; Vogels et al., 2001).

Three studies of preschool children, however, are often taken as evidence that children are no more sensitive to NAPs than MPs (Abecassis et al., 2001; Ons & Wagemans, 2011; Sera & Millett, 2011). While these studies seem to show an *increase* in NAP sensitivity with age, they do not speak to the relative sensitivity to NAP vs. MP differences. In order to make any valid claims about such relative sensitivities, it is necessary to make sure the physical image differences in MPs and NAPs compared are of the same magnitude. In fact, when such measures were applied to the stimuli used in Abecassis et al. (2001) and Sera and Millett (2011), we found that the MP image differences were much larger than the NAP differences to which they were compared, potentially explaining why the children did not show a greater sensitivity to NAPs in their study (Amir & Biederman, 2014). As the present investigation shows, when the image differences are properly controlled, preschool children too, show greater sensitivity to NAPs.

Our finding that preschool children are more sensitive to NAPs, which are invariant to view changes, may help to explain their ability to rapidly learn novel objects. By focusing on the view invariant NAPs children may be able to generalize and identify a novel object which they have only seen from a handful of views, or even a single view, such as a new animal learned from a single picture in a book. Indeed, the pervasiveness of greater NAP sensitivity suggests that it is a hallmark of a visually shape-competent organism.

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