Spatial and featural cue weighting in children's developing object representations

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Abstract

To accurately represent an object, it must be individuated from the surrounding objects and then classified with the appropriate category or identity. To this end, adults flexibly weight different visual cues when perceiving objects. However, less is known about whether, and how, the weighting of visual object information changes over development. The current study examined how children use different types of information— spatial (e.g., left/right location) and featural (e.g., color)—in different object tasks. In Experiment 1, we tested whether infants and preschoolers extract both the spatial and featural properties of objects, and, importantly, how these cues are weighted when pitted against each other. We found that infants relied primarily on spatial cues and neglected featural cues. By contrast, preschoolers showed the opposite pattern of weighting, placing greater weight on featural information. In Experiment 2, we tested the hypothesis that the developmental shift from spatial to featural weighting reflects a shift from a priority on object *individuation* (how many objects) in infancy to object *classification* (what are the objects) at preschool age. Here, we found that preschoolers weighted spatial information more than features when the task required individuating objects without identifying them, consistent with a specific role for spatial information in object individuation. We discuss the relevance of spatial-featural weighting in relation to developmental changes in children's object representations.

Keywords: cue combination, object perception, individuation, identification, ventral and dorsal streams

Introduction

The visual world is cluttered and complex. For example, a natural scene typically contains partially occluded objects, and, yet we readily parse the world into individual objects. We also readily classify objects into individual categories and/or individual identities. How do such robust abilities develop?

In adulthood, individuation and classification are accomplished by flexibly integrating different sources of visual information (Pylyshyn, 1989; Scholl, 2001; Treisman & Gelade, 1980). For example, spatial cues may be particularly informative for object individuation because individual objects cannot occupy multiple locations simultaneously (Pylyshyn, 1989; Treisman & Zhang, 2006). Likewise, featural cues may aid in object classification because object identities are most often distinguished by features such as color and shape (Landau, Smith, & Jones, 1988; Naor-Raz, Tarr, & Kersten, 2003). However, there are also conditions in which spatial cues may aid in classification, such as when location is particularly diagnostic of identity (e.g., the real Eiffel tower is in Paris; Huttenlocher & Lourenco, 2007), and in which featural cues are well suited to individuation, such as when objects overlap in the visual scene (e.g., partial occlusion; Needham, 1997). Although adults have been shown to use a combination of spatial and featural cues to represent objects, and do so flexibly, far less is known about the development of this ability. In the present study, we examined how infants and preschoolers weight spatial and featural cues when representing multiple objects and how these cues get used for individuation and classification at different ages.

Studies with infants suggest that, from early in development, humans are sensitive to spatial cues, such as location, and featural cues, such as color and shape¹. Newborn infants, for example, discriminate objects on the basis of egocentric distance (Slater, Mattock, & Brown, 1990) and categorize them on the basis of spatial position (left vs. right) relative to a landmark (Antell & Caron, 1985; Gava, Valenza, & Turati, 2009). Moreover, newborns discriminate colors (Adams, 1987; Adams & Courage, 1998) and shapes (Quinn, Slater, Brown, & Hayes, 2001; Turati, Simion, & Zanon, 2003), as well as demonstrate shape constancy across changes in orientation (Slater & Morison, 1987). By 6 months of age, infants are able to subdivide a space into left and right regions without a relational landmark (Quinn, 2012) and, within a large sandbox, they detect differences in an object's location by as little as 8 inches (Newcombe, Huttenlocher, & Learmonth, 1999). Moreover, 6-month-olds exhibit adult-like category boundaries when discriminating colors (Bornstein, Kessen, & Weiskopf, 1976) and form shape categories from as few as three exemplars (Ayzenberg & Lourenco, 2019; Bomba & Siqueland, 1983; Quinn et al., 2001).

Despite a sensitivity to both spatial and featural cues from early in development, extant studies suggest that there is a developmental shift in how children weight these cues when multiple objects are present. In particular, infants younger than 12 months seemingly favor spatial information over an object's features (for reviews, see Leslie, Xu, Tremoulet, & Scholl, 1998; Stavans, Lin, Wu, & Baillargeon, 2018). For example, infants are more likely to detect changes to objects' spatial locations following occlusion than they are to detect changes in color or shape (Kibbe & Leslie, 2013; Mareschal & Johnson, 2003). Moreover, infants as young as 6 months, accurately represent the quantity of objects following occlusion when the objects are presented in distinct spatial locations, but it is not until 12 months of age that features are used for quantification (Van de Walle, Carey, & Prevor, 2000; Xu & Carey, 1996). Even in the absence of occlusion, infants preferentially

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segment objects by the presence of spatial separation, rather than featural cues (Kestenbaum, Termine, & Spelke, 1987; Needham, 1997; Xu, Carey, & Welch, 1999).

However, by 4 years of age, children seemingly favor featural information over an object's spatial location (Dessalegn & Landau, 2008; Haun, Call, Janzen, & Levinson, 2006; Lourenco, Addy, Huttenlocher, & Fabian, 2011; Miller, Vlach, & Simmering, 2017). For example, Haun et al. (2006) pitted spatial information against features in an manual search task. Here, a reward was hidden within one of three spatially (left, middle, right) and featurally (gray cube, white sphere, brown cylinder) distinct containers. During an occlusion period, two of the containers were swapped, such that the reward could either be in the original location, but in a new container, or in the original container, but in a new location. Consistent with prior work, 12-month-old infants searched in the container indexed by the original location (e.g., left container), even though the feature of the container changed. By contrast, 4-year-old children searched in the container indexed by the featural information (e.g., gray cube), even though the location of the container changed.

Although these findings suggest that there is a qualitative shift between infancy and preschool age in how spatial and featural cues are weighted, open questions remain. In particular, previous studies (e.g., Haun et al., 2006) placed spatial and featural cues in conflict with one another, but they did not test the extent to which each cue was encoded separately. Without testing each cue in isolation, it is impossible to know whether the putative greater weighting reflects weighting *per se* (involving multiple cues) or the perception of just one of these cues. Moreover, search tasks are a poor method by which to measure the content of infants' object representations because young children have difficulty inhibiting previous reaching behaviors which affect performance following location changes (Bremner, 1978; Bremner & Bryant, 1977; Smith, Thelen, Titzer, & McLin, 1999). Finally, these studies do not address the mechanism by which potential developmental changes in weighting might occur. In other words: why might children weight spatial information more heavily early in development but featural information later? What would lead to such a shift in cue weighting?

To address these questions, we first tested both infants and preschoolers on an age-matched task where spatial and featural cues were both available for distinguishing objects. In both groups of children, we assessed whether each type of information was represented, and if so, how the cues were weighted relative to one another. This task was minimally structured such that children were simply required to distinguish a target (rewarded) object from another (non-rewarded) object in a context where both the relative positions of the objects (left vs. right) and their features (color or shape) could be used to distinguish between them. To foreshadow our results, we found that infants primarily encoded spatial cues, whereas 4-year-olds encoded both spatial and featural cues, but weighted features more heavily. In a second experiment, we focused on 4-year-olds specifically to determine the extent to which weighting reflects differential object processes: namely, individuation versus classification. In particular, we tested whether 4-year-olds, who weighted featural cues more in a minimally structured task, would weight spatial information more heavily if the task explicitly required individuation. As predicted, we found that when 4-year-olds were asked to individuate objects, they favored the spatial information.

Experiment 1a

In Experiment 1a, we examined the weighting of spatial and featural cues in 12-month-olds. More specifically, we used an eye-tracking paradigm to test whether and how infants encode multiple sources of information. We chose to test 12-month-olds because this is the age when both spatial

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and featural cues are incorporated into children's object representations, at least when cues are presented in isolation (Wilcox, 1999; Wilcox & Baillargeon, 1998a; Xu et al., 1999). However, it is unclear whether both are encoded simultaneously and how they are weighted relative to one another.

To this end, we used a learning-contingent reward anticipation task (McMurray & Aslin, 2004; Shukla, Wen, White, & Aslin, 2011) in which infants were trained to anticipate a visual 'reward' at one of two objects. The target object was distinguishable from the distractor in both spatial and featural properties (e.g., *blue* circle on the *left* vs. green circle on the right; see Figure 1A). At test, we conducted two assessments. First, we measured whether children extracted both the spatial and feature cues by presenting each in isolation (see Figure 1B,C). It was crucial to assess infants' sensitivity to each cue in isolation because a measure of cue weighting depends on both types of cues having been represented. The crucial test of weighting occurred by pitting spatial and featural cues against one another (see Figure 1D).

Method

Participants. An a priori power analysis revealed that a minimum of 44 participants was needed to detect a moderate effect ($d = 0.50$) with 90% power. To ensure that we had a sufficient number of infants in each condition, we used a convenience sampling procedure and recruited 57 full-term 12-month-old infants ($M = 12.14$ months; range = 9.53 to 13.80 months; 30 female). To ensure that effects were not unduly influenced by sample size decisions, we include Bayesian and non-parametric tests, in addition to classic null-hypothesis tests throughout.

Following previous research (Shukla et al., 2011), infants only proceeded to a test trial if they met the a priori learning criteria. Infants who completed at least one test trial were included in the analyses. Three infants were excluded for failing to meet this criterion (2 from the color condition; 1 from the shape condition). Although demographic information was not collected systematically, the children appeared to represent the demographics of a large metropolitan community in the United States of America. This experiment was approved by the [blinded] Internal Review Board (IRB) under the project 'Spatial Origins' (Study Number IRB0003452).

Procedure. Infants were seated on a caregiver's lap approximately 60 cm from a 22-inch computer monitor (1920 × 1080 px). Caregivers were instructed to keep their eyes closed and to refrain from interacting with the infant during the study session. The experiment was controlled by a custom program written in Visual Basic (Microsoft) and gaze data were recorded with an Eye-Link 1000 plus eye tracker recording at 500 Hz (SR-Research). Prior to the start of the experiment, the eye tracker was calibrated to each infant using a 5-point calibration routine.

The experiment consisted of two types of trials—training and test—interspersed throughout the experiment. During the training trials, infants were provided with spatial and featural cues for a pair of objects (see Figure 1). Then, in the test trials, we assessed the extent to which infants learned each type of cue in isolation, as well as their relative weighting when in conflict with one another. Each trial began with a centrally placed attention-getting stimulus that consisted of a colorful swirling disc with an accompanying 'jingling' sound, which played until infants fixated it for a minimum of two seconds.

Training. In the training trials, infants were trained to anticipate a visual reward at a target object. The target object could be determined by its spatial and/or featural properties (e.g., blue target on the left vs. green distractor on the right; see Figure 1A). The stimuli were always a pair of objects

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(6.75×6.75 cm; $\sim 6.5^\circ \times 6.5^\circ$) of different colors (blue and green; matched luminance) or shapes (rectangle and circle; matched width/diameter) presented side-by-side (6.75 cm apart; $\sim 6.5^\circ$) in one of six randomly chosen locations onscreen (never centrally). We varied the location of the object pair on the screen to ensure that infants learned the spatial relations between the objects (left/right) instead of developing a stereotyped looking response to one location on the screen (Marcovitch & Zelazo, 1999). The objects remained onscreen for 1.5 s (anticipatory period), at which time, infants' fixations were recorded. Following the anticipatory period, the visual reward was presented, such that the target object bounced and made a 'boing' sound. The target's spatial position (left or right) and feature (color: blue, green; shape: circle, square) in the training phase were counterbalanced across infants. To keep infants engaged, objects were presented with smiley-faces.

Using a sliding-window procedure, we analyzed infants looking behaviors online. Following the procedure of Shukla and colleagues (2011), infants were required to meet one of three learning criteria before continuing to a test trial. The criteria were: (1) at least 65% looking time towards the target object in the last five training trials; (2) first fixation to the target in three out of the last five training trials; or (3) a significant *t*-test comparison confirming greater looking to the target versus the distractor object on the last five training trials ($p < 0.05$). Once one of the three criteria was met, a test trial began. A set of training trials was administered between every test trial and infants were required to meet the learning criteria within each set. On average, infants completed 6.93 training trials ($SD = 2.06$ trials) prior to each test, and an average of 34.87 training trials ($SD = 7.57$ trials) across the entire session. This procedure maximized the possibility that infants began each test trial having associated the target object with the reward.

Test. Infants were presented with three types of test trials: 'space', 'feature', and 'conflict'. In the space and feature trials, only spatial or featural information was informative during test, allowing us to assess whether infants learned each cue in isolation. More specifically, in the space trials, both objects were featurally identical (e.g., both blue; Figure 1B) and we measured whether infants looked to the previously trained location (e.g., left object). In the feature trials, left/right spatial information was removed by orienting the objects vertically (6.75 cm apart, $\sim 6.5^\circ$; Figure 1C) and we measured whether infants looked to the previously trained feature (e.g., blue object). In the conflict trial, we measured which cue infants weighted more heavily by pitting spatial and featural cues against each other (see Figure 1D). For instance, if infants were trained to anticipate the reward at the blue object on the left, then, during conflict, the blue object was presented on the right and the green object was presented on the left. Here, fixations to the left object (despite being green) indicated greater spatial weighting, whereas fixations to the blue object (despite being on the right) indicated greater feature weighting.

Object pairs were presented centrally and remained onscreen for 1.5 seconds at test. Each test trial was presented twice during a complete session. Presentation of the test trials was blocked such that infants were presented with each test trial type (space, feature, and conflict) at least once before repetition. The first test trial presented during the session was counterbalanced across infants, with the remainder of the test trials within a block presented in a randomized order. The order of test trials was the same for both blocks. The feature used in the spatial test trial and the top/bottom positions in the feature test trial were counterbalanced across infants. Infants were not provided with a visual reward at test.

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Figure 1. Examples of color (left) and shape (right) trials in Experiment 1. (A) During training, infants (Exp. 1a) and preschoolers (Exp. 1b) were taught to anticipate a reward at a target object (indicated with a red outline for illustration purposes) with both spatial and featural (color or shape) properties (e.g., *blue* on the *left*; *square* on the *right*). (B) In space test trials, object features were identical in order to assess the extent to which children encoded the left-right positions of the objects. (C) In feature test trials, left/right spatial information was removed in order to assess the extent to which children encoded either the colors or shapes of the objects. (D) In conflict test trials, spatial and featural cues were pitted against one another by switching the position of the cues from what was presented during training. Responses to the previously trained spatial location indicated greater weighting of spatial information, whereas responses to the previously trained feature indicated greater weighting of featural information.

Results

To control for individual differences in overall attention, infants' looking times on each trial were analyzed as the proportion of their looking time to the target object relative to overall looking (i.e., looking time to the target divided by total looking time to both the target and distractor). On conflict trials, a proportion closer to 1 indicated greater spatial weighting, whereas a proportion closer to 0 indicated greater featural weighting. An analysis of infants' first fixations revealed qualitatively similar results (see Supplemental Table 1).

Every infant who completed at least one test trial was included in the analyses. In total, 51 infants completed at least one test trial in block 1 and 33 infants completed at least one test trial in block 2. Given the difference in the number of infants included in each block, we analyzed the data separately by block.

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We first evaluated whether the learning criteria were sufficient for infants to learn to anticipate the reward at the target object. One-sample t-test comparisons to chance (0.50) revealed that, during the training trials, infants looked to the target object significantly above chance in both block 1 ($t(53) = 5.48, p < .001, d = 0.75, BF_{10} > 100$, and block 2, $t(50) = 3.73, p < .001, d = 0.52, BF_{10} > 54.06$. Binomial tests further confirmed that the majority of infants showed these effects (block 1: 40/54 infants, $p < .001$; block 2: 36/54 infants, $p = .005$).

Having confirmed that infants met the learning criteria, we next examined whether infants encoded both spatial and featural cues during training, as well as how the cues were weighted relative to one another. Comparisons to chance revealed that, in the spatial trials, infants looked to the previously rewarded spatial cue ($t[32] = 3.65, p < .001, d = 0.64, BF_{10} = 34.84$; 27/33 infants, $p < .001$; Binomial test) in block 2, but not block 1 ($p = .111, d = 0.23, BF_{10} = 0.52$). In the feature trials, infants did not look to the previously rewarded feature in either block ($ps > .248, BF_{10} < 0.34$). Analysis of the conflict trials revealed that infants looked to the previously rewarded spatial target in block 2 ($t[32] = 3.55, p < .001, d = 0.62, BF_{10} = 26.89$; 25/33 infants, $p = .005$; Binomial test). Looking to the spatial target in block 1 did not meet the criteria for significance as indicated by Bayesian and non-parametric statistics ($t[50] = 2.09, p = .042, d = 0.29, BF_{10} = 1.12$; 30/51 infants, $p = .262$; Binomial test). Taken together, these results suggest that when spatial and featural cues were presented in combination, infants encoded the relative location of the target object, not its features (color or shape), at least by the second block. Not surprisingly, then, infants favored spatial over featural information in the conflict trials.

Exploratory analyses. The previous analyses revealed no evidence of feature encoding by infants. However, it is possible that the coding of features depends on the type of feature presented (Kibbe & Leslie, 2019; Mareschal & Johnson, 2003). Indeed, prior work found that infants encode shape earlier in development than color (Wilcox, 1999). Thus, in subsequent analyses, we explored whether our results varied as a function of feature type (color, shape). It is important to note that, because feature type was varied as a between-subject factor, splitting the data by feature type reduces the sample size and, therefore, these results should be interpreted with caution.

Using a repeated-measures ANOVA, we first tested for a potential effect of feature type (i.e., color vs. shape; between-subject factor) across the different trial types (space, feature, or conflict; within-subjects factor) separately for the two blocks. This analysis revealed no main effect of feature type in either block 1 ($p = .226, BF_{10} = 0.25$) or block 2 ($p = .998, BF_{10} = 0.31$), nor was there a feature by trial type interaction in block 1 ($p = .353, BF_{10} = 0.02$). However, we did find a significant feature by trial type interaction in block 2, $F(3, 75) = 5.71, p = .002, \eta_p^2 = 0.21, BF_{10} = 12.31$. Follow-up post-hoc comparisons (Holm-Bonferroni corrected) were used to determine whether infants' performance for the different trial types differed as a function of feature type. These analyses revealed that, in the feature trial, infants looked significantly longer at the target feature when it was distinguished by shape, but not color, $t(33) = 2.68, p = .012, d = 0.91, BF_{10} = 4.52$. Consistent with this finding, one-sample comparisons to chance revealed that, in the feature test trial of block 2, infants looked to the previously rewarded target when it was distinguished by shape ($t[19] = 3.13, p = .006, d = 0.70, BF_{10} = 8.42$; 15/20 infants, $p = .041$; Binomial test), but not when it was distinguished by color ($p = 0.322, BF_{10} = .41$). No significant differences between color and shape were found for the other trial types ($ps > .062, BF_{10} < 1.36$)².

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Figure 2. Results of Experiment 1. (A-B) The proportion of responses to the target object in the space, and feature trials for (A) infants (block 2) and (B) preschoolers. A proportion greater than 0.50 indicates responding to the target object (rewarded during training). The dotted line indicates chance responding. (C) The proportion of responses to the spatial and featural target in the conflict trial for infants (block 2) and preschoolers. A proportion greater than 0 indicates greater spatial weighting, whereas a proportion less than 0 indicates greater feature weighting.

Discussion

The results of Experiment 1a show that when objects have both spatial and featural properties, infants primarily encode the spatial information. Indeed, infants learned the object's spatial properties regardless of feature type. Importantly, because the spatial relations here were specified allocentrically, rather than egocentrically, our findings rule out alternative coding strategies based on motor inhibition (Bremner, 1978) or a stereotyped looking response (Marcovitch & Zelazo, 1999). These findings are consistent with previous research suggesting that spatial information is favored over features in infancy (Haun et al., 2006; Xu & Carey, 1996). They also extend previous research by demonstrating that the use of spatial over featural information generalizes across tasks.

Our results, however, are less clear with respect to infants' ability to encode featural information when spatial information is also present. As we described earlier, the preference for spatial information could reflect greater weighting when both spatial and featural information have been encoded. However, it might, alternatively, reflect the exclusive encoding of spatial information, despite the availability of featural information. Unfortunately, the present experiment does not distinguish between these possibilities. Although infants may have encoded the objects' shapes, as indicated by their performance on the shape trials of block 2, there was no evidence that they encoded the objects' colors. Our findings are consistent with previous work suggesting earlier development of shape sensitivity compared to color (Wilcox, 1999). Moreover, our findings suggest that even though infants of this age are capable of encoding spatial and featural information, at least when each is presented in isolation (Quinn, 2004; Wilcox, 1999), they prioritize spatial information when both spatial and featural information are simultaneously available.

Finally, although we did not predict a difference between test blocks, we nevertheless base our conclusions on the second block of trials from this task, in which the sample size was reduced. Although all of the effects were corroborated with Bayesian and non-parametric statistics, we acknowledge that additional research will be useful to ensure that these findings replicate.

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Importantly, despite the block-specific effects, our findings are consistent with previous research suggesting greater weighting of spatial information (Haun et al., 2006; Xu & Carey, 1996) and differential sensitivity to featural cues (Wilcox, 1999). We suspect that the difference between blocks may have been due to insufficient training to support generalization to a new display. Despite showing that infants learned the rewarded target object, infants may have had difficulty translating this learning to a novel display during test. By the second block, following more training and exposure to test trials, infants may have been better able to generalize the objects' spatial properties, and perhaps their shapes, to new display types.

Experiment 1b

In Experiment 1b, we examined the weighting of spatial and featural cues in 4-year-olds. We focused on 4-year-olds specifically because previous research suggests that, by 4 years of age, object features are preferentially weighted over their spatial locations (Haun et al., 2006; Lourenco et al., 2011; Miller et al., 2017). However, as with infants, it is unclear whether the previously reported preference reflects exclusive encoding of featural information or a greater weighting of featural information when both types of information are represented. We adapted the anticipatory reward task used in Experiment 1a with infants for use with 4-year-olds to assess how they weighted the relative location and features of objects. Together with Experiment 1a, Experiment 1b provides an important cross-sectional test of the development of cue weighting in children's object representations.

Method

Participants

An a priori power analysis revealed that a minimum of 44 participants was needed to detect a moderate effect ($d = 0.50$) with 90% power. To ensure that we had a sufficient number of children in each condition, we used a convenience sampling procedure and recruited 46 preschool-aged children ($M_{age} = 3.95$ years, $range = 3.49$ to 4.69 years; 19 females). As in Experiment 1a, we further ensured that effects were not unduly influenced by sample size decisions, by including Bayesian and non-parametric tests, in addition to classic null-hypothesis tests. Children represented the demographics of a large American metropolitan community. As in Experiment 1a, children were included in the analyses if they completed at least one test trial. No children were excluded from the analyses. This experiment was approved by the [blinded] IRB under the project 'Spatial Symbols' (Study Number IRB0003571).

Procedure

The procedure in Experiment 1b was similar to that of Experiment 1a, except that children responded by tapping the target object on a touchscreen – a procedure more typical with children of this age. Children were seated approximately 35 cm from a 22-inch touchscreen computer (1920 × 1080 px). They were told that the game required them to tap one of two smiley faces that they thought was “happier”. Because both objects (target and distractor) had “smiley faces”, these instructions were designed to encourage children to learn the association between one of the objects and the reward. The experiment was controlled by a custom program written in Visual Basic (Microsoft). To ensure that neither the instructions, nor the face stimuli, biased children towards a feature response, we also replicated this experiment with faceless stimuli and instructions to “choose the one that is going to bounce” (see Supplemental Materials).

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As in Experiment 1a, each trial began with a centrally placed attention-getting stimulus consisting of a colorful swirling disc, which children were required to tap in order to initiate the trial. In the training trials, children learned to anticipate a visual reward at a target object. The target object could be determined by its spatial and/or featural properties (e.g., *blue* target on the *left* vs. *green* distractor on the *right*; Figure 1A). As in the previous experiment, on each training trial, object pairs were presented, side-by-side, in one of six randomly selected locations onscreen (never centrally). The objects remained onscreen until children made a response. If the target object was chosen, then the object bounced, and the experimenter stated: “Good job! That is the happier smiley face.” If the distractor object was chosen, then the objects disappeared, and the experimenter stated: “Good try. But the other smiley face was happier.” Children received four repetitions of the reward anticipation task, such that, on each repetition, the target was displayed with a new combination of spatial (left or right) and featural (blue, green, circle, or square) properties. Children were presented with each possible spatial position and feature as the target (within-subjects). Children were required to touch the target object on five consecutive training trials before they proceeded to the first test trial within a repetition. For subsequent test trials, children were required to touch the target object on three consecutive training trials. On average, children completed just under six training trials ($M = 5.81$; $SD = 1.1$) prior to each test, and an average of just over 128 training trials ($M = 128.26$; $SD = 29.37$) across the entire session.

As in Experiment 1a, children were presented with three types of test trials: space, feature, and conflict. The space and feature trials provided an assessment of the extent to which children encoded each type of cue and the conflict trials provided an assessment of which cue was given more weight. Test trials were displayed as in Experiment 1a. Each test trial was presented 8 times in the experiment (2 per repetition).

Results

Following the previous experiment, children’s responses on each trial were analyzed as the proportion of responses to the target object (i.e., the number of responses to the target divided by the total number of responses to the target and distractor). To facilitate comparisons with the previous experiment, responses in the conflict trials were coded such that a proportion closer to 1 indicated greater spatial weighting, whereas a proportion closer to 0 indicated greater feature weighting.

We first evaluated whether the learning criterion was sufficient for children to learn to anticipate the reward at the target object during the training trials. Comparisons to chance (0.50) confirmed that children selected the target object reliably during this phase, $t(45) = 64.53$, $p < .001$, $d = 9.51$, $BF_{10} > 100$, with every child in the sample showing consistent selection of the target during training.

Having confirmed that children met the learning criteria, we examined whether children learned both the spatial and featural properties of the objects, and how they were weighted relative to one another. Comparisons to chance (0.50) revealed that children selected the target object during the space, $t(45) = 11.79$, $p < .001$, $d = 1.74$, $BF_{10} > 100$, and feature, $t(45) = 12.58$, $p < .001$, $d = 1.85$, $BF_{10} > 100$, test trials, with the majority of children selecting the target object (spatial: 43/46 $p < .001$; featural: 41/46, $p < .001$; Binomial tests) in these conditions, suggesting that preschoolers encoded both cues simultaneously. Even though children were able to encode both cues, in the conflict trials, preschoolers chose the featural target more often than the spatial target ($t[45] = 10.97$, $p < .001$, $d = 1.62$, $BF_{10} > 100$; 41/46, $p < .001$; Binomial test; see Figure 2C), suggesting greater featural than spatial weighting at this age. Indeed, a between-experiment comparison to infants revealed that, in

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the conflict trials, preschooler's weighted features significantly more than did infants, $t(76) = 8.78$, $d = 2.02$, $BF_{10} > 100$. Thus, by 4-years of age, children simultaneously encode both the spatial and featural properties of objects, but weight featural information more heavily.

Preschoolers, however, received more repetitions of the task than did infants, which may have led preschoolers to alter their strategy over the course of the testing session. To ensure that the amount of training did not affect children's strategies, we examined only the first repetition of trials presented to preschoolers. This analysis revealed that preschoolers selected the correct target in the spatial, and featural trials ($ps < .001$, $ds > 1.09$, $BF_{10} > 100$), and, in the conflict trials, selected the featural target over the spatial target, $t(45) = 5.77$, $p < .001$, $d = 0.85$, $BF_{10} > 100$, with the majority of children showing these effects in each case (space: 40/46; feature: 42/46; conflict: 38/46: $ps < .001$; Binomial test). Likewise, a comparison with infants in the conflict trial, again, revealed that preschoolers weighted features significantly more heavily than infants, $t(76) = 6.40$, $d = 1.47$, $BF_{10} > 100$.

In a final analysis, we investigated whether these effects varied as a function of feature type (color vs. shape). Because feature type was a within-subjects factor, we retained adequate power to investigate these effects. A repeated-measures ANOVA with test trial type (space, feature, or conflict) and feature type (color or shape) as within-subjects factors revealed no main effect of feature type or feature by trial type interaction ($ps > .198$, $BF_{10} < 0.61$). Qualitatively similar results were obtained when only the first repetition of trials was analyzed ($ps > .106$, $BF_{10} < 0.23$). Thus, unlike infants, preschoolers were equally good at encoding the objects' color and shape properties and were consistent throughout the experimental session.

Discussion

The results of Experiment 1b show that preschoolers readily encode both the relevant spatial and featural properties of objects. Moreover, preschoolers weighted the features of objects more heavily than their relative positions. This pattern of performance contrasts with that of infants who preferentially encoded spatial information. Thus, unlike infants, preschoolers prioritize featural information on a task in which no specific instructions were provided except to distinguish the two objects. These results are consistent with evidence suggesting that 4-year-old children may have a bias for the features of objects (Haun et al., 2006; Miller et al., 2017), though, importantly, the present experiment confirms that this bias does not negate the encoding of spatial information—both types of information are represented by preschoolers.

What might account for the developmental shift between 1 and 4 years of age? One possibility, which we test in the next experiment, is that the developmental shift in cue weighting reflects a change in priority during object perception: in particular, a prioritization of object *individuation* in infancy and object *classification* in preschoolers. Research with adults suggests that the perception of objects proceeds in two stages: *individuation* then *classification* (Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989). Object individuation is the process of mentally indexing the quantity of discrete objects within a scene using spatial (or temporal) information. These initial representations are thought not to include featural information (Pylyshyn, 2001) but, rather, are attentional markers pointing to the existence of distinct objects within the scene. By contrast, object classification involves binding features to these markers so as to determine the identity of the object. Indeed, successful feature binding occurs by directing attention towards a particular location in space (Kovacs & Harris, 2019). Moreover, behavioral and neural data suggest that adults preferentially prioritize spatial information and often neglect featural information in individuation tasks (Flombaum, Scholl, & Santos, 2009; Scholl, Pylyshyn, & Franconeri, 1999), and, by contrast,

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prioritize featural information and neglect spatial information in classification tasks (Biederman & Bar, 1999; Han, Roig, Geiger, & Poggio, 2020). Thus, even though the task in Experiment 1 was not explicitly made to be an individuation or classification task, it is possible that infants nevertheless focused on spatial information because they prioritize the process of individuation, whereas preschoolers focused on featural information because they prioritize the process of classification.

Experiment 2

To test whether spatial and featural weighting is related to the processes of individuation and classification, we examined 4-year-old children's weightings in a task that explicitly required individuation. More specifically, we designed a novel task for children in which objects could be individuated by their distinct locations in space or by their distinctive features. We focused on 4-year-olds in particular because the previous experiment demonstrated that they favored featural information, suggesting a prioritization on classification. Here we examined whether, when required to engage in individuation specifically, they would instead favor spatial information. In other words, if the weighting of spatial and featural information is related to individuation and classification, then 4-year-olds should place greater weight on spatial information when the task requires individuation. If true, this result would suggest that changes in cue weighting reflect changes in object processing priorities across development.

Methods

Participants

An a priori power analysis revealed that a minimum of 44 participants was needed to detect a moderate effect ($d = 0.50$) with 90% power. To ensure that we had a sufficient number of children in each condition, we used a convenience sampling procedure to recruit 45 preschoolers ($M = 4.00$ years, range = 3.53 to 4.59 years; 17 girls). Children represented the demographics of a large American metropolitan community. This experiment was approved by the [blinded] University IRB under the project 'Spatial Symbols' (Study Number IRB0003571).

Procedure

Children were seated approximately 35 cm from a 22-inch touchscreen computer (1920×1080 px) and completed a two-alternative forced choice task controlled by a custom program written in Visual Basic (Microsoft). The experimenter began the task by describing two characters, each of whom wanted to play with an exact number of objects (either one or two objects; see Supplemental Materials for a script of the instructions).

On each trial of the task, children were shown two displays, a *space* display and a *feature* display, presented simultaneously, side-by-side (22.7×22.7 cm; $\sim 22^\circ \times 22^\circ$). In the *space* display, there were always objects in two distinct locations (1.5 cm separation), but with identical features (see Figure 3A). In the *feature* display, there were always objects with two distinct features, but in adjacent locations (no separation; see Figure 3B,C). These conditions were intended to create an individuation conflict on every trial, such that the quantity of objects could be determined by the presence of two spatial locations in the spatial display or two features in the feature display.

The objects (5×5 cm; $\sim 5^\circ \times 5^\circ$) in the display could be one of three possible colors (blue, green, pink; matched luminance) or shapes (square, circle, triangle; matched height/diameter). Objects

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were presented on a background depicting a picnic table and green foliage (see Figure 3). We included this background to further emphasize the distinct locations in the space display.

The task was comprised of two trial types: ‘choose *two*’ and ‘choose *one*’. In the ‘choose *two*’ trials, children were instructed to indicate which display (space or feature) depicted two objects. Here, choosing the space display indicates individuation by spatial information, whereas choosing the feature display indicates individuation by featural information (i.e., color or shape; see Figure 3). In the ‘choose *one*’ trials, children were instructed to choose the display that showed one object. Here, choosing the feature display indicates individuation by spatial information because it suggests that children individuated the objects in the spatial display and perceived more than one object. By contrast, choosing the space display in this condition indicates individuation by features because it suggests that children individuated the objects in the feature display and perceived more than one object. Inclusion of these two trial types ensured that children did not select displays based on an unrelated preference for the space or feature display. Children received 24 ‘choose one’ and 24 ‘choose two’ trials. Half of the feature displays differed by color; the other half differed by shape (randomized order). Side of displays was counterbalanced across trials. All children received both trial types in a counterbalanced order.

To ensure that children were familiar with the concepts of ‘one’ and ‘two’, they were administered an abridged version of the give-a-number task commonly used to assess numerical understanding (Wynn, 1990). Before the start of each condition, children were asked to give the experimenter one and two coins (i.e., one, then two) from a basket of coins. Any child who was unable to complete this task was excluded from the analyses ($n = 4$), leaving 41 children in the final sample.

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Figure 3. (A-C) The three display types used in Experiment 2 and (D) an illustration of an individual trial. (A) An example of the space display, in which objects were presented in two distinct locations. (B) An example of a feature display, in which objects were presented with two distinct colors. (C) Another example of feature display, in which objects were presented with two distinct shapes. (D) An example of an individual trial in which space and feature displays were presented simultaneously.

Results

Children's responses on each trial were coded so that responses indicating greater spatial weighting were assigned a 1 (space displays in 'choose *two*' trials; feature displays in 'choose *one*' trials) and responses indicating greater feature weighting were assigned a 0 (feature displays in 'choose *two*' trials; space displays in 'choose *one*' trials). Thus, across trials a proportion closer to 1 indicated greater spatial weighting, whereas a proportion closer to 0 indicated greater feature weighting.

To test whether children placed greater weight on spatial information compared to features when individuating objects, we compared their performance to chance (0.50)—that is, whether there were no differences between the responses to the space or feature displays. We found that children preferentially selected the space display, $t(40) = 2.64$, $p = .012$, $d = 0.66$, $BF_{10} > 100$, with the majority of children showing this effect (30/41, $p = .004$; Binomial test). Thus, whereas preschoolers placed greater weight on features in an undirected object perception task (Experiment 1b), they weighted spatial information more heavily when the task required individuation.

As in the previous experiments, we next examined whether children's weighting varied as a function of feature type. A repeated-measures ANOVA with trial type (choose-one, choose-two; within-subjects) and feature type (color, shape; within-subjects) revealed a significant main effect of feature type, $F(1, 40) = 11.38$, $p = .002$, $\eta_p^2 = 0.22$, $BF_{10} = 21.05$, as well as a feature by trial type interaction $F(1, 40) = 4.45$, $p = .041$, $\eta_p^2 = 0.10$, $BF_{10} = 10.29$. There was no main effect of trial type ($p = .192$, $BF_{10} = .04$). Post-hoc comparisons (Holm-Bonferroni corrected) revealed a significant difference between shape and color in the choose-two trial type, $t(40) = 4.35$, $p < .001$, $d = 0.68$, BF_{10}

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> 100, but not the choose-one trial type ($p = .695$, $BF_{10} = 0.28$). Analysis of the choose-two trials revealed that children consistently chose the space display as containing two objects when the contrasting feature was shape ($t[40] = 4.17$, $p < .001$, $d = 0.65$, $BF_{10} > 100$; 30/41 children, $p = .004$; Binomial test), but were at chance when the contrastive feature was color ($p = .621$, $BF_{10} = 0.17$). These results suggest that children were equally likely to use spatial and color cues to individuate objects in the 'choose-two' trial. However, there was no difference in the 'choose-one' trial as a function of feature type, such that children relied more on the spatial information for individuation. Taken together, these findings suggest that 4-year-olds weight spatial cues more heavily than features when individuating objects, even when the contrastive feature was color.

Figure 4. Children's spatial and feature weightings in the (A) 'choose one' or (B) 'choose two' condition when the features were color or shape. A proportion greater than 0 indicates greater spatial weighting, whereas a proportion less than 0 indicates greater feature weighting.

Discussion

The results of Experiment 2 demonstrate that 4-year-old children are more likely to individuate objects by spatial, rather than featural, information. Their use of spatial information in this case contrasts with their greater weighting of featural information in the previous task (Experiment 1b). Taken together, the present findings suggest that, whereas featural information may be favored for classification, spatial information may be favored for individuation.

Nevertheless, the results of Experiment 2 also suggest that 4-year-olds may be flexible in what kinds of cues they use to individuate objects, such as their use of color in the choose-two condition. One reason for the difference between color and shape is that color cues may provide clear object borders (Needham & Kaufman, 1997). Much like objects in different locations, contrasting colors may be used to indicate an object's border (Gheorghiu & Kingdom, 2007; Mullen, Beaudot, & McIlhagga, 2000) and, therefore, the presence of two objects. However, and importantly, when children were asked to choose the display with one object, they selected the feature display more consistently, suggesting they individuated the objects in the space display and, thus, weighted spatial information more heavily than featural information. In other words, although both location and color were used for individuation, children nevertheless favored spatial information for this

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purpose. Taken together, the results from this experiment indicate that, when individuating objects, 4-year-olds weight spatial information more heavily than featural information.

General Discussion

How are spatial and features cues integrated in children's object representations? To answer this question, we began by comparing how 1- and 4-year-old children weighted spatial and featural cues in comparable, discrimination tasks. We found that infants readily encoded the left-right relations of objects, but their use of features (shape or color) was less consistent. By contrast, preschoolers encoded both types of information, but weighted features more heavily. What accounts for this developmental shift? We hypothesized that such a shift might reflect a qualitative change in the object process that children prioritize at each age. In this view, spatial information is favored first because infants need to successfully individuate objects from one another prior to classifying them. Featural information, then, comes to be prioritized later to support tasks that involve classifying objects into categories. To test this possibility, we examined whether preschoolers would weight spatial information more than featural information when the task explicitly required individuation, without classification. Consistent with this hypothesis, we found that when the task focused on individuation, preschoolers weighted spatial information more heavily than features.

Development of individuation and classification

Why might infants prioritize the process of individuation over classification? One explanation is that before objects can be identified, it is necessary to determine which discrete units of visual information constitute individual objects (Leslie et al., 1998; Sagi & Julesz, 1984; Xu & Chun, 2009). More specifically, researchers argue that the process of individuation forms the initial representation of an object on the basis of an object's spatial location (Pylyshyn, 1989; Pylyshyn, 2001). This initial object representation does not contain any featural information, but instead, featural information becomes mapped to the object at a later stage with focused attention (Pertzov & Husain, 2014; Treisman & Zhang, 2006; Treisman & Gelade, 1980). Indeed, disruptions to participants' ability to perceive distinct object locations often leads them to incorrectly map features to the wrong object (Cohen & Ivry, 1989; Robertson & Treisman, 1995; Treisman & Schmidt, 1982). Thus, in this view, infants must first prioritize spatial information and the process of object individuation before featural information and classification, because individuation is a prerequisite to object classification.

However, by 4 years of age, children have likely mastered the process of individuation and may now prioritize the process of object classification. One potential trigger for this shift to classification is the onset of language learning. Indeed, as children begin to verbally identify objects they are increasingly better at encoding objects' features (Vlach, 2016; Westermann & Mareschal, 2014), suggesting that the development of language may contribute to a focus on identification (Smith, Jones, & Landau, 1996; Xu & Carey, 1996; Xu et al., 1999). Interestingly, mature nonverbal primates (e.g., gorillas, orangutans, and chimpanzees), who presumably have mastered object individuation, continue to favor spatial information over features (Haun et al., 2006), lending further support to the hypothesis that language may give rise to the shift in focus on classification. Given that substantial language learning occurs between the ages of 1 and 4 years, this learning may cause a general shift in focus from individuation to classification.

Development of dorsal and ventral visual pathways

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The differential prioritization of individuation and classification across development and, correspondingly, spatial and featural cue weighting, mirrors the distinctions and developmental trajectory of dorsal and ventral visual pathways. For instance, brain regions known to be involved in object individuation, such as the posterior intraparietal sulcus (pIPS) along the dorsal stream, are primarily sensitive to the spatial locations of objects, not their featural properties (Goodale, Milner, Jakobson, & Carey, 1991; Ungerleider & Haxby, 1994; Xu, 2009). Damage to this region may cause Balint's syndrome, a disorder characterized by a difficulty perceiving the spatial locations of objects, as well as individuating multiple objects (Friedman-Hill, Robertson, & Treisman, 1995; Rafal, 2003; Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997). By contrast, brain regions known to be involved in object classification, such as the inferior temporal lobe (IT) along the ventral stream, are more sensitive to featural than spatial cues (Grill-Spector, Kourtzi, & Kanwisher, 2001; Lafer-Sousa & Conway, 2013; Xu, 2009). Damage to the inferior temporal lobe has been shown to result in an impairment in perceiving object identity while leaving object individuation intact (Behrmann & Kimchi, 2003; Konen, Behrmann, Nishimura, & Kastner, 2011).

An intriguing possibility suggested by our data is that an increasing prioritization on classification reflects the relative maturity of dorsal and ventral streams or the connections between streams. Evidence from monkeys suggests earlier maturation of the dorsal stream relative to the ventral stream (Bachevalier, Hagger, & Mishkin, 1991; Distler, Bachevalier, Kennedy, Mishkin, & Ungerleider, 1996; Kiorpes, Price, Hall-Haro, & Anthony Movshon, 2012; Rodman, 1994; but, see Dilks, Hoffman, & Landau, 2008), which could lead to greater spatial than featural weighting. Although work with human infants suggests that the dorsal and ventral streams are functionally dissociable by 6 months of age (Wilcox & Biondi, 2015; Wilcox et al., 2009; Wilcox, Haslup, & Boas, 2010), little is known about the maturity of these streams or how they interact in humans (Johnson, Mareschal, & Csibra, 2008). Future research will be needed to determine how the maturity of, and connectivity between, the two streams may support the coordination of individuation and classification in human development.

Conclusion

Although our data suggest that children prioritize spatial information for individuation and featural information for classification, it is important to note that this mapping is not inflexible. In particular, the results of Experiment 2 showed that color may be particularly informative for individuation. Moreover, even infants may rely on featural cues over space when the stimuli being individuated involve human faces (Kibbe & Leslie, 2019; Mareschal & Johnson, 2003). Likewise, discontinuities in spatial information can even disrupt object classification performance in adults (Cox, Meier, Oertelt, & DiCarlo, 2005; Golomb, Kipit, & Thiemann, 2014). Thus, mature object perception ultimately involves the ability to flexibly combine different visual properties as the task necessitates. Nevertheless, our results highlight the developmental trajectory of cue integration and its link to visual object perception.

Footnotes

1. Although an object's geometric shape can be defined in spatial terms, here we are specifically defining shape as a feature of the object and spatial cues as the location of that object in the environment.
2. Although there was no significant difference between color and shape in the conflict trial, one might ask whether space was still favored over featural information, if that information was shape rather than color. We found that infants looked to the spatial target numerically

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($M = 0.61$), but not significantly more than chance (.50; $t[19] = 1.54$, $p = .141$, $d = .34$, $BF_{10} = 0.61$). However, these analyses may be unpowered to detect a difference.

Supplemental Materials

Supplemental Experiment 1. One explanation for preschool children's greater weighting of features in Experiment 1b is that the presence of faces on the stimuli and the prompt "tap the happier face" may have biased children to selectively attend to the features (i.e., color and shape). To rule out this possibility, we ran an additional group of children ($n = 10$) with faceless stimuli and instructions to "choose the one that is going to bounce." All other aspects of the procedure were identical to that of Experiment 1b.

One-sample comparisons to chance revealed that children consistently chose the correct target in the training trials ($t[9] = 21.01, p < .001, d = 6.65, BF_{10} > 100$). Moreover, as in Experiment 1b, children performed consistently on feature ($t[9] = 7.97, p < .001, d = 2.52, BF_{10} > 100$) and space ($t[9] = 2.50, p = 0.051, d = 0.71, BF_{10} = 1.74$), trials. Moreover, and crucially, in the conflict trials, children weighted featural information more heavily than spatial location, $t(9) = 7.24, p = .001, d = 2.29, BF_{10} > 100$. Thus, preschool children's prioritization of featural cues in Experiment 1b was not dependent on the presence of faces on the stimuli, nor the instructions.

Detailed instructions for Experiment 2. To keep children engaged and to help children better understand the instructions in the individuation task, they were told stories about characters wanting exactly *one* (in the 'choose *one*' condition) or *two* (in the 'choose *two*' condition) objects. More specifically, in the 'choose *two*' condition, children were shown a picture of two mice and told: "This is Cheesy and this is Whiskers. Cheesy and Whiskers are going outside to play with some toys. They like to play together, but they don't share toys. So we need two toys for Cheesy and Whiskers. Not one toy. Now, I'm going to show you some pictures with toys. You should tap the picture that has two toys for Cheesy and Whiskers." In the 'choose *one*' condition, children were shown a picture of one mouse and told: "This is Grumpy. Grumpy is going outside to play with his toy. Grumpy likes to play, but he only plays with one toy and he doesn't share toys. So we need one toy for Grumpy. Not two toys. Now, I'm going to show you some pictures with toys. You should tap the picture that has one toy for Grumpy to play with."

Supplemental Table 1. Analysis of infants first fixations to the target in the space, feature, and conflict test trials in Experiment 1a. Data are presented as the proportion of fixations to the target object compared to the distractor. On conflict trials, a proportion closer to 1 indicated greater spatial weighting, whereas a proportion closer to 0 indicated greater featural weighting.

Block	Trial Type	<i>M</i>	<i>t</i>	<i>df</i>	<i>p</i>	<i>d</i>	BF_{10}
Block 1							
	Space	0.491	0.14	52.00	.892	-0.02	0.15
	Feature	0.538	0.55	51.00	.584	0.08	0.18
	Conflict	0.588	1.27	50.00	.211	0.18	0.32
Block 2							
	Space	0.706	2.60	33.00	.014	0.45	3.25
	Feature	0.541	0.49	36.00	.628	0.08	0.20
	Conflict	0.694	2.50	35.00	.017	0.42	2.65

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