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Development of sensitivity to spacing versus feature changes in pictures of houses: Evidence for slow development of a general spacing detection mechanism?

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ABSTRACT

Adults are expert at recognizing faces, in part because of exquisite sensitivity to the spacing of facial features. Children are poorer than adults at recognizing facial identity and less sensitive to spacing differences. Here we examined the specificity of the immaturity by comparing the ability of 8-year-olds, 14-year-olds, and adults to discriminate houses differing in the spacing between features versus those differing in the shape of the features themselves. By 8 years of age, children were more accurate for discriminations involving the feature set compared with the spacing set, and the difference in accuracy compared with adults was greater for the spacing set than for the feature set. Importantly, when sets were matched in difficulty for adults, this greater immaturity on the spacing set than on the feature set remained. The results suggest that, at least by age 8, immaturities in sensitivity to the spacing of features may be related to immaturities in general perceptual mechanisms rather than face-specific mechanisms.

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Introduction

Many aspects of vision are fully developed by 6 or 7 years of age, including spatial and temporal contrast sensitivity (Ellemberg, Lewis, Liu, & Maurer, 1999) and the extent of the peripheral visual field (Bowering, Maurer, Lewis, & Brent, 1997). However, some aspects of vision continue to develop after age 7 and even into early adolescence, including vernier acuity, three-dimensional object recognition,

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and sensitivity to contour integration, subjective contours, and biological motion (Hadad, Maurer, & Lewis, 2010a, 2010b, 2011; Lewis et al., 2004; Rentschler, Juttner, Osman, Muller, & Caelli, 2004; Skoczenski & Norcia, 2002).

Early research suggested that face recognition does not become adult-like until 10 years of age or even later (Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Diamond & Carey, 1977; but see Carey, 1981). However, the differences between adults and children may be related to general perceptual and/or cognitive development rather than changes in face processing per se (Crookes & McKone, 2009), at least after age 8 (Mondloch, Maurer, & Ahola, 2006b). A recent review by Nishimura, Scherf, and Behrmann (2009) suggested that object recognition also continues to develop into adolescence. In this article, we compare the ability of 8-year-olds, 14-year-olds, and adults to discriminate houses using stimulus manipulations used previously with faces. The aim was to test whether the pattern of development is similar to or different from that found previously for faces, as well as to add to the literature on the development of object recognition more generally.

Adults can use several different cues to recognize a face, including the shape of the external contour, hair and eye color, the shape of individual internal features (e.g., shape of the nose), and the spacing among the internal features (e.g., interocular distance). Rapid integration of information across the whole face ("holistic processing") may facilitate the use of such cues. Although adults are better at using any of these cues in upright own-race human faces than in any other category (e.g., inverted faces, other-race faces, monkey faces, objects), their sensitivity to the spacing of features appears to be tuned especially tightly (e.g., Bredart & Devue, 2006; Brooks & Kemp, 2007; Ge, Luo, Nishimura, & Lee, 2003). This conclusion is supported by evidence that adults' discrimination of spacing changes is less accurate for monkey faces than for the same-sized changes in human faces (Mondloch et al., 2006b), that their certainty about vertical eye position is lower for inverted faces than for upright faces (Robbins, McKone, & Edwards, 2007), and that extremely large changes are needed in upright houses to bring accuracy up to the level found for smaller spacing changes in upright faces (Robbins, Nishimura, Mondloch, Lewis, & Maurer, 2010; Yovel & Duchaine, 2006).

Newborns orient toward face-like stimuli (stimuli that have more high-contrast elements in the top half of an oval pattern [e.g., Cassia, Turati, & Simion, 2004; Johnson, Dziurawiec, Ellis, & Morton, 1991]) and can recognize a face learned *en face* when it is turned to a three-quarters view (Turati, Bulf, & Simion, 2008). By 5 months of age, infants can discriminate faces based only on the spacing of features so long as the changes are large (Bhatt, Bertin, Hayden, & Reed, 2005, Experiment 2; Hayden, Bhatt, Reed, Corbly, & Joseph, 2007, Experiment 2; see Mondloch & Thomson, 2008, for a review). This ability to detect spacing changes is, of course, also present in older children (e.g., Freire & Lee, 2001; McKone & Boyer, 2006; Pellicano, Rhodes, & Peters, 2006).

Studies of older children asked to recognize the identity of faces based on the spacing of features indicate, however, that it takes many years for accuracy to reach adult levels. For example, Mondloch, Le Grand, and Maurer (2002) studied children's and adults' ability to discriminate faces by comparing faces that differed only in features (i.e., a face with the eyes and mouth swapped with those from other faces to make four new versions) or differed only in spacing among features (i.e., a face with the eyes and mouth moved to create four new combinations). They used a sequential same/different task with children (6-, 8-, and 10-year-olds) and adults (18- to 28-year-olds). By 6 years of age, children were nearly as accurate as adults in detecting the feature changes, but even at age 10 they were significantly worse than adults at detecting the spacing changes. The authors concluded that face processing is immature until at least age 10 and that spacing discrimination takes longer to become adult-like than feature discrimination. Later results indicate that even 14-year-olds are not as accurate as adults at detecting spacing changes (Mondloch, Le Grand, & Maurer, 2003) and that until age 11 children are not as accurate as adults in judging whether the spacing of the eyes is the same or different in two images of the same face (Baudouin, Gally, Durand, & Robichon, 2010).

Interestingly, two pieces of evidence suggest that development in the ability to discriminate differences in feature spacing may reflect the development of general mechanisms rather than mechanisms tuned to upright faces, at least after 8 years of age. First, the difference in accuracy between 8-year-olds and adults is reduced (but not eliminated) by reducing memory demands (Mondloch, Dobson, Parsons, & Maurer, 2004). Second, accuracy in detecting spacing changes improves as much between age 8 and adulthood for monkey faces—which the child does not experience—as for human faces (Mondloch et al., 2006b).

In the current experiment, we used houses to compare the ability of adults, 14-year-olds, and 8-year-olds to discriminate spacing and feature differences. We began testing at 8 years of age because by that age sensitivity to changes in facial features is nearly adult-like but there are still large differences in accuracy in detecting spacing changes in faces (e.g., 8-year-olds are 16.7% worse than adults; Mondloch et al., 2002); we chose 14-year-olds as the older child age group because at that age most aspects of visual cognition are adult-like (e.g., global form: Lewis et al., 2004; global and biological motion: Hadad et al., 2011; contour integration: Hadad et al., 2010b; vernier acuity: Skoczenski & Norcia, 2002), but nevertheless, children make more errors than adults in detecting facial spacing changes (8.8% more errors; Mondloch et al., 2003). If improvements after age 8 for upright faces reflect improvements in some general perceptual or cognitive mechanism, then the pattern of changes for houses should parallel that found previously for faces—greater differences between 8-year-olds and adults for spacing than for featural changes and residual differences at age 14 only for spacing changes.

Houses have been compared with faces previously, for example, to study inversion effects across development (Carey & Diamond, 1977), to test the effect of context on part recognition (Tanaka & Farah, 1993), to test whether deficits in face recognition are really face specific (Yovel & Duchaine, 2006), and to compare the effects of inversion on spacing and feature changes using line drawings (Leder & Carbon, 2006). Houses are a good comparison stimulus for our purpose because, like faces, they have distinct features (doors and windows versus eyes, nose, and mouth). Thus, the features,

Fig. 1. The three kinds of house stimuli: changes in spacing (A), changes in features (B), and control stimuli (C) with different houses. There were 10 houses of each type.

or the spacing between them, can be manipulated just as they have been for faces. Houses are also something that children see in their everyday environment.

Here we investigated developmental changes in the processing of houses and compared them with analogous data with faces collected previously. Specifically, we tested the ability of 8-year-olds, 14-year-olds, and adults to recognize houses that differed only in features (specific windows and doors) or the spacing among the features (e.g., distance between the windows). Faces were not retested in the current study because of the difficulty of matching the size of spacing changes in faces and houses without making changes so large that the faces look unnatural (cf. Yovel & Duchaine, 2006). Instead, we adjusted the spacing changes in houses to achieve a similar level of accuracy in adults to the previous study with faces and compared the pattern of results found here for houses with that found previously for faces (Mondloch et al., 2002, 2003).

We used a delayed match-to-sample task in which a single picture of a house was shown, followed by a pair of houses, one of which matched the house seen previously. The nonmatching houses differed in either the specific doors and windows (feature set) or the spacing between the doors and windows (spacing set) but not both. The rest of the house was always the same (see Fig. 1). We also included a control set with completely different houses as a comparison set to verify that children understood the task. To remove low-level differences between the sets, we matched the average spatial frequency amplitude across all sets. We tested equal numbers of males and females and included gender as a factor in the analysis because there is some indication of possible gender differences in the ability to use spacing information in nonface stimuli (e.g., Koenig, Reiss, & Kosslyn, 1990).

Method

Participants

The final sample consisted of 36 8-year-olds (±3 months), 36 14-year-olds (±3 months), and 36 adults (18–24 years of age, *M* = 19.75 years, *SD* = 1.84). Each group consisted of 18 males and 18 females, and all participants had normal or corrected-to-normal vision, defined as linear letter acuity (Lighthouse Visual Acuity Chart) of at least $20/20^{-2}$ in each eye with up to an additional −2.0 diopter correction (to rule out myopia >2 diopters that would reduce vision at our testing distance of 50 cm), worse acuity with a +3 diopter lens (to rule out farsightedness >3 diopters), fusion at near on the Worth Four-Dot test, and stereo acuity of at least 40 arcsec (seconds of arc) as measured by the Titmus test. An additional 10 participants (3 8-year-olds, 1 14-year-old, and 6 adults) were excluded because they either failed visual screening (2 8-year-olds and 5 adults) or failed the control task (i.e., accuracy <75%; 1 in each age group). The 8- and 14-year-olds were recruited from a database of parents who had volunteered to be contacted for future studies when their children were born. Adults were undergraduate students who participated for course credit or friends who volunteered their time for no compensation. The experiment took approximately 20 min for adults and 14-year-olds, and took approximately 40 min for 8-year-olds (the youngest group took longer because the experimenter entered responses, provided extra encouragement, and allowed short breaks).

Design

A delayed match-to-sample task was used: participants saw one house and then a choice of two houses, one of which matched the first house and the other of which differed in features (windows and door), spacing of features, or both aspects (control). A total of 50 trials were shown for each of the three house sets. These were created from 10 houses per set, each divided into two half sets and then combined in all possible pairings across the two half sets (e.g., Half 1 House 1 + Half 2 House 1, Half 1 House 1 + Half 2 House 2 . . . Half 1 House 5 + Half 2 House 5). Trials were blocked by house set to encourage participants to use different processing strategies across sets and to better match the previous task with faces (Mondloch et al., 2002). Participants were randomly assigned to a specific order of house set, with each of the six possible orders being tested an equal number of times. Participants were free to take breaks between blocks.

Stimuli and apparatus

Images of houses were taken with a variety of digital cameras, after which three sets of house stimuli (spacing, feature, and control) were created using Adobe Photoshop CS 8.0. As in the previous study with faces (Mondloch et al., 2002), photographs were converted to grayscale. House stimuli were created following the style of Husk, Bennett, and Sekuler (2007), but instead of modifying features and spacing between features simultaneously, we manipulated the two independently (as was done for faces in Mondloch et al., 2002). Specifically, we modified a single picture of a house to create 10 versions for each of the spacing and feature sets. For the spacing set, the same door and windows were used throughout, but the positions were altered to create 10 unique combinations (see Fig. 1A for representative examples of the photographs). Upper windows were moved in or out, whereas the lower window was moved up or down and the door was moved left or right. The spacing changes were adjusted during a pilot study to increase accuracy to 77% for adults so that it was neither at floor nor at ceiling and was quite closely matched to the previous results for faces (78% in Mondloch et al., 2002). The in/out changes of the top windows measured 55.0–116.8 arcmin (minutes of arc) of visual angle, compared with the 13.8–27.6 arcmin of visual angle for the in/out changes of the eyes in previous studies by Mondloch and colleagues (i.e., four times larger in houses than in faces in absolute terms, although only approximately twice as large when the size of the stimuli is taken into account given that the houses were shown approximately two times larger than the faces). The other changes were also somewhat larger than those in the previous study of faces: 27.5–96.25 arcmin for the up/down changes in the lower window and 26.5 arcmin for the left/right changes of the door compared with 13.8–27.6 arcmin for the up/down changes of eyes and 7.2–14.4 arcmin for the up/down changes of the mouth. For the feature set, the doors and windows (features) of the original house were replaced with doors and windows from different houses, but the spacing remained unchanged (see Fig. 1B for representative examples). For the control set, 10 photographs of unique houses were used (see Fig. 1C for representative examples).

As in Husk and colleagues (2007), spatial frequency amplitude was matched by applying the average amplitude spectrum of the set to each house using MATLAB. This ensured that the stimuli differed only in global phase spectra and ensured that participants could not exploit differences in overall contrast or relative contrast at specific spatial frequencies as a cue for recognition (cf. Sekuler & Bennett, 1996).

Stimuli were presented with SuperLab Pro (Version 1.77) on an HP P1130 Trinitron cathode ray tube monitor (21 inches diagonally) connected to a PowerMac G4 cube. Houses were 12 cm wide by 18 cm high, which at the 50-cm viewing distance corresponds to a visual angle of 13.7° by 20.4°.

Procedure

The institutional ethics board approved the procedures. Informed consent was obtained from each adult participant and a parent of each child. Informed assent was also obtained from each child.

Participants sat in a darkened room approximately 50 cm from the monitor. Instructions were explained verbally and displayed on the monitor. Participants were told that they would see a house flash quickly in the center of the screen, immediately followed by two houses, one of which would be the same as the initial house. They were told to say which of the two houses matched the first house they had seen. Adult and 14-year-old participants pressed a key corresponding to the side of the screen on which the matching house appeared (“z” for left and “m” for right), and the youngest child participants raised the hand corresponding to the matching side. Responses were recorded by the experimenter (who was seated so as not to see the screen).

Prior to the initial block, participants were given three practice trials with simple shapes instead of houses to ensure that they understood the task and responses. They were required to complete all three correctly before moving on to the experiment, and all participants did so within four rounds of three trials each. Before each block, participants were shown all 10 houses in that block and reminded that the houses were very similar such that they needed to “look very carefully, look at the whole house, and don’t just focus on one thing.” They were given unlimited time to examine these 10 houses. Feedback was not given at any stage.

A fixation cross was displayed between trials until the space bar was pressed (by the participants or, for the 8-year-olds, by the experimenter), signaling that the participant was ready. A single photograph of a house remained in the center of the screen for 1 s, followed immediately by the pair of houses to the left and right of center that remained on screen until the participant responded. The two houses of a pair were presented equidistant from the center, with the distance between the closer edges of the pair equal to 3 cm or 3.4° of visual angle.

Data analysis

The control set was used to ensure that participants understood the task; anyone whose accuracy was less than 75% was excluded from further analysis. This resulted in three participants (one from each age group) being replaced because they failed to meet this criterion (see "Participants" above). For completeness, data are shown for the three sets, including the control set, but analyses were restricted to the spacing and feature sets. Reaction time was not analyzed because the experimenter keyed in responses for 8-year-olds, but an examination of the means showed no speed–accuracy trade-offs.

Results were analyzed first with a mixed 3 (Age: adults, 14-year-olds, or 8-year-olds) × 2 (Gender: male or female) × 2 (House Set: feature or spacing) × 2 (Set Order: feature before spacing or spacing before feature) analysis of variance (ANOVA), with planned Dunnett's *t* tests for age effects. Homogeneity of variance was violated (according to F_{max}); however, sample sizes were equal, making the tests robust to this violation (Harris, 1994).

A possible problem with interpreting our results is that the feature and spacing sets were not matched for difficulty in adults (see Rotshtein, Geng, Driver, & Dolan, 2007, for a discussion of a similar problem in studies using faces) despite an attempt to do so based on pilot work. To address this problem, we took the four pairs (eight trials) on which adults were most accurate for spacing and the four pairs (eight trials) on which they were least accurate for features and then reanalyzed the results based on these pairs. Because of gender differences in the main analysis, we matched the pairs separately for each gender. In the case of ties (more than four pairs that could be selected), we created two versions but we report only the first version because the results did not differ. For these subsets, adults' accuracy was equal for the spacing and feature trials both for adult females ($M = 90.28\%$, $SD = 9.82$ for spacing trials and $M = 93.75\%$, $SD = 10.42$ for feature trials), $t(17) = 1.04$, $p = 0.31$, and for adult males ($M = 93.06\%$, $SD = 12.65$ for spacing trials and $M = 93.75\%$, $SD = 8.59$ for feature trials), $t(17) = 0.17$, $p = 0.86$. We then repeated the ANOVA and planned comparisons following the structure of the analysis of the full set of trials.

Results

Accuracy for each house set is shown in Fig. 2 divided by gender and age. Adults were generally more accurate than 8-year-olds but not 14-year-olds, and the spacing changes were generally more difficult to discriminate than the changes in either of the other two sets. The difference between adults and 8-year-olds was numerically larger for the spacing set than for the feature set.

The mixed 3 (Age) × 2 (Gender) × 2 (House Set) × 2 (Set Order) ANOVA showed that the only effect of order was an age by set order interaction, $F(1, 96) = 3.72$, $p = 0.03$, partial $\eta^2 = 0.07$. An examination of the means showed that 8-year-olds and adults were slightly worse overall when tested on the harder spacing task before the feature task than vice versa (a nonsignificant difference of 1.89%, $p = 0.42$, for adults and a significant difference of 5.22% for 8-year-olds, $t(34) = 2.11$, $p = 0.04$), but 14-year-olds showed a nonsignificant difference in the opposite direction (−3.05%, $t(34) = 1.72$, $p = 0.09$). Because there is no theoretical reason to expect set order to affect 14-year-olds differently and because set order did not interact significantly with house set, we collapsed over set order in the later analyses. There was a significant three-way interaction among house set, age, and gender, $F(2, 96) = 5.22$, $p = 0.01$, partial $\eta^2 = 0.10$, as well as an interaction between age and gender, $F(1, 96) = 3.24$, $p = 0.04$, partial $\eta^2 = 0.06$, and main effects of house set, $F(1, 96) = 487.06$, $p < 0.001$, partial $\eta^2 = 0.84$, and age, $F(2, 96) = 18.31$, $p < 0.001$, partial $\eta^2 = 0.28$. All other effects were not significant (*p*s > 0.06).

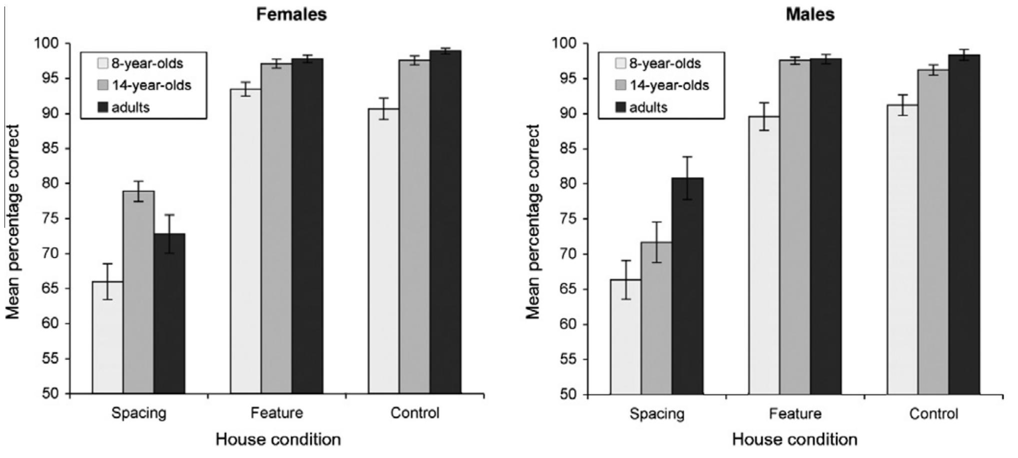

Fig. 2. Accuracy on each set of houses for each age group (8-year-olds, 14-year-olds, and adults), starting from chance performance (50%). Females are shown on the left, and males are shown on the right. Error bars represent ±1 standard error.

Based on the house set by age by gender interaction and the lack of theoretically interesting set order effects, we next conducted 3 (Age) × 2 (House Set) ANOVAs for each gender separately. For females, there were significant main effects of house set, $F(1, 51) = 354.41$, $p < 0.001$, partial $\eta^2 = 0.84$, and age, $F(2, 51) = 9.27$, $p < 0.001$, partial $\eta^2 = 0.27$, and a house set by age interaction, $F(2, 51) = 4.86$, $p = 0.01$, partial $\eta^2 = 0.16$. Planned one-tailed Dunnett's t tests comparing each age child group with adults showed a significant difference between 8-year-old and adult females for features (mean difference = 4.33, $p < 0.001$) and for spacing (mean difference = 6.78, $p = 0.04$). There were no significant differences between adult and 14-year-old females for features (mean difference = 0.67, $p = 0.38$) or for spacing (mean difference = −6.11, $p = 0.06$). Thus, for females, accuracy becomes adult-like for both features and spacing sometime between 8 and 14 years of age.

For males, there were again significant main effects of house set, $F(1, 51) = 167.54$, $p < 0.001$, partial $\eta^2 = 0.77$, and age, $F(2, 51) = 10.61$, $p < 0.001$, partial $\eta^2 = 0.29$, but the house set by age interaction did not reach significance, $F(2, 51) = 2.39$, $p = 0.10$, partial $\eta^2 = 0.09$. Planned one-tailed Dunnett's t tests showed significant differences between adults and 8-year-old males for features (mean difference = 8.22, $p < 0.001$) and for spacing (mean difference = 14.44, $p = 0.001$). For adults compared with 14-year-old males, there was also no significant difference for features (mean difference = 0.22, $p = 0.50$), but there was a significant difference for spacing (mean difference = 9.11, $p = 0.03$). Thus, for males, accuracy becomes adult-like for features by 14 years of age but is still immature for spacing at age 14.

Overall, the results suggest that the ability to discriminate spacing may mature more slowly that the ability to discriminate features. To ensure that this was not the result of the spacing task being harder than the feature task (see Fig. 2), we matched subsets of trials for feature and spacing tasks in adults (as described above).

Subset analysis

A 3 (Age) × 2 (Gender) × 2 (House Set) × 2 (Set Order) ANOVA showed no main effect or interactions with set order (all $ps > 0.15$). There were significant main effects of house set, $F(1, 96) = 41.47$, $p < 0.001$, partial $\eta^2 = 0.30$, age, $F(2, 96) = 14.45$, $p < 0.001$, partial $\eta^2 = 0.23$, and gender, $F(1, 96) = 4.90$, $p = 0.03$, partial $\eta^2 = 0.05$, and a significant house set by age interaction, $F(2, 96) = 8.19$, $p = 0.001$, partial $\eta^2 = 0.15$. No other effects were significant ($ps > 0.13$). The house set by age interaction reflects larger differences between spacing and feature sets for the 8- and 14-year-olds than for the adults and more adult-like accuracy on the feature task. In fact, as shown in Fig. 3, for the matched subset of trials, 8-year-olds are nearly as accurate as adults for the feature set but are substantially less

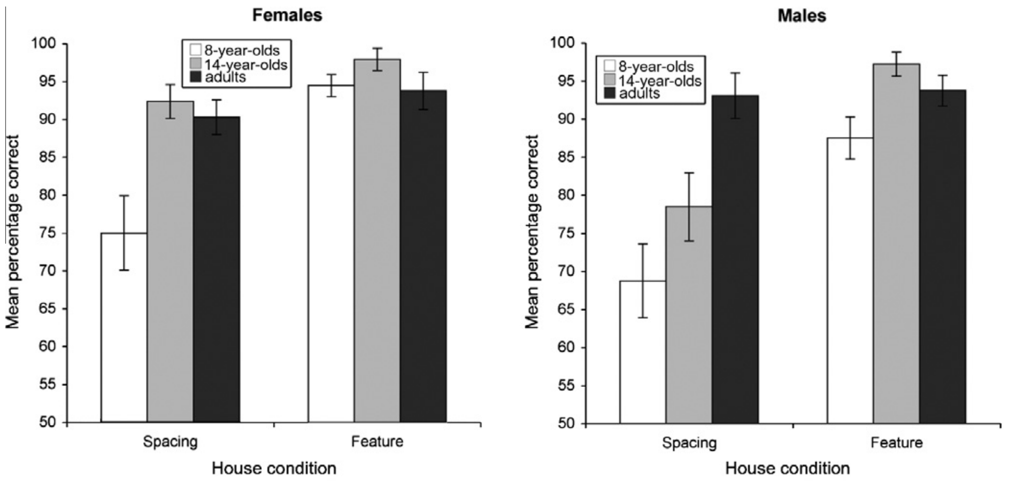

Fig. 3. Accuracy on spacing and feature sets for each age group (8-year-olds, 14-year-olds, and adults) for the subset of pairs that adults found to be easiest for spacing and hardest for features, chosen for each gender separately. Adults' accuracy was matched for these two subsets. Error bars represent ±1 standard error.

accurate for spacing (females = 15% less, males = 24% less). A similar result was found for 14-year-old males (14% worse) but not females. Because each gender was compared with same-gender adults and because of the main effect of gender we conducted follow-up tests for each gender separately.

For females, a 3 (Age) × 2 (House Set) ANOVA showed significant main effects of house set, $F(1, 51) = 17.54$, $p < 0.001$, partial $\eta^2 = 0.26$, and age, $F(2, 51) = 7.06$, $p = 0.002$, partial $\eta^2 = 0.22$, and a house set by age interaction, $F(2, 51) = 4.89$, $p = 0.01$, partial $\eta^2 = 0.16$. For males, there were also significant main effects of house set, $F(1, 51) = 23.82$, $p < 0.001$, partial $\eta^2 = 0.32$, and age, $F(2, 51) = 8.99$, $p < 0.001$, partial $\eta^2 = 0.26$, and a house set by age interaction, $F(2, 51) = 5.32$, $p = 0.01$, partial $\eta^2 = 0.17$. Planned one-tailed Dunnett's t tests comparing each age group with adults showed results similar to the full analysis. For features, there were no significant differences between adults and 8-year-old females (mean difference = −0.69, $p = 0.47$), between adults and 14-year-old females (mean difference = −4.17, $p = 0.11$), or between adults and 14-year-old males (mean difference = −3.47, $p = 0.22$), but there was a significant difference between adults and 8-year-old males (mean difference = 6.25, $p = 0.05$). For spacing, there were significant differences between adults and 8-year-old females (mean difference = 15.28, $p = 0.003$), between adults and 8-year-old males (mean difference = 24.31, $p < 0.001$), and between adults and 14-year-old males (mean difference = 14.58, $p = 0.02$), but there was no difference between adults and 14-year-old females (mean difference = −2.08, $p = 0.44$). This subset analysis, therefore, confirms slower development of sensitivity to spacing than to features when the two tasks are matched for accuracy in adults.

Discussion

Overall, 8-year-olds and (in some cases) 14-year-olds were worse at discriminating houses than adults, spacing changes were harder to discriminate than feature changes, and the difference between adults and the child age groups was larger for the spacing set than for the feature set over all pairings tested and in the matched sets. Taken together, the results suggest slower development of the ability to discriminate spacing changes than the ability to discriminate feature changes in houses.

There was an unexpected gender difference suggesting that females may mature more quickly than males such that by 14 years of age they are as accurate as female adults for the spacing set. This may be related to the higher overall accuracy of male adults, especially for the spacing sets (see Fig. 2), and hence the higher level to which male children need to mature. However, we can offer no explanation for these differences, and given the relatively small number of participants of each gender, the gender differences might not be reliable. Previous studies have reported no gender differences in discriminating either spacing or feature changes in faces at any age (Mondloch et al., 2002, 2003) or in picking up metric information in geometric shapes, at least in adults (Koenig et al., 1990).

Previous results for face identity have suggested that, although children are generally worse than adults at discriminating both spacing and feature changes, the difference is disproportionately large for spacing changes (Mondloch et al., 2002). For example, 8-year-olds are approximately 16% worse than adults for spacing changes but are nearly as accurate as adults for feature changes even when tested with feature changes that adults find to be difficult (Mondloch, Robbins, & Maurer, 2010), and their immaturity for spacing persists even when the memory component of the task is removed (Mondloch et al., 2004). Although we did not directly compare faces and houses, the pattern of the current results is similar to the previous results for faces (Mondloch et al., 2002) and consistent with the idea that immaturity for spacing at and after 8 years of age might not be specific to faces but rather may reflect an immaturity of general mechanisms used to discriminate information about layout or distances (Mondloch et al., 2006b); at age 8 with the matched house sets, children were 19.8% worse for the spacing set but, as with faces, were nearly as accurate as adults for the feature set (2.8% worse). Note that 8-year-olds were still worse than adults on feature trials, but this is also consistent with previous results for faces (Mondloch et al., 2002). At age 14, children's special difficulty with the spacing set persisted, at least in males, as it does in children of both genders for faces (Mondloch et al., 2003). Even for 14-year-old females, scores were higher for the feature subset than for the spacing subset that adult females find to be equally difficult. The conclusion that immaturities in spacing discrimination at age 8 may be general and not related to the development of face-specific processing is consistent with previous findings that 8-year-olds are 14% less sensitive than adults to spacing changes in both human and monkey faces even though the spacing changes were identical in the monkey and human faces and face expertise applies only to the latter set (Mondloch et al., 2006b).

Our developmental conclusions are consistent with evidence that, in adults, sensitivity to spacing in faces depends on both a face-specific component and a more general spacing detection mechanism. Evidence for the face-specific component comes from findings that adults' sensitivity is best for faces of the type they encounter in everyday life; they are more sensitive to spacing changes in upright faces than in inverted faces (e.g., Robbins et al., 2007), in human faces than in monkey faces (Mondloch et al., 2006b), in own-race faces than in other-race faces (Rhodes, Hayward, & Winkler, 2006), and even in personally familiar faces than in the faces of strangers (Brooks & Kemp, 2007). They also appear to be more sensitive to spacing in faces than in houses; the changes required to match performance in houses make faces look bizarre (Yovel & Duchaine, 2006). Indeed, in the current study, the spacing changes between pairs of houses were on average four times larger in absolute terms than those in the previous developmental study using faces (Mondloch et al., 2002) and twice as large when the size of the stimuli is taken into account; yet adults' accuracy in detecting spacing differences was similar for the two tasks and not at ceiling. Our current results suggest that, in addition to a face-specific mechanism, there is a general mechanism that is sensitive to spacing that adults can apply to nonface categories such as houses, that is still immature at 8 years of age, and that improves slowly into adolescence. This general component also seems to be unaffected by early visual deprivation. Patients treated for bilateral congenital cataract later can discriminate spacing differences normally in houses and monkey faces even though they show deficits in discriminating spacing in upright human faces (Robbins et al., 2010). Combined, the data suggest that by age 8, immaturities in discrimination of spacing changes may be caused mainly by immaturities in a general component. However, it remains possible that other aspects of face recognition continue to develop and that immaturities in spacing discrimination before age 8 are face specific (see, e.g., McKone & Boyer, 2006; Mondloch, Leis, & Maurer, 2006a; Pellicano et al., 2006, for debate on the latter issue).

Interestingly, there is a similar difference in the rate of development for visual sensitivity to fine detail (acuity and contrast sensitivity) versus the location of the detail (vernier acuity and contour integration); acuity and contrast sensitivity are adult-like by 6 or 7 years of age (Ellemberg et al., 1999), but there are improvements in vernier acuity until at least age 10 (Skoczenski & Norcia, 2002) and in contour integration even after age 14 (Hadad et al., 2010b). A similar pattern emerged in a study by Koenig colleagues (1990) examining the ability to tell whether a dot is above or below a line versus closer or farther than 3 mm away from the line. Children as young as 5 and 6 years were at ceiling on the above/below task, but even 7- and 8-year-olds were less accurate than adults at the metric task.

Previous imaging studies with adults have found an area in the parahippocampal gyrus associated with scene or "place" representation that is strongly activated by houses (e.g., Aguirre, Zarahn, & D'Esposito, 1998; Epstein & Kanwisher, 1998) and visual scenes (as opposed to the objects in them) (see Epstein, 2005, for a review). There are separate areas, including the fusiform gyrus, that are part of a network that is more strongly activated by faces than by objects (e.g., Haxby, Hoffman, & Gobbini, 2000; Kanwisher, McDermott, & Chun, 1997). Golarai and colleagues (2007) found that children (7- to 11-year-olds) have similar regions that respond selectively to places and faces, but the regions are smaller than those in adults and their size correlates with recognition memory for the relevant stimuli. However, Scherf, Behrmann, Humphreys, and Luna (2007) found adult-like activation for places, but not for faces, in 8- to 10-year-olds using dynamic stimuli, and Pelphrey, Lopez, and Morris (2009) found adult-like size and sensitivity for the place area from 7 years of age. For older children, Golarai, Liberman, Yoon, and Grill-Spector (2010) found no difference in the size of the place area in the parahippocampal gyrus between 12- to 16-year-olds and adults. These results may still be broadly consistent with our current findings given that none of the imaging studies looked at the processing of featural versus spacing cues.

Future studies might compare faces and houses within the same participants using the same methods and might investigate the developmental trajectories for sensitivity to horizontal versus vertical deviations in feature spacing in faces and houses. Based on their finding that vertical but not horizontal eye changes are affected by inversion, Goffaux and Rossion (2007) argued that vertical changes may be more important for processing faces and horizontal changes may be assessed by a more general mechanism. Obviously, this does not mean that all vertical changes are assessed by a face-specific mechanism, but there may be differences in development for the two kinds of discrimination. In Mondloch and colleagues (2002, 2003), changes to the location of the eyes were made in both the vertical and horizontal directions at the same time, whereas the mouth was moved only up and down. In the current study, the top windows were moved only horizontally and the bottom window was moved only vertically. An additional difference is that the holistic processing that is applied to faces but not to houses (Tanaka & Farah, 1993) may lead participants to process both horizontal and vertical deviations of facial features automatically but allow them to attend more easily to a single dimension of houses. The current study does not allow us to unravel these variables, but they may be worth keeping in mind for both face and object studies.

In conclusion, our results suggest that previous findings of improvements in spacing discrimination in faces with age might not be completely face specific at least by 8 years of age. The slow development of sensitivity to spacing in houses may be related to improvements in a general perceptual ability, such as vernier acuity or contour integration, and/or specific processes mediated by the parahippocampal place area and others that underlie spatial perception and navigation and that develop in parallel with face processing.

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References

Aguirre, G. K., Zarahn, E., & D'Esposito, M. (1998). An area within human ventral cortex sensitive to "building" stimuli: Evidence and implications. *Neuron, 21*, 373–383.

Baudouin, J.-Y., Gally, M., Durand, K., & Robichon, F. (2010). The development of perceptual sensitivity to second-order facial relations in children. *Journal of Experimental Child Psychology, 107*, 195–206.

Bhatt, R. S., Bertin, E., Hayden, A., & Reed, A. (2005). Face processing in infancy: Developmental changes in the use of different kinds of relational information. *Child Development, 76*, 169–181.
Bowering, E. R., Maurer, D., Lewis, T. L., & Brent, H. P. (1997). Constriction of the visual field of children after early visual deprivation. *Journal of Paediatric Ophthalmology and Strabismus, 34*, 347–356.
Bredart, S., & Devue, C. (2006). The accuracy of memory for faces of personally known individuals. *Perception, 35*, 101–106.
Brooks, K., & Kemp, R. (2007). Sensitivity to feature displacement in familiar and unfamiliar faces: Beyond the internal/external feature distinction. *Perception, 36*, 1646–1659.
Carey, S. (1981). The development of face perception. In G. Davies, H. Ellis, & J. Shephard (Eds.), *Perceiving and remembering faces* (pp. 9–38). New York: Academic Press.
Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science, 195*, 312–314.
Carey, S., Diamond, R., & Woods, B. (1980). Development of face recognition: A maturational component? *Developmental Psychology, 16*, 257–269.
Cassia, V. M., Turati, C., & Simion, F. (2004). Can a nonspecific bias toward top-heavy patterns explain newborns' face preference? *Psychological Science, 15*, 379–383.
Crookes, K., & McKone, E. (2009). Early maturity of face recognition: No childhood development of holistic processing, novel face encoding, or face-space. *Cognition, 111*, 219–247.
Diamond, R., & Carey, S. (1977). Developmental changes in the representation of faces. *Journal of Experimental Child Psychology, 23*, 1–22.
Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325–2333.
Epstein, R. A. (2005). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in Cognitive Science, 12*, 388–396.
Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature, 392*, 598–601.
Freire, A., & Lee, K. (2001). Face recognition in 4- to 7-year-olds: Processing of configural, featural, and paraphernalia information. *Journal of Experimental Child Psychology, 80*, 347–371.
Ge, L., Luo, J., Nishimura, M., & Lee, K. (2003). The lasting impression of Chairman Mao: Hyperfidelity of familiar-face memory. *Perception, 32*, 601–614.
Goffaux, V., & Rossion, B. (2007). Face inversion disproportionately impairs the perception of vertical but not horizontal relations between features. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 995–1002.
Golarai, G., Ghahremani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D., et al (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience, 10*, 512–522.
Golarai, G., Liberman, A., Yoon, J., & Grill-Spector, K. (2010). Differential development of the ventral visual cortex extends through adolescence. *Frontiers in Human Neuroscience, 3*, 80–99.
Hadad, B. -S., Maurer, D., & Lewis, T. L. (2011). Long trajectory for the development of sensitivity to global and biological motion. McMaster University, submitted for publication.
Hadad, B.-S., Maurer, D., & Lewis, T. L. (2010a). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*, 163–176.
Hadad, B., Maurer, D., & Lewis, T. L. (2010b). The effects of spatial proximity and collinearity on contour integration in adults and children. *Vision Research, 50*, 772–778.
Harris, R. J. (1994). *ANOVA: An analysis of variance primer*. Itasca, IL: Peacock.
Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2000). The distributed human neural system for face perception. *Trends in Cognitive Sciences, 4*, 223–233.
Hayden, A., Bhatt, R. S., Reed, A., Corbly, C. R., & Joseph, J. E. (2007). The development of expert face processing: Are infants sensitive to normal differences in second-order relational information? *Journal of Experimental Child Psychology, 97*, 85–98.
Husk, J. S., Bennett, P. J., & Sekuler, A. B. (2007). Inverting houses and textures: Investigating the characteristics of learned inversion effects. *Vision Research, 47*, 3350–3359.
Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' preferential tracking of face-like stimuli and its subsequent decline. *Cognition, 40*, 1–19.
Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience, 17*, 4302–4411.
Koenig, O., Reiss, L. P., & Kosslyn, S. M. (1990). The development of spatial relation representations: Evidence from studies of cerebral lateralization. *Journal of Experimental Child Psychology, 50*, 119–130.
Leder, H., & Carbon, C.-C. (2006). Face-specific configural processing of relational information. *British Journal of Psychology, 97*, 19–29.
Lewis, T., Ellemberg, D., Maurer, D., Dirks, M., Wilkinson, F., & Wilson, H. (2004). A window on the normal development of sensitivity to global form in glass patterns. *Perception, 33*, 409–418.
McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology, 94*, 134–162.
Mondloch, C. J., Dobson, K. S., Parsons, J., & Maurer, D. (2004). Why 8-year-olds cannot tell the difference between Steve Martin and Paul Newman: Factors contributing to the slow development of sensitivity to the spacing of facial features. *Journal of Experimental Child Psychology, 89*, 159–181.
Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception, 31*, 553–566.
Mondloch, C., Le Grand, R., & Maurer, D. (2003). Early visual experience is necessary for the development of some – But not all – Aspects of face processing. In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood: Current perspectives* (pp. 99–117). New York: Nova Science.
Mondloch, C. J., Leis, A., & Maurer, D. (2006a). Recognizing the face of Johnny, Suzy, and me: Insensitivity to the spacing among features at 4 years of age. *Child Development, 77*, 234–243.
Mondloch, C. J., Maurer, D., & Ahola, S. (2006b). Becoming a face expert. *Psychological Science, 17*, 930–934.

Mondloch, C., Robbins, R., & Maurer, D. (2010). Discrimination of facial features by adults, 10-year-olds, and cataract-reversal patients. *Perception, 39*, 184–194.

Mondloch, C. J., & Thomson, K. (2008). Limitations in 4-year-old children's sensitivity to the spacing among facial features. *Child Development, 79*, 1514–1524.

Nishimura, M., Scherf, S., & Behrmann, M. (2009). Development of object recognition in humans. *F1000 Biology Reports,* p. 56. doi: 10.3410/B1-56.

Pellicano, E., Rhodes, G., & Peters, M. (2006). Are preschoolers sensitive to configural information in faces? *Developmental Science, 9*, 270–277.

Pelphrey, K. A., Lopez, J., & Morris, J. P. (2009). Developmental continuity and change in response to social and nonsocial categories in human extrastriate visual cortex. *Frontiers in Human Neuroscience, 3*, 25.

Rentschler, I., Juttner, M., Osman, E., Muller, A., & Caelli, T. (2004). Development of configural 3D object recognition. *Behavioural Brain Research, 149*, 107–111.

Rhodes, G., Hayward, W. G., & Winkler, C. (2006). Expert face coding: Configural and component coding of own-race and other-race faces. *Psychonomic Bulletin and Review, 13*, 499–505.

Robbins, R., McKone, E., & Edwards, M. (2007). Aftereffects for face attributes with different natural variability: Adapter position effects and neural models. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 570–592.

Robbins, R. A., Nishimura, M., Mondloch, C. J., Lewis, T. L., & Maurer, D. (2010). Deficits in sensitivity to spacing after early visual deprivation in humans: A comparison of human faces, monkey faces, and houses. *Developmental Psychobiology, 52*, 775–781.

Rotshtein, P., Geng, J. J., Driver, J., & Dolan, R. J. (2007). Role of features and second-order spatial relations in face discrimination, face recognition, and individual face skills: Behavioral and functional magnetic resonance imaging data. *Journal of Cognitive Neuroscience, 19*, 1435–1452.

Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places, and objects emerges along different developmental trajectories. *Developmental Science, 10*, F15–F30.

Sekuler, A. B., & Bennett, P. J. (1996). Spatial phase differences can drive apparent motion. *Perception and Psychophysics, 58*, 174–190.

Skoczenski, A. M., & Norcia, A. M. (2002). Late maturation of visual hyperacuity. *Psychological Science, 13*, 537–541.

Tanaka, J. W., & Farah, M. J. (1993). Parts and wholes in face recognition. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 46*, 225–245.

Turati, C., Bulf, H., & Simion, F. (2008). Newborns' face recognition over changes in viewpoint. *Cognition, 106*, 1300–1321.

Yovel, G., & Duchaine, B. (2006). Specialized face perception mechanisms extract both part and spacing information: Evidence from developmental prosopagnosia. *Journal of Cognitive Neuroscience, 18*, 580–593.