The development of spatial frequency biases in face recognition

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Previous research has suggested that a mid-band of spatial frequencies is critical to face recognition in adults, but few studies have explored the development of this bias in children. We present a paradigm adapted from the adult literature to test spatial frequency biases throughout development. Faces were presented on a screen with particular spatial frequencies blocked out by noise masks. A mid-band bias was found in adults and 9- and 10-year-olds for upright faces but not for inverted faces, suggesting a face-sensitive effect. However, 7- and 8-year-olds did not demonstrate the mid-band bias for upright faces but rather processed upright and inverted faces similarly. This suggests that specialization toward the mid-band for upright face recognition develops gradually during childhood and may relate to an advanced level of face expertise.

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Introduction

The visual system is composed of multiple channels tuned to a wide range of spatial frequencies in the environment (Campbell & Robson, 1968; de Valois & de Valois, 1980). A large quantity of research has been dedicated to understanding how the perceptual system extracts and analyzes this information and uses it in performing visual computations. One key area in which the use of spatial frequencies has been studied is adult face processing, where many have argued that the most important information for identity recognition is provided by the low spatial frequencies (LSFs, e.g., less than 8 cycles per face/image). This band has been proposed to convey the configural properties of the face, that is, the distances between different features within the face (Boeschoten, Kemner, Kenemans, &
van Engeland, 2005; Goffaux, Hault, Michel, Vuong, & Rossion, 2005). Other studies have also found that featural information, which is thought to be conveyed by the high spatial frequencies (HSFs, e.g., more than 32 cycles per image (Goffaux et al., 2005)), can be used independently when configural information is removed by scrambling the face (Collishaw & Hole, 2000; Hayward, Rhodes, & Schwaninger, 2008).

**The “mid-band hypothesis” in adults**

A different line of investigation in the literature has argued that the critical band of spatial frequencies for face recognition is neither in LSFs nor in HSFs but rather in spatial frequencies within a mid-band that has generally been found to lie somewhere within the range of 8–25 cycles per face (cpf) (Costen, Parker, & Craw, 1994, 1996; Hayes, Morrone, & Burr, 1986; Näsänen, 1999; Parker & Costen, 1999; Tanskanen, Näsänen, Montez, Päälysaho, & Hari, 2005; Tieger & Ganz, 1979). Costen and colleagues (1994) proposed that this mid-band could be crucial because it contains some key information about a face that has “disproportionate importance” to face recognition, that is, that configural information is extracted from the mid-band and not from the LSFs. Another interpretation of this “mid-band bias” is that it may enhance the integration of the coarse information provided by the LSFs and the more detailed information from the HSF band, thereby aiding identification. It is important to remember, however, that although the mid-band may be an optimal band that triggers the best performance, it does not seem to be a critical band for face recognition (Ruiz-Soler & Beltran, 2006), as can be seen in studies demonstrating that both HSFs and LSFs are useful and sufficient for face recognition (e.g., Fiorentini, Maffei, & Sandini, 1983; Halit, de Haan, Schyns, & Johnson, 2006; Rotshtein, Vuilleumier, Winston, Driver, & Dolan, 2007; Vuilleumier, Armony, Driver, & Dolan, 2003). It seems likely that a more flexible diagnostic system, such as that described by Schyns and Oliva (1994, 1999), could have developed the optimal “strategy” for retrieving the most important information from a face stimulus to aid recognition. A system of this kind would clearly be influenced by an individual's visual experience throughout his or her development, and the current study aimed to examine how differing levels of experience with faces relate to the type of information extracted for face recognition.

**Spatial frequency processing in children**

One way to investigate spatial frequency processing in individuals with differing levels of face experience is by comparing children with adults. However, relatively few studies have considered the development of spatial frequency processing during the years between infancy and adulthood (see Leat, Yadav, and Irving (2009), for a review). Those that have done so most commonly use measures of “contrast sensitivity” that determine the minimum level of contrast required to detect objects of all possible sizes and distinguish them from their background (Adams & Courage, 2002; Beazley, Illingworth, Jahn, & Greer, 1980). One of the most interesting findings for the current investigation is an asymmetry in the development of contrast sensitivity for LSFs compared with HSFs (Adams & Courage, 2002; Benedek, Benedek, Kéri, & Janáky, 2003; but see Leat et al. (2009), for some studies that find equal development over all spatial frequencies). These investigations have found that sensitivity at LSFs is greater than that at HSFs at birth and develops gradually, not achieving adult-like levels until around 9 years of age (Adams & Courage, 2002; Benedek et al., 2003). Although worse at birth, sensitivity to HSFs increases very quickly and appears to be greater than sensitivity to LSFs between 4 and 9 years of age (Adams & Courage, 2002). This asymmetry suggests that children may be biased toward using different spatial frequencies at different points in their development due to the relative sensitivities of their visual system at any given stage. This may also be a contributing factor to a mid-band bias in adult face recognition given that adults are maximally sensitive to intermediate spatial frequencies and less sensitive to either very low or very high ends of the spectrum (Sekuler & Blake, 1994). This is not to say that LSFs and HSFs are not perceived or used by adults, but it may be that their processing bias for faces relies on the optimal spatial frequencies for the developed visual system.

The specific role of spatial frequency biases in face recognition has received much less attention in children than in adults. The majority of this research has been carried out by Deruelle and colleagues, who reported that typically developing children were biased toward LSFs in face matching and
identity naming tasks (Deruelle & Fagot, 2005; Deruelle, Rondan, Gepner, & Tardif, 2004; Deruelle, Rondan, Salle-Collemiche, Bastard-Rosset, & Da Fonseca, 2008). Interestingly, this LSF bias was also found in adults for the stimuli presented by Deruelle and Fagot (2005), whereas the review of the adult literature above generally agrees on a mid-band bias in face recognition. One other study by Boeschoten, Kenemans, van Engeland, and Kemner (2007) found that LSF-filtered faces activated mainly frontal areas of the brain in typically developing children, whereas HSF-filtered faces activated occipital brain areas. However, no differences were reported in recognition accuracy between HSF- and LSF-filtered faces. Due to the mixed results and interpretations of the previous studies conducted with different age groups, therefore, it is clearly important to use the same stimuli and methods across development. The current study aimed to provide an appropriate paradigm for this purpose, producing a clearer picture of the developmental trajectory within the spatial frequency and face processing literature than currently exists.

An effect of experience?

Although relatively little research has been conducted on the development of spatial frequency biases in face recognition, there has been extensive debate as to the development of adult-like face processing during childhood. It has been argued that “expert” face recognition relies on the use of configural information (e.g., Carey, 1992; Mondloch, Dobson, Parsons, & Maurer, 2004; Mondloch, Le Grand, & Maurer, 2002) and that young children are worse at using this information to identify faces than older children and adults (Mondloch et al., 2002, 2004), presumably because they have less experience with face stimuli. In fact, the work by Mondloch and colleagues demonstrates that configural processing develops much more slowly than the use of features or of the external contour of the face, not becoming adult-like until at least 10 years of age. This extended period of development displayed in behavioral tasks has also been mirrored in studies investigating brain responses to face stimuli through both event-related potentials (e.g., Taylor, Batty, & Itier, 2004) and brain imaging (e.g., Aylward et al., 2003; Golarai et al., 2007; Passarotti, Smith, DeLano, & Huang, 2007; Passarotti et al., 2003; Scherf, Behrmann, Humphreys, & Luna, 2007; see Cohen Kadosh & Johnson, 2007, for a review). Although they made no comment on the use of configural information as such, these studies did report a developmental shift in the activation of brain areas associated with face processing, with face-sensitive areas becoming increasingly specialized over developmental time.

However, the neuroimaging studies described above have not been able to clarify whether changing activation of face-responsive brain areas is directly due to increasing expertise with faces or reflects general maturation of the brain. Furthermore, in contrast to the idea that children become gradually more specialized or expert at recognizing faces, some researchers have argued that adult-like face processing abilities can already be found in very young children (e.g., Crookes & McKone, 2009; Gilchrist & McKone, 2003; McKone & Boyer, 2006; McKone, Kanwisher, & Duchaine, 2007; Pellicano, Rhodes, & Peters, 2006). McKone and colleagues contended that any improvement in face recognition is not due to face-specific developmental changes but rather is due to the general cognitive development of children during this time period, particularly improvements in memory, focusing attention, and their visual system as a whole (Crookes & McKone, 2009; see also Mondloch, Maurer, & Ahola, 2006). The current study aimed to compare the two accounts of the development of face recognition through a very different method, namely, manipulating the spatial frequency information in a face image rather than the original structure of the face. Although it must be remembered that LSF information cannot be entirely responsible for conveying the configural properties of a face and that HSF information cannot be entirely responsible for conveying the featural properties of a face (Rotshstein et al., 2007; Wenger & Townsend, 2000), this methodology allows some comparison to be made of the relative use of featural and configural information in different age groups.

**Testing the mid-band bias in children and adults**

The aim of this experiment was to develop a paradigm with which to test the mid-band hypothesis in children while retaining important characteristics from the previous adult literature. Participants were tested with a paradigm adapted from Tanskanen et al. (2005) to produce a child-friendly “game”
that could track any changes in spatial frequency biases over developmental time. In this game, participants learned to recognize facial identities and then needed to determine which face was “hiding” behind a range of spatial frequency masks. To compare previous studies’ reports of adult-like face processing in children, a group of 7- and 8-year-olds (e.g., Crookes & McKone, 2009) and a group of 9- and 10-year-olds (Mondloch et al., 2002) were recruited for the current experiment. The inclusion of two ages in each group arises from the recruitment of children from their schools because this is how year groups are structured in the U.K. schooling system. Previous piloting found that children below 7 years of age found the task to be extremely challenging. Because children below this age would also have a different schooling context from the older children, 7-year-olds were the youngest age group assessed.

The experiment also aimed to extend the current understanding of the mid-band bias by presenting participants with both upright and inverted faces. This meant that it was possible to test whether the bias was face sensitive because inverted faces are processed differently from upright faces, with inversion significantly disrupting recognition performance (e.g., Yin, 1969). Although some previous research has found that the inversion effect was not influenced by spatial frequency (Boutet, Collin, & Faubert, 2003; Gaspar, Sekuler, & Bennett, 2008), a recent article using spatial frequency manipulations by Goffaux (2009) did find differences in the effect of orientation on LSF- and HSF-filtered faces when participants were attending to the eye region. In the developmental literature, none of the studies on spatial frequency processing in face recognition has investigated an inversion effect. Therefore, it is important to investigate the effect of inversion on the current stimuli not only to discriminate between previous accounts in adults but also to improve our understanding of the development of any face-specific spatial frequency biases that may emerge.

Based on the previous literature on spatial frequency biases in adults, it was predicted that (a) adults’ performance would be significantly worse when the middle spatial frequencies (MSFs) of an upright face were masked than when only LSFs or HSFs were masked and (b) there would be a significant effect of inversion on adults’ performance, with recognition accuracy being reduced for the inverted faces compared with the upright faces at all spatial frequency masks. Because findings from the development of face recognition are so mixed, there are two possible outcomes for the children studied in the current experiment. If children have a fully developed face recognition system early in childhood, then even the youngest age group (7–8 years) should show a mid-band bias similar to that of adults. If, on the other hand, strategies for the visual processing of faces develop gradually throughout childhood, then 7- and 8-year-olds should not show the mid-band spatial frequency bias, although it may be present by 10 years of age. As mentioned earlier, the effects of inversion on spatial frequency biases are not specified in the literature concerning children. However, following from the previous debate, it would seem likely that if children were to demonstrate the adult-like mid-band bias for upright faces, they would also be affected by inversion at all spatial frequency masks.

Method

Participants

Participants were 33 adults (14 women and 19 men, mean age = 28.37 years, SD = 8.20), 18 7- and 8-year-olds (9 girls and 9 boys, mean age = 8.00 years, SD = .47), and 20 9- and 10-year-olds (7 girls and 13 boys, mean age = 10.19 years, SD = .31), with normal or corrected-to-normal vision, who were recruited through a university-run database or through the children’s schools. Data from an additional 7 participants (2 7- and 8-year-olds, 3 9- and 10-year-olds, and 2 adults) were not included in these analyses for failing to perform significantly above chance on the identification of the training faces (described below). This means that in the current two-alternative forced-choice task, where the binomial probability is .5, seven of eight of the training faces needed to be correctly identified to be included in the analyses. Data from a further 2 adults were not included in the analyses because they achieved ceiling performance for all spatial frequency masks in the upright trials. Informed consent was obtained from the parents of the children taking part and from all adult and child participants before testing began.
Materials

Stimuli

Stimuli were adopted from a set created by Näsänen (1999). These stimuli consisted of faces covered with a noise mask at different spatial frequencies, thereby allowing the entire spatial frequency spectrum to be presented in the face with only a narrow band blocked out. This is a more sensitive method than presenting a face that had been low- or high-pass filtered because reduced face recognition would imply a bias toward a particular spatial frequency band even when others were available for use.

Four synthetic male faces were chosen from a total set of eight face images provided by Tanskanen et al. (2005; for full details of the original face set and its production, see Näsänen, 1999). One of the face images in this set was created by averaging photographs of four different faces. The other images were created through “warping” this face according to corresponding points of real photographs of seven other faces. The stimuli were presented in sets of two, with four possible combinations used in the experiment: AB, AC, BD, and CD (see Fig. 1). The other two possible combinations were not included because during piloting they had been found to cause significantly reduced accuracy due to their similarity, which also resulted in more participants in these conditions failing to achieve the baseline score required for inclusion in the analyses. Only two faces were presented to each participant so as to keep memory demands as low as possible for the youngest children in the study. A recent study on face processing in children presented altered versions of only two faces, requiring 8-year-old participants to identify stimuli as belonging to the “team” of one of two face identities (Pimperton, Pellicano, Jeffery, & Rhodes, 2009). This task is closer to the current experiment than tasks involving more stimuli and requiring a same-different judgment (e.g., Freire, Lee, & Symons, 2000; Mondloch et al., 2002) or face matching (e.g., Deruelle et al., 2004), each of which may be solved based on perceptual characteristics and not on recognition of the facial identity. To reduce the length of training required

![Fig. 1. Upper panel: The four unmasked stimuli used in the experiment. Each condition consisted of a combination of two of the four faces, and participants viewed only one pair each. Lower panel: Testing procedure for adults and children. Children first went through a training session. All participants then completed the same practice phase, followed by the upright trials and the inverted trials. A fixation stimulus was presented until participants were judged as ready to begin the trial. A single face (target) was then viewed for the times shown above, followed by two faces presented simultaneously. Participants judged which of the two stimuli had been the target face. (Note that the smaller size of the images presented in this figure may alter the salience of spatial frequency bands compared with the original stimuli.)](image-url)
and the task difficulty in the current experiment, therefore, each participant viewed only one pair of faces drawn from the set displayed in Fig. 1.

The unmasked versions of the faces were used for initial training and for the forced-choice task (described below). The target stimuli were presented as either “noisy” faces or the original faces covered with black bars (training faces). The latter stimuli were produced in the Paint program using the line tool to draw 1-mm-thick lines on top of the original face images. The lines, therefore, subtended .1 degree of visual angle. Noisy faces were the weighted sum of a face image and a noise mask, once again adopted from the set created by Näsänen (1999). The original noise masks were produced by filtering white Gaussian noise with rectangular bandpass Fast Fourier Transform filters, with the center spatial frequency (SF) varying from 2 to 45 cycles per image (cpi) (Tanskanen et al., 2005). For the current study, only noise masks with center SFs of 8, 16, 23, and 32 cpi were used and were represented in the analysis as LSF, MSF, HSF1, and HSF2, respectively. These SFs related to 1.1, 2.2, 3.2, and 4.4 cycles per degree (cpd) during presentation. Two HSF noise masks were used here due to the different cutoffs used in previous studies (e.g., 24 cpi in Halit et al., 2006, and Vuilleumier et al., 2003; 32 cpi in Goffaux, 2008, and Goffaux, Gauthier, & Rossion, 2003) with the intention of finding the most appropriate cutoff to use with the current stimuli. The bandwidth of the noise was always 2 cpi, and contrast was constant at all SF bands (see Tanskanen et al. (2005), for further details).

**Equipment**

Trials were created using E Prime software on a Dell laptop computer. Faces were presented on the 15.4-inch screen of an Acer laptop, with each face measuring 6.6 × 6.6 cm. Thus, the stimuli subtended approximately 7 × 7 degrees of visual angle at a viewing distance of approximately 53 cm. Stimuli were presented individually (target face) or in pairs (response faces). Single stimuli were presented in the center of the screen, whereas paired stimuli appeared 5 cm from each side of the screen along the x axis, subtending 5.4 degrees of visual angle and centrally in the vertical dimension. Accuracy responses were recorded using the mouse attached to the laptop. Additional “face cards” were also produced for the child training period. These face cards consisted of five printed copies of each of the four stimuli (measuring 9 × 9 cm) that had been cut out and attached to a blue card background (measuring 10.5 × 10.5 cm).

**Design**

A three-way (Mask × Orientation × Age) mixed design was used, with participants in each age group viewing all spatial frequency masks at both orientations.

**Procedure**

Each participant viewed only one pair of faces, creating four conditions to which individuals were assigned randomly. As can be seen in Fig. 1, each child took part in a short training phase before proceeding to the adult test phase. Extensive piloting with children had demonstrated the need for this prior familiarization with the faces to achieve a baseline performance (i.e., basic recognition of the unmasked faces) similar to that of adults. A range of different tasks was adopted to prevent direct perceptual matching by the children, with each “game” focusing on the identity of the face and attempting to avoid any direct matching of pictures by the children (see description below).

**Training phase**

Children were taken to a quiet room in their school, where the tasks were explained to them and consent was obtained. The training period then began with the experimenter introducing the two identities in that particular condition using the face cards. Two cards were shown to each child (e.g., one “Bob” and one “Jimmy”), and they were then placed into a “Bob” pile on one side of the child or a “Jimmy” pile on the other side. Next, the child was given another card at random and was asked to tell the experimenter which picture was presented before placing it in the correct pile. This was repeated until five of each face identity had been placed in the correct pile. Mistakes were corrected by the experimenter in such a way as to ensure that the child did not feel distressed by wrong
answers (e.g., “He tricked you! Bob goes in that pile!”). Five face cards were then chosen at random, with four placed face down on the table and one given to the child. The child was asked to tell the experimenter which identity that card showed and was then told whether he or she was correct or incorrect. The experimenter took away the card and asked the child to “find another picture of the same person.” The experimenter made sure that the child judged which identity each individual card was before taking the card and awarding a point for each correct picture the child found.

Finally, the child was asked to sit in front of the screen so as to play the game. The introduction and practice phase was then identical for children and adults except that adults recorded their own responses on the mouse, whereas children pointed to their chosen face on the screen and the experimenter recorded their answers. The two faces assigned to the condition were shown on the screen with their associated names (“Bob”, “Jimmy”, “Max,” or “William”). Participants were then presented with a single face identity or both of the faces and were asked either to say whom they saw (single presentation) or to point to the face named by the experimenter (simultaneous presentation). The latter condition was then used throughout the practice and test phases.

**Practice phase**

The main procedure involved a two-alternative forced-choice paradigm, as depicted in Fig. 1. The experimenter outlined the task to the participants, explaining that they would be presented with one of the face identities for a short time, followed by a second slide presenting the two faces simultaneously. Their task was to choose one of the two faces on the second slide that they had seen “pop up” on the first slide either by using the buttons on the mouse to record their choice (for adults) or by pointing to one of the faces (for children). To ensure that participants understood these instructions, a practice phase was set up with the target faces presented behind black bars. These training faces were used to ensure that participants could complete the experiment when some information was blocked from the face without using the masks from the test phase. Trials were initiated by the experimenter and began when participants were ready. One of the two faces then appeared behind bars in the center of the screen for 500 ms (for the two oldest age groups) or for 2 s (for the youngest age group) before being replaced by the two unmasked faces in randomized positions (e.g., left or right) for 5 s (or for an unlimited time for the youngest age group). These time changes for the target faces were based on work by Pellicano and colleagues (2006) suggesting that very short exposures tend to produce lower face recognition levels in young children. Based on piloting with children of different ages, the 2-s exposure was adopted for the current experiment for use with the 7- and 8-year-olds. Because previous testing had found that 10-year-olds showed no difference in performance between the .5- and 2-s exposure times, the shorter duration was chosen for the current experiment. Errors made during training were corrected by the experimenter verbally, and the practice phase was ended when participants had correctly identified the target identity in three consecutive trials.

**Test phase**

Participants were told that the target faces may still be “hidden” behind bars or that they may now be disguised behind some noise masks. Examples of masked faces were presented using noise masks not included in the main experiment. It was explained that some of the faces may be very hard to recognize but that if participants were unsure, they should make a guess based on their immediate impression. Participants were asked to respond as accurately and rapidly as possible. Target faces were randomly presented, showing one of the two identities combined with either bars or LSF, MSF, HSF1, or HSF2 masks. This meant that each type of noise mask was presented a total of eight times, with a further eight training faces presented randomly throughout the experiment providing the baseline measure of performance.

Following the upright trials, participants were given a short break before completing the experiment again with inverted faces. Trials were blocked to allow participants to develop a face processing strategy for each set of trials. Inverted trials always followed upright trials so as to make the upright face recognition as naturalistic as possible. For example, viewing inverted faces first could bias participants toward using an unusual strategy for recognizing upright faces, whereas seeing upright faces first would promote a strategy that was more likely to be used in the real world given that children and adults are rarely presented with inverted faces outside of the laboratory (see Annaz, Karmiloff-Smith, Johnson, & Thomas,
Results

The percentage of correct responses at each spatial frequency was calculated for each age group and can be seen in Fig. 2. Data were collapsed across stimulus pair because there was no significant main effect (\( F = .80, p = .50 \)) or significant interactions of this variable with spatial frequency mask, ori-
entation, or age group (Fs < 2.30, ps > .09). In addition, only data from LSF, MSF, and HSF2 masks are reported.¹ All post hoc comparisons are reported using Bonferroni corrections.

Comparing all participants

A three-way mixed analysis of variance (ANOVA) was conducted on accuracy responses, with age group (7–8 years, 9–10 years, or adults) providing the between-participants factor and with spatial frequency mask (LSF, MSF, or HSF2) and orientation (upright or inverted) providing the within-participants factors. These analyses revealed significant main effects on accuracy of spatial frequency mask, \( F(2, 136) = 12.13, \text{MSE} = 394.98, p < .001, \eta^2_p = .20 \) (Greenhouse–Geisser statistic reported), of orientation, \( F(1, 68) = 14.25, \text{MSE} = 231.68, p < .001, \eta^2_p = .20 \), and of age group, \( F(2, 68) = 5.98, \text{MSE} = 617.44, p < .01, \eta^2_p = .20 \). Significant interactions were also found between spatial frequency mask and age group, \( F(4, 136) = 2.43, \text{MSE} = 394.98, p = .05, \eta^2_p = .10 \), and among spatial frequency mask, orientation, and age group, \( F(4, 136) = 3.26, \text{MSE} = 236.43, p = .01, \eta^2_p = .10 \), but not between orientation and age group (\( F = 2.60, \text{MSE} = 231.68, p = .08 \)) or between SF mask and orientation (\( F = 2.36, \text{MSE} = 236.43, p = .10 \)). To explore the three-way interaction, further analyses were conducted on each age group separately and can be seen below.

Adults

A 3 (SF Mask) \( \times 2 \) (Orientation) repeated-measures ANOVA was conducted on the adult data, revealing significant main effects on accuracy of spatial frequency mask, \( F(2, 64) = 6.48, \text{MSE} = 371.59, p < .01, \eta^2_p = .20 \), and of orientation, \( F(1, 32) = 5.07, \text{MSE} = 149.64, p = .03, \eta^2_p = .10 \). As can be seen in Fig. 2, there was also a significant interaction between SF mask and orientation, \( F(2, 64) = 4.06, \text{MSE} = 223.18, p = .02, \eta^2_p = .10 \), with only the HSF mask producing significantly worse performance in the inverted trials than in the upright trials, \( t(32) = 3.79, p = .001 \). This interaction was further explored through a one-way repeated-measures ANOVA conducted on the upright and inverted trials separately. A significant main effect of spatial frequency mask was found in the upright data, \( F(2, 64) = 7.92, \text{MSE} = 288.33, p = .001, \eta^2_p = .20 \), and in the inverted data, \( F(2, 64) = 3.35, \text{MSE} = 306.43, p = .04, \eta^2_p = .10 \). Planned simple contrasts in the upright data revealed that this effect was driven by accuracy at the MSF mask (72%) being significantly lower than that at the LSF mask (86%) and the HSF mask (86%) (\( p < .01 \)). In the inverted data, the MSF mask was only significantly lower than the LSF mask (\( p = .02 \)) and did not differ from the HSF mask (\( p = .90 \)). A mid-band bias, therefore, was found in upright trials for adults but not in inverted trials for adults.

9- and 10-year-olds

A further 3 \( \times 2 \) repeated-measures ANOVA was conducted on the data collected from the 9- and 10-year-olds. These analyses revealed significant main effects on accuracy of spatial frequency mask, \( F(2, 38) = 4.73, \text{MSE} = 352.31, p = .02, \eta^2_p = .20 \), and of orientation, \( F(1, 19) = 9.56, \text{MSE} = 368.42, p < .01, \eta^2_p = .30 \). There was also a significant interaction between SF mask and orientation, \( F(2, 38) = 4.44, \text{MSE} = 258.84, p = .02, \eta^2_p = .20 \). Post-hoc \( t \) tests demonstrated that accuracy was significantly lower for inverted trials than for upright trials only at the HSF mask, \( t(19) = 2.44, p = .03 \), and the LSF mask, \( t(19) = 3.96, p < .01 \). To further explore this interaction, a one-way repeated-measures ANOVA was conducted on the upright and inverted trials separately. A significant effect of spatial frequency mask was found in only the upright data, \( F(2, 38) = 7.45, \text{MSE} = 368.28, p < .01, \eta^2_p = .30 \), and planned simple

¹ The HSF2 mask was chosen for the study because analysis with the HSF1 mask revealed much smaller effects. In particular, significant differences in accuracy were found between the MSF and HSF2 masks in the adult (\( p < .01 \)) and 9- and 10-year-old (\( p = .04 \)) groups, whereas a nonsignificant trend was found between these masks in 7- and 8-year-olds (\( p = .067 \)). With the HSF1 mask, these differences were removed for both of the child groups and the effect was much reduced for adults (\( p = .05 \)). It is noted that both the LSF and HSF2 cutoffs are one octave from the mid-band cutoff, whereas the HSF1 mask is much closer to the MSF mask. This could be one reason for the reduced effects with this mask. This is supported by the research by Hayes and colleagues (1986), who found that 25 cpf produced the best recognition, suggesting that this may still be included in the mid-band of spatial frequencies.
contrasts revealed that this was driven by accuracy at the MSF mask (62%) being significantly lower than that at the LSF mask (84%) and the HSF mask (79%) (ps < .02). A mid-band bias, therefore, was found only for upright faces in this group, in line with the performance of adults outlined above.

7- and 8-year-olds

A final 3 × 2 repeated-measures ANOVA was conducted and revealed a significant effect on accuracy of spatial frequency mask, F(2, 34) = 6.91, MSE = 339.82, p < .01, η² = .30. As can be seen in Fig. 2, however, there was no significant effect of orientation on accuracy (F = .75, MSE = 233.27, p = .40) and no significant interaction between orientation and spatial frequency mask (F = .85, MSE = 236.33, p = .40) in the data collected from 7- and 8-year-olds.

Discussion

A bias in adults toward a mid-band of spatial frequencies for upright faces was replicated from previous work, with adults demonstrating a decrease in accuracy when MSFs were masked despite the LSFs and HSFs remaining available for use. Our additional data collected for inverted faces also provided further insight into the nature of spatial frequency biases in face recognition given that the mid-frequency bias was not observed with inverted stimuli. Although masking the mid-band produced similarly low performance in both upright and inverted conditions, inverted faces caused adults to rely on the HSF information to a much greater degree, thereby removing the bias toward the mid-band. Interestingly, although adults seem to rely on both MSFs and HSFs equally when faces are inverted, recognition accuracy is significantly less disrupted when the LSFs are masked in this condition. One cautious interpretation of this effect could involve the relationship between LSFs and the configural properties of a face (e.g., Goffaux et al., 2005). If the spatial frequency system can efficiently diagnose the most useful information provided by a particular visual stimulus (e.g., Schyns & Oliva, 1999), then this system should not be biased toward LSFs for an inverted face because configural processing can be disrupted by inversion (Yin, 1969). However, the bands providing more detailed information should be preferentially accessed, as can be seen in the current adult data.

One important finding is how similar the adult pattern of biases is to that demonstrated by the 9- and 10-year-olds for upright faces but not by the 7- and 8-year-olds. The older children not only demonstrated a mid-band bias for upright faces but also followed the adult pattern of inversion by demonstrating no such bias for inverted faces (although there was a greater reliance on LSFs in these children than in adults). The 7- and 8-year-olds, on the other hand, showed no mid-band bias for upright faces and no significant effect of orientation or interaction with spatial frequency mask, performing at a level comparable to that of the older children for upright faces. It is possible that the younger children are less affected by face inversion because they are using similar strategies for both upright and inverted faces. This supports the finding by Carey and Diamond (1977) that older children were more affected by inversion than younger children (but see Crookes & McKone (2009), who argued that the inversion effect does not become stronger after 7 years of age). This finding of a different processing style between the two child groups is not likely to be a product of the slightly modified child procedure described above. Specifically, changing the amount of time spent viewing a masked face did not produce different biases during previous testing of 10-year-olds who were tested at both exposure times. The other difference between the adult and child procedures was the training period, which was found to be necessary to produce the same level of baseline performance in the younger children as in the adults. Because the group of 9- and 10-year-olds demonstrated a more adult-like pattern while receiving the same training period as the younger children, it is doubtful that the training had any effect on spatial frequency biases in the current task.

Development of the mid-band bias

Analyses of the child data provided substantial support for the argument that the development of face recognition is a gradual process, demonstrating that young children (at least up to 8 years of age)
do not display the mid-band bias found in adult face recognition. Interestingly, the time span of this development is in line with the development of contrast sensitivity during childhood described by Adams and Courage (2002), where a bias toward using HSFs might be expected due to a greater sensitivity to this band than to lower SF bands until 9 years of age. Although the 7- and 8-year-old group did not show significantly worse performance for HSF masks than for MSF masks (although there was a nonsignificant trend, p = .067 (see Fig. 2)), this group did display lower accuracy than adults and older children only when the HSFs were masked in the upright faces. This suggests that younger children may be taking a much more feature-based approach to upright face processing compared with the older groups (e.g., Schwarzer, 2000).

The lack of a specialist mid-band strategy in the younger children also combines with the imaging data discussed previously (e.g., Golarai et al., 2007; Passarotti et al., 2003, 2007; Scherf et al., 2007) to suggest that the development of face perception abilities is a gradual process that occurs throughout childhood (e.g., Mondloch et al., 2002, 2004). Although conclusions cannot be made from the current behavioral data about the neural basis of the mid-band specialization, these results are consistent with the finding that brain areas associated with face perception become gradually more fine-tuned with age (Cohen Kadosh & Johnson, 2007; Johnson, 2005). In future research, it will be necessary to investigate how the specialization of these face-sensitive brain areas relate to changes throughout development in the use of configural versus featural information and to different spatial frequency biases.

It is also important to note that although young children do not show a bias toward the mid-band, their accuracy is disrupted as much as that of the older children and the adults when the mid-band is masked. This suggests that although young children may be just as sensitive to the mid-band and, therefore, capable of adult-like face perception at a young age (as suggested by McKone and colleagues), their visual system might not have sufficient experience to select the most useful spatial frequency for a specific task. It seems that the “diagnostic” system described by Schyns and Oliva (1994, 1999) may need more time to learn which band holds the most useful information for recognizing faces. It is also important to recognize that the adult-like sensitivity to configural differences between faces found by McKone and Boyer (2006) and Pellicano and colleagues (2006) were due to the large size of these spacing changes in their studies. Mondloch and Thompson (2008) found that when the configural differences are more subtle in a face, 4-year-olds are not as sensitive as adults across a range of tasks. This is further supported by data from McKone and Boyer (2006), who showed that children were sensitive only to medium or large differences between faces and not to small ones.

Comparison with previous studies of SF biases in children

It is important to consider why the current data reveal different SF biases from those observed by Deruelle and colleagues (Deruelle & Fagot, 2005; Deruelle et al., 2004, 2008), who found a bias toward LSFs in children and adults. One way in which the current methods differed from these experiments was through the presentation of only two faces for each participant rather than an array of different stimuli. There is a possibility, therefore, that face recognition in the current study relied on idiosyncratic differences between the two stimuli presented to each participant. Sekuler, Gaspar, Gold, and Bennett (2004) found that when they presented only two face images, particular regions of the face were used to discriminate between the stimuli (especially in the eye region). A bias toward using a specific feature to distinguish between face identities might be reduced if more faces were included in the stimulus set. However, it is unclear how this bias toward a specific feature could have produced the current results because the older children and adults do not demonstrate a bias toward using HSFs in either the upright or inverted trials. Even if the 7- and 8-year-olds were more affected by these idiosyncratic differences between the faces, thereby causing their greater reliance on HSFs, the data still show that younger children are relying on different information from the older groups, supporting the conclusion that expert or adult-like face processing is the result of gradual development.

A more likely explanation of the differences between the current results and those of Deruelle and colleagues (Deruelle & Fagot, 2005; Deruelle et al., 2004, 2008) lies in the filtering method used in the latter studies. Closer inspection of their stimuli reveals that the LSF stimuli presented were low-pass filtered at 2 cpd, preserving spatial frequency information that in the current study would be classified as LSF and MSF. Halit et al. (2006) found that adults demonstrate an advantage when 2 SF bands are
combined compared with when only one SF is presented, and this would explain why the LSF stimulus in the studies conducted by Deruelle and colleagues might produce a bias toward that face over an HSF stimulus preserving only one SF band. The difference in results between studies again highlights the need for a unified approach in this area and emphasizes how the filtering method may produce less realistic face processing.

**The inversion effect**

In terms of the data from inverted faces, we have shown that adults and older children show both quantitatively and qualitatively different patterns of accuracy in comparison with upright faces, with the mid-band bias disappearing when inverted faces were presented. This finding differs from the findings of Boutet et al. (2003), who found an inversion effect for all of their SF masks, and Gaspar and colleagues (2008), who found that identification relied on the same band of spatial frequencies for upright and inverted faces. There are several differences between the current study and the one conducted by Gaspar and colleagues that could account for the discrepancy between findings. We used a masking method that had been applied in two previous studies and involved adding noise to a specific bandwidth within a face stimulus (see Näsänen, 1999). The other study embedded the face to be recognized in high-pass filtered or low-pass filtered noise and simply removed much larger or much smaller bandwidths from the face. This makes it difficult to compare the spatial frequency bands across the two experiments. For example, the low-pass filtered noise with a cutoff of 16.8 cpf in Gaspar and colleagues (2008) study would correspond roughly to the LSF mask in the current study because it retains bands that we have classified as MSF and HSF in the stimulus. However, a high-pass filter at the same cutoff does not correspond to any of our masks because only the HSF band is presented in the face. In addition, the significant effect of orientation found in the current study may have been due to the greater number of participants involved in the experiment than in Gaspar and colleagues’ study. It is clearly important, therefore, that researchers in this area reach a consensus on the most useful methodology for future investigations to promote ease of comparison across studies.

It is also important to consider why the current study did not find an inversion effect at all of the SF masks, as was found by Boutet et al. (2003). If the morphed stimuli used in the current study had been processed in a different way from normal faces, then we would not have expected to find an effect of inversion for any of the stimuli. In addition, if the main effect of orientation had been a result of the mental rotation required to complete the task in the inverted condition, then we would have expected to find an inversion effect for all of the SF masks. Perhaps the inability to find an inversion effect for all of the SF masks in the current study could be due to a practice effect resulting from the inverted trials always following the upright trials. As mentioned earlier, this trial order was implemented to maintain the most naturalistic processing strategy for upright faces possible in this experimental setting. The fact that a significant main effect of orientation was still found for the adults and older children despite this possible practice effect suggests that orientation is an important factor in face recognition accuracy in the current task. In addition, any reduction of an orientation effect in the 7- and 8-year-olds is likely to have only decreased the similarity between upright and inverted trials seen in this group, thereby implying that the difference between younger and older children could be even clearer than is apparent in the current data. Therefore, although interpretations of the inverted data must be cautious, any practice effect present in the data could not detract from the conclusion that the mid-band bias develops over an extended period of time and becomes a hallmark of upright face processing during late childhood and adulthood.

Despite the different results found in adults across the studies described above, it is the developmental data that are the most informative here in relation to the inversion effect. Crookes and McKone (2009) argued that there is no qualitative change in the inversion effect from 7 years of age until adulthood and that studies that did find a developmental shift were either poorly matched or suffered from ceiling or floor effects. Their conclusion of no change during development was based on the finding of a disproportionate inversion effect for faces over objects (dogs) in 7-year-olds and adults with no developmental change in the size of this disproportion. Although the current study does not tackle this issue directly by comparing inversion effects for faces and objects, the data do imply that there is a
qualitative shift in the processing of upright versus inverted faces between 7 years of age and adulthood. In particular, it seems that the 9- and 10-year-olds might be more affected by inversion than either the younger children or the adults, relying on all SFs when attempting to identify inverted faces while showing a clear mid-band bias for upright faces. This result is at odds with the work of Crookes and McKone (2009) and suggests that face recognition ability might not develop linearly from early childhood to adulthood. As mentioned earlier, although it is possible that accuracy for inverted faces may have been improved by practice in the current task, this should occur for all children and, thus, cannot explain the different pattern of spatial frequency biases found between the two child groups. The pattern of biases in the 7- and 8-year-olds, however, is in line with previous research by Carey and Diamond (1977) and Schwarzer (2000), who suggested that younger children could be taking a qualitatively different approach to processing the face stimulus from the approach taken by older children and, therefore, are less affected by inversion. Furthermore, although adults show a clear mid-band specialization for upright faces, their system could be flexible enough to deal with inverted faces without such drastic effects on accuracy as seen in the 9- and 10-year-olds (e.g., Ruiz-Soler & Beltran, 2006; Schyns & Oliva, 1994, 1999). Although it is possible that young children demonstrate a disproportionate inversion effect for faces over objects (e.g., Crookes & McKone, 2009), it seems that they may be relying on different visual information from the face to achieve the same outcome as adults. The current paradigm, therefore, provides evidence that there is a gradual change in the inversion effect throughout childhood and is a useful tool for studying this effect over developmental time.

Conclusions

The current study has extended research into spatial frequency biases in face recognition by considering the development of these biases over developmental time. Importantly, our experiments showed for the first time that young children, unlike adults, do not depend most heavily on mid-band frequencies in face processing. Although it is true that adult-like biases can be detected in very young children in some circumstances, our developmental approach adds to a growing body of evidence demonstrating the gradual development of face processing ability with age. Although individuals are capable of processing multiple spatial frequency bands, the mid-band bias found in adult face recognition develops slowly, not reaching adult-like levels until around 9 or 10 years of age. The current data cannot resolve the issue of whether the mid-band bias is a result of experience with faces or whether it is a consequence of visual system maturation that is unrelated to levels of face expertise. However, future work could attempt to tease apart these opposing accounts by studying groups with differing levels of expertise with faces as well as groups of experts in other visual domains. It will also be important to use neuroimaging techniques to complement the behavioral data presented here so as to make firmer conclusions as to the neural basis of the effects found in the current study. Nevertheless, by studying the mid-band bias from a developmental perspective for the first time in this study, the door to these future research questions has been opened.

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