LEARNING TO PROCESS FACES

LEARNING TO PROCESS FACES: LESSONS FROM DEVELOPMENT AND TRAINING

By

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Abstract

The present collection of studies examined the development of the ability to recognize facial identity rapidly and accurately, using two complementary approaches: comparing the performance of children and adults, and by training observers to learn novel stimuli in a laboratory setting. Across studies, children 8 to 10 years old performed less accurately than adults, a finding that confirms previous research that face processing takes many years to develop. However, results from two studies suggest that by 8 years of age, children encode individual facial identities relative to the average of previously experienced faces, in a manner similar to adults. The findings suggest that the basic mental architecture supporting face recognition is in place by 8 years. Additionally, children improved their ability to recognize unfamiliar faces from various viewpoints after just two, one-hour sessions of training, although the rate of learning was more variable than that observed in adults. The results from two studies also revealed that children's recognition accuracies of facial identity were lower than those of adults. An examination of children's similarity judgments of facial identity revealed that such immaturities in children's face processing may stem from greater variability in the mental representation of facial identities, rather than from immaturities in the encoding process per se. Findings from a final study suggest that the ability to make fine perceptual discriminations among individual faces arises, in part, from experience differentiating faces at the individual level, unlike the experience with non-face objects that typically involves recognition at the

category level. The findings from the studies presented in this thesis suggest that such perceptual expertise may arise only with years of experience recognizing individual faces, and with sufficient neural development to support a stable mental representation of individual facial identities.

Preface

Two studies (reported in Chapters 2 and 5) in the current thesis have been accepted for publication in scientific journals and were written in collaboration with other researchers. Chapters 3 and 4 describe studies that have been written as manuscripts to be submitted to scientific journals. My supervisor, Daphne Maurer, is a co-author on all manuscripts in recognition of her helpful comments and insights throughout all stages of the studies. Additional co-authors and contributors, and their roles in the collaboration, are described in detail below for each study.

The study described in Chapter 2 has been accepted for publication in *Developmental Science*. It modified a previously published paradigm to examine, for the first time, adaptation aftereffects of facial identity in children. Co-authors Gillian Rhodes and Linda Jeffery had created the stimuli for a previous study using a different paradigm with adults (Rhodes & Jeffery, 2006). My contribution to this work involved modifying the design of the paradigm to be suitable for use with children (e.g., deciding to use only two identities to be learned by children instead of all four identities used previously with adults, developing a "cover story" so that the experiment appeared to be a game for children, and choosing the appropriate number of test trials), collecting data from 32 adult participants and 24 of the 32 eight-year-olds, analyzing the data, reviewing the relevant developmental findings that have been published previously, and writing the manuscript, taking into account suggestions from my co-authors. Additional co-authors are Elizabeth Pellicano, who provided data for 8 eight-year-olds and comments on drafts of the manuscript, and my supervisor Daphne Maurer.

The study described in Chapter 3 is a manuscript in preparation, to be submitted to *Vision Research*. I conducted the necessary background research to develop an original paradigm to examine the nature of children's face-space when salient hair cues are removed from the face stimuli, and provided an assessment of the convergence of two different methods of collecting similarity judgments about facial identity from adults. I created the stimuli (selected from a larger database of faces collected previously by Sybil Geldhart, a former graduate student in my lab, which I then modified in Adobe Photoshop), and I wrote the computer script for stimulus presentation and data collection in Experiment 1. I collected the data presented in Experiments 1 and 2b. The majority of the data presented in Experiment 2a were collected by a 3rd-year undergraduate student, Nicole Folland, as part of the requirements of her research practicum course, co-supervised by me and Daphne Maurer. The details of the paradigm and methods for data analyses were chosen in collaboration with Xiaoqing Gao, a fellow graduate student in my lab who is using the same procedure to examine children's sensitivity to facial expressions, and my supervisor, Daphne Maurer. The computer script for stimulus presentation was written and the cluster analysis in Experiment 2 performed by Xiaoqing Gao. I performed all other analyses, conducted the relevant background research, and wrote the first draft of the manuscript. Co-authors on the manuscript will be Daphne Maurer (second author) and Xiaoqing Gao (third author).

The study described in Chapter 4 is a manuscript in preparation, to be submitted to a scientific journal. It provides original findings of how short-term laboratory training improves children's and adults' recognition of facial identity from various viewpoints, and whether such improvements transfer to sensitivity to the spatial relations of internal facial features. The adult data presented in Experiment 1 were collected by an undergraduate honours thesis student, Samidha S. Joglekar, as part of her honours thesis, whom I co-supervised with Daphne Maurer. The testing paradigm for Experiment 1 was created in collaboration with Samidha Joglekar and Daphne Maurer. Therefore, in its final format, Daphne Maurer will be the second author and Samidha Joglekar will be the third author of the manuscript. My contribution involved taking the photos, helping Samidha design the procedure and analyze the adult data from Experiment 1, modifying the paradigm for Experiment 2, collecting and analyzing the data from children in Experiment 1 and adults in Experiment 2, and writing the first draft of the manuscript.

The study described in Chapter 5 has been accepted for publication in *Perception*, co-authored by my supervisor, Daphne Maurer. It is the first study to examine the role of categorization on sensitivity to the spatial relations of features in novel objects. I designed the experimental paradigm, made the training stimuli, collected and analyzed the data, and wrote the manuscript. Daphne Maurer provided helpful comments throughout the entire process.

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Finally, I would like to thank my family and friends for their love and support. Thank you for always being there for me, even though we do not get to see each other as often as we should. I would like to thank especially Abbey Peters, Allison Norman, Derek Flack, and Jenny Fakla. And thank you to Hidetora Tanaka, for supporting me from beginning to end, and for encouraging me to never stop learning.

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Chapter 1

Introduction: Learning to process faces

The ability to recognize thousands of individual faces rapidly and accurately under varying viewing conditions, despite the fact that all faces share the same structural property of having two eyes above a nose above a mouth, is an amazing computational feat of the human brain. Adults can recognize familiar faces accurately even when they have not been seen for 50 years (Bahrick, Bahrick, & Wittlinger, 1975). Such a remarkable memory undoubtedly evolved because of the social significance of faces in everyday interactions, and the importance of accurate and rapid recognition of kin and romantic partners, as well as recognition of strangers and known enemies.

This thesis examines how rapid and accurate face recognition develops, by using two complementary approaches. One approach is to assess how children and adults differ in their abilities to process faces. A second approach is to examine the impact of short-term learning in a laboratory setting on face processing in children and adults. The two approaches allow an examination of how experience changes the visual system so that faces can be processed efficiently. In this introductory chapter, I will review characteristics of adult face processing, describe how they differ in children, and finally explain how the studies presented in this thesis address remaining questions about the development of expert face processing.

Adult mental representation of faces

A useful framework for understanding how adults represent faces mentally is the theory of face-space: the notion that faces are represented in a multi-dimensional space centered on the average face, and that individual facial identities are coded as vectors representing deviations from the average face or norm (e.g., Valentine, 1991). Within face-space, faces that are similar perceptually occupy similar locations (because they deviate from the norm in a similar way), and by definition, typical faces cluster around the origin whereas distinctive faces are dispersed around the periphery of face-space, farther from the origin (Valentine, 1991). This non-uniform spatial density gradient of face-space explains why adults are better able to recognize the identity of distinctive faces than typical faces: distinctive faces occupy an area with smaller spatial density, and hence are less likely to be confused with a neighbouring face and misidentified (Valentine, 1991). This postulated spatial layout of face-space is also consistent with observed caricature effects: caricatured faces (created by exaggerating individuating properties) are identified as easily or better than the veridical image of a person (and misidentified less often), presumably because caricaturing results in making the face more distinctive than the original face, and hence places it in a region of face-space with fewer confusable neighbours. Similarly, anti-caricatures (faces made to look more like the average face) are more difficult to recognize than the original face, presumably because they occupy a location closer to the dense centre of face-space (e.g., Blanz, O'Toole, Vetter, & Wild, 2000; Lee, Byatt, & Rhodes, 2000; Levin, 1996; Rhodes & Tremewan, 1994; Rhodes, Brennan, & Carey, 1987).

A key assumption of the face-space model is that it is centered on the average face or norm, and that individual faces are coded as deviations from the norm. Norm-based coding provides an efficient encoding strategy because it implies that specific exemplars need not be stored in memory, rather, just the average face (or prototype) and the deviations from it. Norm-based coding can also explain how the visual system can recognize the same individual under various viewing conditions that produce very different images of that person's face on the retina. For example, the image characteristics of a face will differ under varying lighting conditions and viewing angles, as well as when the person ages or changes hairstyles, make-up, facial expressions, etc. Norm-based coding results in generalization across different viewing conditions because averaging cancels out cues that are not useful for individual identification, leaving only the cues that are diagnostic properties that distinguishes that individual from the norm (Burton, Jenkins, Hancock, & White, 2005). The power of averaging was demonstrated by a recent study which used a commercialized computer algorithm that was trained to recognize famous faces (e.g., Bill Clinton). Recognition accuracy improved from 54% to 100% when it was tested with averaged images (e.g., the average of 20 images of Bill Clinton) of various celebrities rather than the original images (Jenkins & Burton, 2008).

Much of the evidence for norm-based coding of faces in humans comes from adaptation paradigms measuring aftereffects. For example, when adults are adapted to a face that is expanded horizontally, they perceive a subsequent face to be narrower than normal (e.g., Watson & Clifford, 2003; Webster & MacLin, 1999). Because the perception of the test face is distorted in the direction opposite to the distortion of the adapting face, the finding suggests a special role for the average face. The aftereffect presumably reflects a shift in the observer's cognitive representation of "the average" to look more like the adapting face (i.e., expanded), such that when a new face is encoded relative to this "expanded average", it appears narrow. Analogous aftereffects have been shown when adults make judgments about facial identity rather than normality. Given an identity such as Dan, an "opposite" face, called an anti-face, can be created by measuring the deviations of Dan's face from the average and producing the deviations in the opposite direction (e.g., if Dan has larger-than-average eyes, anti-Dan has smaller-than-average eyes). Adapting to anti-Dan makes the "cognitive average" (i.e., the mental representation of average) shift towards anti-Dan, such that the "physically average" face (i.e., a digitally morphed average) will look like Dan, an effect termed the identity aftereffect (e.g., Leopold, O'Toole, Vetter, & Blantz, 2001; Rhodes & Jeffery, 2006). The identity aftereffect is only seen for faces that lie on opposite sides of the average face (such as Dan and anti-Dan, but not for Jim and anti-Dan), a finding that supports the importance of the average face as a reference for the representation of individual facial identities (e.g., Leopold et al., 2001; Rhodes & Jeffery, 2006; for a review see Tsao & Freiwald, 2006).

Level of categorization

The theory of face-space was developed in order to explain how individual faces are represented in memory, because unlike other objects, faces are typically categorized at the individual or subordinate level of recognition (e.g., Bob vs. John), whereas other objects are typically categorized at the basic level of recognition (e.g., table vs. chair; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). The typical level at which objects are categorized is a marker of expertise, as dog and bird experts identify objects in their domain of expertise equally often at the basic and subordinate levels, whereas they are more likely to name objects outside of their domain of expertise at the basic level than the subordinate level of categorization (Tanaka & Taylor, 1991). Because adults typically identify faces at the individual level, and have many years of experience doing so, adults are arguably experts at face processing (e.g., Carey 1992; Gauthier & Tarr, 1997; Johnson & Mervis, 1997; Mason & Macrae, 2004; Schwaninger, Carbon, & Leder, 2003).

Adult face inversion effect

Another behavioral manifestation of adults' expert face processing is the inversion effect: a disruption of recognition accuracy when faces are inverted (e.g., Kanwisher, Tong, & Nakayama, 1998; Rhodes, Brake, Atkinson, 1993; Yovel & Kanwisher, 2004). The inversion effect is larger for faces than it is for other mono-oriented visual stimuli, such as airplanes and houses (e.g., Yin, 1969). Presumably, our biased visual diet of upright faces shapes the visual system so that it is hyper-sensitive to subtle differences among upright faces, but not inverted faces (e.g., Farah, Wilson, Drain, & Tanaka, 1998). Additionally, there is some evidence that experts with non-face categories, such as dog experts and handwriting experts, demonstrate an inversion effect with their objects of expertise that novices do not (e.g., Bruyer & Crispeels, 1992; Diamond & Carey, 1986; but see Robbins & McKone, 2007, for a more recent demonstration of a lack of inversion effect in dog experts). These findings suggest that if given sufficient experience in differentiating among individual items in any particular object category, observers may process them in a manner similar to how typical adults process faces, a finding that emphasizes the importance of experience in shaping expert object processing.

Adult configural processing

An important characteristic of faces as an object category is that faces are perceptually very similar, with all faces sharing the same structure of having two eyes above a nose above a mouth in an oval contour. Therefore, to discriminate individual faces, observers must rely on subtle differences among faces, such as the shape and configuration of the internal facial features (e.g., Bartlett, Searcy, & Abdi, 2003; Rhodes, Hayward, & Winkler, 2006; Tanaka & Farah, 1993; Sekuler, Gaspar, Gold, & Bennett, 2004). Features refer to separable local elements that are perceived as distinct parts of the face, such as the eyes, mouth, nose, or chin (e.g., Carey & Diamond, 1977; Sergent, 1984). The spatial interrelationship of such facial features is referred to as configural information (e.g., Bruce, 1988). Configural processing of faces can be broken down further into at least three different types of processing: 1) processing first-order relations (structural properties shared by all faces), 2) holistic processing (gluing together the features to form an unparsed gestalt or whole percept), and 3) processing of second-order relations, which refer to the metric differences in the spatial relations among features, such as the spacing between two eyes (e.g., Carey, 1992; Maurer, Le Grand, & Mondloch, 2002).

Inversion disrupts processing of configural information more than featural information (e.g., Collishaw & Hole, 2002; Leder & Carbon, 2006; Leder, Candrian, Huber, & Bruce, 2001; Rhodes et al., 1993), although the processing of featural information is also disrupted by inversion (Rhodes, Hayward, & Winkler, 2006; Riesenhuber, Jarudi, Gilad, & Sinha, 2004; Sekuler et al., 2004; Yovel & Kanwisher, 2004). Collishaw & Hole (2000) manipulated photographs of faces by two methods: blurring, which preserves the second-order relations of the original face but degrades featural information, and scrambling, which preserves featural information but disrupts configural information (holistic processing, first-order and second-order relations). When adults were shown manipulated images of celebrities or unfamiliar faces that they had learned prior to the test phase, they could identify blurred faces as well as scrambled faces when the faces were shown upright, but inversion impaired recognition only for the blurred faces, a result indicating that adults' sensitivity to second-order relations is tuned to upright faces. Furthermore, blurring and scrambling a face simultaneously had an additive effect and impaired recognition more than the effect of either manipulation alone, a pattern suggesting that blurring and scrambling disrupt two separate but complementary sources of information.

Holistic processing of upright faces is inferred from the fact that face parts are better recognized in the context of the whole face than when they are presented in isolation (e.g., Farah et al., 1998; Rhodes et al., 1993; Tarr & Cheng, 2003; Tanaka & Farah, 1993; Tanaka & Sengco, 1997; Yovel, Paller, & Levy, 2005). Furthermore, recognition accuracy is higher if the parts are shown in the original configuration than if they are shown in a changed configuration (e.g., Barton, Zhao, & Keenan, 2003; Sergent, 1984). This whole/part advantage is not demonstrated when observers are processing inverted or scrambled faces, or non-face objects such as houses (e.g., Farah et al., 1998; Tanaka & Farah, 1993).

Another demonstration of holistic processing is the composite face effect: when composite photographs are created by fusing together top and bottom halves of different faces, it is harder for observers to recognize one half of the face (just the top half or just the bottom half) when the halves are aligned (i.e., the face appears intact) than when they are horizontally misaligned (Young, Hellawell, & Hay, 1987). The effect is assumed to arise from the creation of a holistic percept by the novel configuration that interferes with attempts to identify just one half of the face. The composite effect disappears when faces are inverted, a result suggesting that holistic processing of faces is tuned to upright faces. Because we rarely encounter situations in which inverted faces must be recognized, the finding that adults do not process inverted faces holistically suggests that holistic processing develops from experience individuating upright faces (see also Hole, 1994). There is indirect evidence that protracted experience may be required for holistic processing: the composite effect has not been shown convincingly with objects of expertise other than faces (Robbins & McKone, 2007), possibly because even experts (e.g., dog experts) do not have sufficient and/or the necessary experience with their objects of expertise to develop holistic processing. The role of early visual experience in developing expert object processing is discussed in a later section.

The composite face effect and the part/whole effect suggest that faces are not processed as a collection of separable individual features, but these paradigms are not specific tests of sensitivity to the second-order relations of face. Haig (1984) demonstrated adults' remarkable sensitivity to second-order relations of faces by displacing slightly the eyes, nose, or mouth in a set of face images. He found that adults are highly sensitive to such feature displacements, such that they detect an upward shift of the mouth as small as 1 minute of visual angle, very close to the acuity limit. However, adults' sensitivity to second-order relations is disrupted when faces are inverted (e.g., Bartlett & Searcy, 1993; Collishaw & Hole, 2000; Freire, Lee, & Symons, 2000; Leder & Bruce, 1998, 2000; Leder & Carbon, 2006; Leder, Candrian, Huber, & Bruce, 2001; Malcolm, Leung, &

Barton, 2005; Mondloch, Le Grand, & Maurer, 2002; Schwaninger & Mast, 1999; Searcy & Bartlett, 1996; Sergent, 1984), a finding that suggests that sensitivity to second-order relations is tuned to upright faces and modulated by visual experience. Further evidence of experience shaping sensitivity to second-order relations is the finding that adults are better at detecting changes in second-order relations in human faces than monkey faces (Mondloch, Maurer, & Ahola, 2006b).

Neural mechanisms underlying adult face recognition

Functional magnetic resonance imaging (fMRI) has revealed a network of areas that are particularly active when adults are processing face stimuli. One small area in the fusiform gyrus, termed the fusiform face area (FFA), has received particular attention (Kanwisher, McDermott, & Chun, 1997; Kanwisher, 2000). Typically, FFA activation is greater in the right hemisphere than the left hemisphere (e.g., Kanwisher et al., 1997), and greater for upright than inverted faces (Kanwisher et al., 1998). FFA activity appears to be correlated with the detection of a face, because adults can detect a face whether a face is presented upright or inverted, and FFA activity is robust for both orientations. However, when presented with two-tone Mooney faces, adults perceive the stimulus as a face only when it is presented upright, and the FFA shows correspondingly greater FFA activity in upright than inverted blocks (Kanwisher et al., 1998). Additionally, individuals with congenital prosopagnosia (CP), an impairment in face recognition but not face detection, demonstrate FFA activation in response to faces (Avidan, Hasson, Malach, & Behrmann, 2005). FFA activity does not appear to be correlated with the low-level properties associated with the retinal image of a face, but rather, to the conscious perception of a face. In a binocular rivalry paradigm, in which a photo of a face and a house were presented independently to each eye, adults' conscious perception shifted back and forth between a face and a house (Tong, Nakayama, Vaughan, & Kanwisher, 1998). fMRI results revealed that FFA activity corresponded to the conscious perception of the face, such that activity increased when adults reported perceiving a face, and decreased when adults reported perceiving a house (Tong et al., 1998).

Although early neuroimaging studies implicated the FFA as the locus of face processing, we do not yet have a clear understanding of the role of the FFA in face processing beyond face detection (for a recent review see Peissig & Tarr, 2007). Increased familiarity appears to induce larger FFA activation only when familiarity is examined categorically (e.g., own-race vs. other-race faces; Golby, Gabrieli, Chiao, & Eberhardt, 2001). Repeatedly presenting the same individual face (thereby increasing the familiarity of a single face) leads to adaptation of the fMRI signal in the FFA: activation in the FFA is smaller in blocks when the same face is repeated than in blocks in which different faces are presented sequentially (e.g., Grill-Spector, Kushnir, Edelman, Avidan, Itzchak, & Malach, 1999; Loffler et al., 2005), although there is conflicting evidence about whether fMRI adaptation occurs when the face of the same person is presented from different viewpoints (Andrews & Ewbank, 2004; Grill-Spector & Malach, 2001).

When the specificity of FFA activation is tested rigorously, the FFA also responds to non-face objects of expertise. Gauthier and colleagues (1999) created an artificial object category called 'greebles', with varying levels of similarity between items that allowed trained observers to categorize them at the basic level of categorization (referred to as the greeble "family") and at the individual level. After adults were trained to be greeble experts (i.e., to be equally fast at individual- and basic-level identification), they showed FFA activation when viewing greebles, whereas novices did not. Additionally, car experts showed greater FFA activation when viewing cars than birds, whereas bird experts showed greater FFA activation when viewing birds than cars (Gauthier, Skudlarski, Gore, & Anderson, 2000; but see also Rhodes, Byatt, Michie, & Puce, 2004, for lack of face-like FFA activation in Lepidoptera experts when processing images of Lepidoptera). These findings again suggest that specialized mechanisms can result from experience with any object category with which observers have specialized knowledge.

Although the above studies reveal that the FFA does not respond exclusively to faces, Kanwisher (2000) argues that the neural mechanisms that are optimized for face processing can also be involved in non-face object processing. For example, greebles have two horizontally displaced parts arranged symmetrically above two vertically displaced parts, making them face-like. They were also labeled with proper names, which may have further encouraged face-like interpretations. It is not surprising, then, that the visual system recruits processes optimized for face processing to process the face-like greebles. Additionally, it is important to note that although previous studies reported FFA activation in response to non-face objects of expertise, it was still the case that FFA activation was strongest when viewing faces, even in greeble experts (Gauthier et al., 1999; Gauthier et al., 2000). When FFA activation was examined on a trial-by-trial basis, unlike the block-design of previous studies, FFA activation was correlated with behavioral performance in detecting and identifying specific faces, but not correlated with within-category identification performance of non-face objects, including car experts detecting and identifying cars (Grill-Spector, Knouf, & Kanwisher, 2004). Some of the discrepancies in studies examining the specificity of FFA activation may be due to use of different baseline comparisons (e.g., faces relative to scrambled images, non-face objects, patterns, etc.), different tasks during scanning (passive viewing, 1-back recognition, target identification, gender classification, etc.), and/or different observers. For example, even in the seminal paper by Kanwisher and colleagues (1997) that first reported face-selective activation in the FFA, only 12 out of 15 subjects demonstrated greater activation in the fusiform gyrus in response to faces than non-face objects.

Given the controversy regarding the exact nature of the information coded by the FFA, more recent neuroimaging studies have focused on the large distributed network of face processing mechanisms that overlap with areas involved in non-face object processing, of which the FFA represents a particularly specialized area. Haxby and colleagues (2001) found that patterns of fMRI activation in the ventral temporal cortex while viewing faces and other objects (e.g., houses, cats, chairs) were correlated with the object category being viewed, such that the activation pattern could distinguish which object category was being viewed. However, activation was widely distributed such that no specific area could be singled out as the locus of representation for each object category. There was much overlap in the activation patterns for the different object categories, such that even areas that did not respond maximally to a given object category played an integral role in forming the pattern of activity that predicted the category being viewed by the observers. This pattern of distributed and overlapping activity has been confirmed in subsequent studies (e.g., Cox & Savoy, 2003; Spiridon & Kanwisher, 2002). Additionally, a recent study utilizing fMRI and diffusion tensor imaging technology has revealed that patients with congenital prosopagnosia demonstrate fewer white matter tracts passing through the fusiform gyrus and connecting posterior visual areas to anterior frontal regions of the cortex than matched control adults, a finding that suggests the importance of a distributed network in face recognition (Thomas, Avidan, Humphreys, Jung, & Behrman, manuscript under review).

Other areas besides the FFA that are implicated in adult face processing include face-selective regions in inferior frontal gyrus (e.g., Henson et al., 2003), ventral frontal lobe (e.g., Rotshtein, Henson, Treves, Driver, & Dolan, 2005), right inferior parietal lobe (e.g., Maurer et al., 2007), anterior inferotemporal cortex (Kriegeskorte, Formisano, Sorger, & Goebel, 2007), the right posterior superior temporal sulcus (e.g., Yovel & Kanwisher, 2005; Chao, Martin, & Haxby, 1999), and the occipital face area (OFA), an area located in the inferior occipital area that falls within the larger lateral occipital complex that is important for general object processing (Gauthier et al., 2000). Interestingly, a patient with acquired prosopagnosia showed normal FFA activation but a lack of OFA activation when viewing faces (Steeves et al., 2006). Such a finding suggests that the OFA may play a role in individual face recognition. Although neuropsychological research is useful in revealing what areas are associated with impairments in psychological functions, however, there is no clear evidence that the OFA encodes individual face identity in normal adults. One contrary finding is that the OFA, unlike the FFA, does not respond differently to upright and inverted faces in adults, and its activity is not positively correlated with adults' behavioral inversion effect (Yovel & Kanwisher, 2005). Although an increasing number of studies utilize fMRI to examine the neural mechanisms underlying face processing, it is important to note that face-selective fMRI responses provide only indirect evidence of face processing, because the blood oxygen level-dependent (BOLD) signal is sluggish, and stronger signals may reflect feedback mechanisms from other areas rather than the neural computation underlying recognition of facial identity (Cohen, Noll, & Schneider, 1993; Huettel, Song, & McCarthy, 2004; Maurer et al., 2007).

Converging evidence for specialized neural mechanisms for face processing is provided by face-specific responses measured by event-related potentials (ERPs) using electroencephalography. ERP studies have revealed a negative component, the N170, that peaks roughly 165 ms after a face is presented to the observer (e.g., Sagiv & Bentin, 2001). The N170 is triggered as strongly and quickly by line drawings of faces as photographs, and is also elicited by ape faces (Carmel & Bentin, 2002), a finding that suggests that the N170 represents face detection rather than individual-level face discrimination. This conclusion is supported by the finding that a later positive component, the P300, is sensitive to task-relevant information in a face (e.g., the mouth for smile detection), whereas the N170 is similar when adults make different judgements about a face, such as gender discrimination versus smile detection (Sagiv & Bentin, 2001; Smith, Gosselin, & Schyns, 2004). The N170 may be a marker of expertise, as dog experts show a greater N170 in response to viewing dogs than birds, and bird experts show a greater N170 in response to viewing birds than dogs (Tanaka & Curran, 2001). However, the topography of the N170 to objects of expertise is not identical to that for faces (Tanaka & Curran, 2001), a difference suggesting that different neural substrates underlie the N170 response for different stimulus categories.

The role of experience: The other-race effect

Even within the object class of faces, the visual system appears to be best tuned to the faces that adults typically process in the environment – upright faces of their own race. The other-race effect generally refers to better recognition of the identity of own-race faces than other-race faces (Brigham, Mass, Snyder, & Spaulding, 1982; Meissner & Brigham, 2001; Platz & Hosch, 1988). The other-race effect shown by adults also includes better ability to make perceptual discriminations between own-race faces than between other-race faces (Byatt & Rhodes, 2004; Walker & Tanaka, 2003). Adults demonstrate a larger inversion effect, (Rhodes, Tan, Brake, & Taylor, 1989; Sangrigoli & de Schonen, 2004), more holistic processing (Michel, Caldara, & Rossion, 2006; Tanaka, Kiefer, & Bukach, 2004), and greater sensitivity to changes in feature shape and second-order relations (Rhodes et al., 2006), in own-race faces than other-race faces. Furthermore, the FFA shows higher activation in response to own-race faces than other-race faces (Golby et al., 2001). The other-race effect also fits the predictions from the theory of face-space because encoding an other-race face as a deviation from the own-race average may not capture the appropriate individuating properties of that face (Chiroro & Valentine, 1995; Furl, Phillips, & O'Toole, 2002; Goldstone, 2003; Meissner & Brigham, 2001). Additionally, the other-race effect appears to be mediated by the amount of experience with the other race. For example, when black and white adults were tested on their ability to recognize black and white faces, adults who had a high degree of contact with the other race showed smaller other-race effects than those who had little or no contact with the other race (Chiroro & Valentine, 1995). This finding is also predicted by face-space theory, because with greater experience adults may have sufficient exemplars to form separate face-spaces for the different races (i.e., individual faces will be coded relative to the appropriate race average), rather than attempting to code all faces relative to the own-race average.

The role of experience: Visual exposure during infancy

Experience with faces starts very early in life, as newborns preferentially orient towards visual stimuli with a face-like structure (e.g., Johnson, Dziurawiec, Ellis, & Morton, 1991; de Haan, Humphreys, & Johnson, 2002; Simion, Valenza, Umilta, & Barba, 1998). Recent research has revealed that this innate bias appears to orient newborns to bounded visual stimuli with more energy in the top half, rather than faces per se (Cassia, Turati, & Simion, 2004), although there may also be a special role for direct eye gaze in capturing newborns' interest (e.g., Farroni, Menon, & Johnson, 2006). Whatever the critical characteristics, this innate bias, along with interactions with caregivers, results in newborns being exposed more to faces than to any other object category. Visual exposure appears to shape the visual system very rapidly, because already by two days of age, infants can reliably discriminate their mothers' face from strangers' faces (Bushnell, Sai, & Mullin, 1989). By 3 months of age, infants appear to have the ability to form prototypes, because after familiarization to four individual faces they showed evidence of recognizing the computer-generated average of the four learned faces as well as the individual faces (de Haan, Johnson, Maurer, & Perrett, 2001). However, caution is required in interpreting this finding as evidence of efficient norm-based coding in infancy, because the ability to recognize and discriminate unfamiliar faces rapidly and accurately continues to improve with age throughout childhood and into adolescence (e.g., Bruce, Campbell, Doherty-Sneddon, Import, Langton, McAuley, & Wright, 2000; Carey, Diamond, & Woods, 1980; Ellis, 1992).

Visual experience during infancy appears to be particularly important for normal development of face processing skills. Maurer and colleagues have tested face processing in patients who were born with cataracts in both eyes that blocked all patterned visual input, until the cataracts were removed through surgery and the infants were given a compensatory optical correction. As adults, these patients do not demonstrate holistic processing of faces, because they do not demonstrate the typical composite effect (Le Grand, Mondloch, Maurer, & Brent, 2004), and they do not show normal sensitivity to second-order relations (Le Grand, Mondloch, Maurer, & Brent, 2001). These results suggest that visual exposure to faces early in life may be necessary for the later development of some expert face processing mechanisms. However, a recent study of monkeys who were able to discriminate faces based on second-order relations after growing up in a rich visual environment but with no exposure to faces for 6-24 months, suggests that visual experience (i.e., patterned visual input) is crucial, not visual exposure to faces per se (Sugita, 2008).

In normal development, how the visual diet of faces that infants are exposed to shapes face processing is observed already in infancy. Six-month-old infants have the ability to discriminate monkey faces and human faces alike, whereas 9-month-olds and adults demonstrate an own-species effect, showing better discrimination of human faces than monkey faces (Pascalis, de Haan, & Nelson, 2002). Even within human faces, already by 3 months of age, infants prefer to look at faces from their own race more than faces of another race, but only if they live in a predominantly single-race environment (Bar-Haim, Ziv, Lamy, & Hodes, 2006; Kelly et al., 2005; Kelly, Liu, et al., 2007), and demonstrate better discrimination of morphed faces that resemble their own race more strongly than another race (Hayden, Bhatt, Joseph, & Tanaka, 2007). Preference for own-race faces is not demonstrated by newborns (Kelly et al., 2005), and although 3-month-olds show equal recognition of own-race and other-race faces, 9-month-olds show evidence of recognition only for own-race faces (Kelly, Quinn, Slater, Lee, Ge, & Pascalis, 2007). Interestingly, the own-race bias is also dependent on visual experience beyond infancy, as Korean adults, who had been adopted into French families before 9 years of age, demonstrate better discrimination of Caucasian than Asian faces, much like the French control adults (Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005). Combined, the data demonstrate that infants are sensitive to the type of faces they encounter most often in their environment as shown by the other-race effect, but that the effect is malleable based on later experience, at least up to 9 years of age. The process of specialization is well-illustrated by the study of face-deprived monkeys mentioned earlier (Sugita, 2008). Following the deprivation period, the monkeys were housed alone for a 1-month period during which time they were exposed to either human or monkey faces only. At the end of one month, when they were shown pairs of faces comprised of one human face and one monkey face, they looked longer at faces from the species to which they had been exposed. Furthermore, monkeys exposed to human faces were able to recognize individual human faces, but not individual monkey faces; monkeys exposed to monkey faces were able to recognize individual monkey faces, but not individual human faces. These visual preferences and differential recognition abilities were maintained even after 1 year of being exposed to both human and monkey faces, a finding demonstrating the importance of early visual experience and its effects on face processing abilities.

Childhood development of face processing

Many of the characteristics of adult face processing described earlier in the chapter have also been examined in children, to understand the development of face processing. Although infants as young as 4 -7 months of age demonstrate differential processing of upright and inverted faces, at least under some conditions (e.g., Cohen & Cashon, 2001; Hayden, Bhatt, Reed, Corbly, & Joseph, 2007; Thompson, Madrid, Westbrook, & Johnston, 2001; Turati, Sangrigoli, Ruel, & de Schonen, 2004), even children as old as 4-6 years of age do not demonstrate adult-like inversion effects for recognizing facial identity, either in accuracy or reaction times (e.g., Brace et al., 2001; Carey & Diamond, 1977; Mondloch et al., 2002). Some aspects of configural processing appear to develop relatively early. Thus, holistic processing of faces has been demonstrated in children as young as

4-6 years of age with both the part/whole paradigm (Tanaka, Giles, Kremen, & Simon,1998; Pellicano & Rhodes, 2003; Pellicano, Rhodes, & Peters, 2006) and the composite face effect (Carey & Diamond, 1994; deHeering, Houthuys, & Rossion, 2007; Mondloch, Pathman, LeGrand, de Schonen, & Maurer, 2007).

Indirect measures provide evidence of early sensitivity to second-order relations. Five-month-olds demonstrate recovery from habituation when the second-order relations of a face are changed, if the changes are large (Bhatt, Bertin, Hayden, & Reed, 2005; Hayden et al., 2007), and 7-month-olds prefer to look at faces that have an average eye-to-mouth distance more than the lengthened or shortened versions of the same face (Thompson et al., 2001). Another measure of sensitivity to second-order relations is to test the recognition of individual features in the context of the original facial configuration or in a face in which the second-order relations have been changed (e.g., find Luke's mouth in Luke's original face or in Luke's face with eyes shifted further apart). With this paradigm, children as young as 4 years of age demonstrate sensitivity to second-order relations, and the magnitude of the effect is as large as in adults, at least when the changes are large (Mondloch & Thomson, in press; Pellicano et al., 2006). Four-year-olds also display sensitivity to second-order relations when questioned about the distinctiveness of the face (McKone & Boyer, 2006). However, if the changes are smaller and within the range that is likely to be encountered in everyday life (Farkas, 1981), 4-year-olds fail to perceive changes in second-order relations in their own face, their friends' faces, or in children's faces learned from a storybook (Mondloch & Thomson, in press; Mondloch, Leis, & Maurer, 2006), and even older children continue to be less accurate than adults up to 14 years of age (Mondloch, Geldart, Maurer, & Le Grand, 2003).

Examination of the underlying neural mechanisms of childhood face processing reveals that adult-like FFA activation takes many years to develop. Several fMRI studies have reported no evidence of face-specific FFA activation in children under the age of 9 years, with the first signs of face-specific FFA activity emerging around 11-14 years of age (e.g., Aylward et al., 2005; Gathers et al., 2004; Passarotti et al., 2001, 2003; Scherf et al., 2007). However, a more recent study that accounted for developmental differences in total BOLD activation (e.g., fluctuations in BOLD activations during baseline in children vs. adults) has shown face-specific FFA activation in children as young as 7-11 years of age, although the face-selective areas are much smaller in children and adolescents than in adults (Golari et al., 2007). Similarly, developmental examination of face-related ERP responses reveals face-specific responses even in infancy, although the topography, magnitude, and latency of the response continue to change throughout infancy, childhood, and even into adolescence (e.g., de Haan, Pascalis, & Johnson, 2002; Halit, de Haan, & Johnson, 2003; Itier & Taylor, 2004).

Although the studies described above indicate specific improvements in face processing with age, both behaviorally and in terms of underlying neural mechanisms, it is important to note that general cognitive factors, such as attention and memory, all improve considerably during childhood (e.g., Sophian & Stigler, 1981) and may contribute to the better face processing (Carey, 1992; Gilchrist & McKone, 2003; Want, Pascalis, Coleman, & Blades, 2003) as well as processing of non-face objects (e.g., Thompson & Markson, 1998). For example, like adults, 8-year-olds are better at detecting changes in second-order relations in human faces than monkey faces, and furthermore, the difference in recognition accuracy between human and monkey faces is of equal magnitude in 8-year-olds and adults (Mondloch, Ahola, & Maurer, 2006). Between age 8 years and adulthood, sensitivity to second-order relations improves equally for human and monkey faces, a finding that suggests that improvement after 8 years of age reflects improvement in general perceptual sensitivity to spacing information and not increased experience individuating faces per se. General improvement in sensitivity to second-order relations beyond 8 years of age is further supported by a recent finding that 8-year-olds' immaturity in discriminating changes in house stimuli is larger for spacing changes than changes in feature shapes, a pattern paralleling that for faces (Robbins, Shergill, Maurer, & Lewis, 2007). However, different developmental trajectories for different aspects of face processing, such as sensitivity to internal feature shapes, external contour shapes, and the spacing of internal facial features (e.g., Freire, Lee, & Symons, 1999; Mondloch et al., 2002), suggest that general improvements in processing capacities cannot account fully for the improvement in face processing observed with age.

<u>Present studies</u>

The present collection of studies examines face processing and how it develops. They do so by examining (1) the nature of developmental changes, by comparing children's and adults' face processing, and (2) the role of short-term experience on children and adults, by comparing performance before and after training in a laboratory setting. Perceptual learning studies that train adults to improve their perceptual discrimination abilities have revealed that short-term experience (i.e., several days) can modify how the visual system processes objects, including faces (e.g., Fine & Jacobs, 2002; Gold, Bennett, & Sekuler, 1999; Kourtzi & DiCarlo, 2006; Rainer & Miller, 2000), and have provided useful insights as to how a specialized system may arise through experience (e.g., Behrmann, Marotta, Gauthier, Tarr, & McKeeff, 2005; De Gutis, Bentin, Robertson, & D'Esposito, 2007; Freedman, Riesenhuber, Poggio, & Miller, 2006; Sigala & Logothetis, 2002).

The study described in Chapter 2 examined how children's face-space differs from that of adults at an age when many aspects of face processing are known to be immature. A key feature of face-space is that faces are encoded as deviations relative to the average face or norm. In order to examine whether children demonstrate norm-based coding, I examined the strength of 8-year-olds' identity aftereffect relative to that of adults. The results from Chapter 2 showed that 8-year-olds demonstrate an identity aftereffect of similar magnitude to that of adults, indicative of norm-based coding. Thus, by 8 years of age, children appear to code faces relative to the average face in a manner similar to how adults encode faces. This study was the first to demonstrate an identity aftereffect in children, and to provide evidence that children utilize norm-based coding of facial identity.

To compare the dimensions of face-space between children and adults, in Chapter 3, I used multi-dimensional scaling to represent spatially the perceived similarity among a set of faces as judged by children and adults. The original face-space model did not specify what the dimensions of face-space represent; rather, it stated only that the dimensions represent cues that are important for individual identification (e.g., Rhodes et al., 1987; Valentine, 1991). Specifying the dimensions of face-space is difficult, in part, because adults may not be consciously aware of how they make judgments about faces. For example, the verbal overshadowing effect refers to the fact that the recognition of facial identity is worse after giving a verbal description of the face to-be-remembered (Schooler & Engstler-Schooler, 1990). Furthermore, this effect has been found with own-race faces but not with other-race faces, inverted faces, or with non-face objects such as cars, a pattern which suggests that verbalization disrupts expert perceptual processing (Fallshore & Schooler, 1995; Westerman & Larsen, 1997). Therefore, asking observers to verbalize how they are making similarity judgments of faces may not provide an accurate representation of the dimensions of face-space. A useful statistical tool for exploratory analysis is multi-dimensional scaling (MDS), which requires observers to judge the similarity of faces without specifying how they are making such judgments. The pattern of findings in Chapter 3 revealed some immaturities in 8-year-olds' responses, such as higher variability than adults in the similarity judgments, both within and across individuals, and a greater frequency of children who relied heavily on a single dimension rather than multiple dimensions when making similarity judgments. Nonetheless, the MDS solutions from adults and 8-year-olds were similar in how groups of faces clustered together locally, a finding that suggests some similarities in the face-space of 8-year-olds and adults.

Because children learn to recognize faces in everyday contexts where all cues to identity are available, in Chapters 2 and 3, I examined how children differ from adults when multiple cues to identity are available. The complementary approach is to isolate a specific cue to identity, such as second-order relations, and examine how sensitivity to this cue is modified by experience. To simulate the real-world learning of faces, but in a context that would encourage processing second-order relations, in the study described in Chapter 4, I trained 10-year-olds and adults to recognize unfamiliar faces from different viewpoints. Although children and adults use various cues to facial identity, a distinctive feature, like a mole on the left cheek, is not visible from all viewpoints. However, second-order relations are a structural property of the face that changes with viewpoint in predictable ways, making them a potentially useful cue to support view-independent face recognition. Perhaps then with increasing experience processing faces under varying viewing conditions, including changes in viewpoint, observers become more sensitive to the useful cue of second-order relations rather than relying on salient featural cues that may not always be present. The study in

Chapter 4 examined this hypothesis directly by training children and adults to recognize faces from different viewpoints, and testing their sensitivity to second-order relations before and after training. Both 10-year-olds and adults showed improvement in the ability to recognize faces across changes in viewpoint, but this improvement did not transfer to improved sensitivity to second-order relations in either age group.

The study reported in Chapter 5 also examined the effect of training on sensitivity to second-order relations, but specifically tested the role of level of categorization. Gauthier and Tarr (1997) found that greeble experts were faster at identifying greeble parts if they were presented in the original learned configuration than if they were shown in a transformed configuration (e.g., moving two non-target parts down). This effect was not found in novices, a difference indicating that expertise with greebles had produced greater sensitivity to second-order relations. Gauthier and Tarr argued that it is expertise with a visually homogenous object category, gained through the experience of identifying objects at the individual level, which produces configural sensitivity. However, Gauthier and Tarr (1997) did not measure directly sensitivity to second-order relations before and after training; rather, sensitivity to changes in second-order relations was inferred from the slower response time shown by experts in identifying a greeble part when the second-order relations of the non-target parts had been altered. The goal of the study described in Chapter 5 was to examine whether sensitivity to changes in second-order relations differed before and after training to recognize novel objects at the individual versus basic level. The results suggested that indeed individual-level recognition is particularly important for the development of sensitivity to second-order relations.

The collection of studies reported in this thesis provide new insights into how face processing develops. Specifically, it focuses on how children's face-space differs from that of adults at an age when sensitivity to second-order relations is not yet adult-like, and how sensitivity to second-order relations is influenced by short-term experience. The implications and limitations of the findings, as well as suggestions for future research, are presented in the Discussion.

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Chapter 2

Preface

The study described in this chapter is a manuscript accepted for publication in *Developmental Science*, and has been reproduced in this thesis with permission granted by Jennie Brown, Editorial Manager of *Developmental Science*, and by Blackwell Publishing.

The study examined the development of face recognition by comparing how facial identity is represented mentally in children and adults. The face-space model (Valentine, 1991) has been useful in describing adults' mental representation of faces, however, very little research has examined the nature of children's face-space. One key assumption of the face-space model is that individual faces are encoded as deviations from the average or norm. Evidence of norm-based coding has been shown in adults through the identity aftereffect: a shift in the perceived identity of a face in the direction opposite to the adapting face. The present study tested whether 8-year-olds, an age when children are not yet adult-like on all aspects of face processing, demonstrate an identity aftereffect. The results showed strong evidence of identity aftereffects in 8-year-olds, and moreover, that the magnitude of the identity aftereffect was similar in children and adults. This pattern of findings suggests that the basic coding mechanisms of facial identity are already adult-like by 8 years of age, and that behavioral immaturities on some face processing tasks reported previously for this age group likely stem from other sources.

Running Head: 8-YEAR-OLDS' NORM-BASED CODING OF FACIAL IDENTITY

Fitting the child's mind to the world: Adaptive norm-based coding of facial identity in 8-year-olds

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Abstract

In adults, facial identity is coded by opponent processes relative to an average face or norm, as evidenced by the face identity aftereffect: adapting to a face biases perception towards the opposite identity, so that a previously neutral face (e.g., the average) resembles the identity of the computationally opposite face. We investigated whether children as young as 8 use adaptive norm-based coding to represent faces, a question of interest because 8-year-olds are less accurate than adults at recognizing faces and do not show the adult neural markers of face expertise. We found comparable face identity aftereffects in 8-year-olds and adults: perception of identity in both groups shifted in the direction predicted by norm-based coding. This finding suggests that, by 8 years of age, the adaptive computational mechanisms used to code facial identity are like those of adults and hence that children's immaturities in face processing arise from another source.

Several lines of evidence suggest that adults represent faces in a multi-dimensional face-space centered on an average face or norm (Rhodes, Brennan, & Carey, 1987; Rhodes, Jeffery, Watson, Clifford, & Nakayama, 2003; Valentine, 1991). According to this framework, each individual face is represented by a unique multi-dimensional vector from the norm, with the dimensions of face-space representing information that is critical for face identification. Exaggeration of the difference between an individual face and an average face creates a caricature that is easier to recognize than the original face, as would be expected if identity is represented as a deviation from the norm (Rhodes et al., 1987).

Norm-based coding of facial identity has recently been demonstrated in adults using adaptation paradigms: adapting (exposure) to a face for several seconds biases perception of a subsequent face, so that an average face, seen correctly as having no particular identity before adaptation, begins to resemble the computationally opposite identity (Leopold, O'Toole, Vetter, & Blanz, 2001). For example, if Dan has a larger-than-average forehead and a smaller-than-average mouth (among other differences from average), adapting to a face computationally opposite to Dan (e.g., a face with a small forehead and a large mouth) causes an average to look more like Dan (see Figure 1).

Neuroimaging studies also support norm-based coding of facial identity. Activation in the fusiform face area (FFA), an area in the fusiform gyrus that responds selectively to face stimuli (Kanwisher, McDermott, Chun, 1997), decreases with multiple presentations of faces that vary along a single identity vector relative to the average face (e.g., faces that have an increasingly broad chin or an increasingly thin nose), but does not decrease with multiple presentations of faces that are equidistant from the mean but fall on different identity vectors (Loffler, Yourganov, Wilkinson, & Wilson, 2005). Consistent with these findings, recent electrophysiological findings from nonhuman primates also provide evidence of norm-based coding of faces. Individual face-responsive neurons in the monkey anterior infero-temporal cortex respond to deviations from the average, with systematic increases in firing as faces are moved along identity vectors away from the average face (i.e., with increasing identity strength; Leopold, Bondar, & Giese, 2006).

To date, no study has examined the face identity aftereffect in children, even though developmental differences in the use of adaptive face coding mechanisms could potentially account for children's immature face recognition skills. In the present study, we examined whether 8-year-old children demonstrate adaptive coding of facial identity, consistent with norm-based coding. By age 8, acuity, contrast sensitivity, and many aspects of higher-order vision are adult-like (Ellemberg, Lewis, Liu, & Maurer, 1999; Mayer & Dobson, 1982; Parrish, Giaschi, Boden, & Dougherty, 2005), and children perform (nearly) as well as adults on some measures of face processing, such as holistic processing (Carey & Diamond, 1994; de Heering, Houthuys, & Rossion, 2007; Mondloch, Pathman, Maurer, Le Grand, & de Schonen, in press; Pellicano & Rhodes, 2003; Tanaka, Kay, Grinnell, Stansfield, & Szechter, 1998) and recognizing faces based on changes in feature shape or external contour (e.g., Mondloch, Le Grand, & Maurer, 2002). However, they are much worse than adults at recognizing facial identity across changes in point of view or based on the spatial relations of facial features, such as the distance between the two eyes (Mondloch, Geldart, Maurer, & Le Grand, 2003; Mondloch et al., 2003; but see also Gilchrist & McKone, 2003, and Pellicano, Rhodes, & Peters, 2006). Their immaturity in processing the spatial relations of features is evident even when memory demands are eliminated, as well as when the salience of feature cues is reduced (Mondloch, Dobson, Parson, & Maurer, 2004).

Neurological evidence also reveals significant changes in face processing after age 8. Two studies reported no evidence in 8-year-olds of selective activation in the right anterior fusiform gyrus, or the classic FFA (Aylward et al., 2005; Gathers, Bhatt, Corbly, Farley, & Joseph, 2004), with the earliest face-selective activation in the FFA evident at age 9-11 (Gathers et al., 2004) or 12-14 years (Aylward et al., 2005). Other studies documented changes in the distribution of face-selective areas beyond 12 years of age (Passarotti, Paul, & Stiles, 2001; Passarotti, Paul, Bussiere, Buxton, Wong, & Stiles, 2003). A more recent study, carefully taking into account age-related differences in BOLD signals that index neural activity, revealed that children aged 7-11 years do demonstrate face-selective right FFA activation, although this face-selective area was significantly smaller than in adults until 12-16 years of age (Golari et al., 2007). Similarly, the responsiveness of the face-selective negative event-related potential (ERP) component N170 (Bentin, Allison, Puce, Perez, & McCarthy, 1996) to different types of facial stimuli (e.g., inverted vs. upright faces) changes with age from 8 years to adolescence (Itier & Taylor, 2004). Therefore, given such immaturities in children's face processing, a natural question arises as to whether 8-year-olds demonstrate facial identity aftereffects, which are indicative of norm-based coding.

In order to test for adaptive face coding in children, it was necessary to modify previous paradigms that have been used with adults (e.g., Leopold et al., 2001; Rhodes & Jeffery, 2006) to be more child-friendly and appropriate for testing 8-year-olds. We developed a cover story involving a team of brothers who look similar to each other and who are competing against another team of brothers. To facilitate children's learning during the training phase, we also chose to require children to learn only two identities; that is, two teams of brothers, whereas adult paradigms have used 4 identities (e.g., Leopold et al., 2001). We first trained 8-year-olds and adults to recognize two facial identities (Dan and Jim for half the subjects; Dan and Rob for the other half), and then tested their recognition of faces with weaker identity strengths both before and after adaptation. If children, like adults, use adaptive face coding, then adapting to a particular facial identity (e.g., anti-Dan) should bias the child's perception such that the average face (i.e., a neutral identity) begins to resemble a face that is computationally opposite to the adapting face (i.e., Dan; see Figure 1). Adapting to a face on a different identity vector (e.g., anti-Jim) should have no such effect.

If children do not use adaptive face coding, being exposed to an adapting face should not shift children's perception of a subsequent face in the direction opposite the adapting face.

Methods

Participants

32 adults (16 male; M = 20.3 years, SD = 2.6 years) and 32 8-year-olds (19 male; M = 8.2 years, SD = 0.4 years) participated in the study. All participants were Caucasian, with normal or corrected-to-normal vision. Children were recruited from names on file of mothers who had volunteered for developmental studies at the time of the child's birth, or through a longitudinal study on the development of cognitive and perceptual skills. Adults were recruited from a first year psychology course and received course credit for their participation. One additional child did not pass the training criterion (described below) and therefore was excluded from the study.

Participants were divided into two groups based on the face pair they were discriminating: Dan vs. Jim or Dan vs. Rob.

Stimuli

The average face was created by morphing 20 adult male faces using Gryphon Morph. The training and test stimuli were taken from identity trajectories that pass through the average face, with an original face and an anti-face on opposing sides. There were 3 original adult male faces (Dan, Jim, and Rob; Figure 2). Anti-faces were created by caricaturing the structure of the average face away from the original faces by 80% (Rhodes & Jeffery, 2006; Figure 2). The training and test stimuli were created by morphing each original face towards the average face, in order to create faces with weaker identity strengths of the original faces (Figure 3). All faces had the texture of the average face. The size of the oval window through which the faces could be seen was 7.6 cm x 9.5 cm (viewing angle of 4.35° x 5.44° from a viewing distance of 100cm).

Procedure

The task and the purpose of the study were explained briefly to the children, their parents, and the adult participants. The children gave verbal assent along with their parents' written consent for participation, and the adult participants gave written consent. The task required approximately 30 – 45 minutes to complete. Each participant was tested individually in a small room with dim lighting at a university. This study was approved by the research ethics boards of McMaster University and the University of Western Australia.

Children and adults first completed a training block of 20 trials in which they were introduced to two faces, referred to as "team captains", Dan and Jim (Group 1) or Dan and Rob (Group 2)[1]. Only faces of 100% identity strength were shown. For the first 10 trials, the faces remained on the screen until a response was made; for the last 10 trials, each face was shown for 400ms. Auditory feedback on accuracy was given on each trial. Each participant was required to

[1] Statistical analyses with *group* (Dan/Jim or Dan/Rob) as an additional between-subjects variable revealed no significant interactions with *age* (8-year-olds vs. adults), and therefore data were collapsed across this variable.

correctly identify all of the faces shown on the last 5 trials in order to proceed to the next training phase. If necessary, the training block was repeated once (7 children, 2 adults).

Children and adults were then introduced to the 40% and 60% identity strength faces as "brothers of the team captains that are on their team". During this training phase, identity strengths of 40%, 60%, and 100% of each target face were shown twice per block, and participants were asked to indicate whether the face that appeared on the screen was on Dan's team or Jim/Rob's team. The purpose of this second training phase was to ensure that 8-year-olds could identify faces with weaker identity strengths as resembling the correct target face. For the first block of 12 trials, each face remained on the screen until a response was made; for all subsequent blocks of 12 trials, each face was shown for 400 ms. Blocks were repeated until the participant correctly identified four of the last five 40% and 60% identity strength faces. Auditory feedback was given on each trial. Only one child could not reach this criterion after 30 minutes of training, and his data were excluded from the analysis.

During the baseline phase, participants saw four identity strengths of each face (0%, 30%, 60%, and 90% Dan and Jim/Rob; see Figure 3) eight times for a total of 64 trials, divided into three blocks. The order of presentation within each block was randomized, and each face appeared on the screen for 400ms. Observers were asked to respond whether the face belonged to a person on Dan's team or Jim/Rob's team. No feedback was given. Following Leopold et al. (2001), half of the trials of 0% identity strength (i.e., the average face) were assigned to each identity (Dan or Jim/Rob) and scored "correct" if the response matched that identity.

During the adaptation phase, children and adults were required to watch the adapting face (anti-Dan or anti-Jim/Rob; Figure 2) for 5 seconds before the target face appeared for 400ms. In order to ensure that 8-year-olds would attend fully to the adapting face and also enjoy the task, we modified previous paradigms (e.g., Leopold et al., 2001; Rhodes & Jeffery, 2006) into a game in which participants were the judges responsible for assigning points to two competing teams. We explained that the adapting faces were "robbers trying to steal something", and that two teams of brothers would work hard to catch these robbers. Participants were warned to keep watching the robber's face carefully because as soon as the robber disappeared, they would see who caught the robber (target face) for only a short time, and we would not want to mistakenly assign a point to the wrong team. Points were assigned to the teams based on the participant pressing one of two keys, depending on whether the person who caught the robber was on Dan's team or Jim/Rob's team. The instructions were identical for children and adults.

On matched trials, the anti-face and the target face were from the same identity trajectory (e.g., anti-Dan followed by 0, 30, 60, or 90% Dan). On mismatched trials, the anti-face and the target face were from different identity trajectories (e.g., anti-Dan followed by 0, 30, 60, or 90% Jim/Rob). There were 6 matched trials and 6 mismatched trials per target face (96 trials total). Some "escape" trials were included in which no target face appeared because "the robber had escaped", so as to allow children to take a short break and choose a sticker to take home. Adults were also given the option of taking a short break. Participants were not required to provide any response on these escape trials (12 total). The 108 trials were divided into 6 blocks of 18 trials (8 matched trials, 8 mismatched trials, and 2 escape trials per block)[2]. No feedback was given, other than words of encouragement.

Results

Both 8-year-olds and adults showed the pattern of responses predicted by norm-based coding. Adapting to a face shifted the perception of target faces on the same identity trajectory (matched trials) towards the opposite face (Figure 4); that is, after adapting to anti-Dan, all identity strengths of Dan looked more like Dan, and the previously neutral 0% (average) face took on the identity of Dan. These effects were not observed on mismatched trials where the adapting and test faces were not opposite. Importantly, the size of the shifts was similar for the two age groups, indicating mature norm-based coding in 8-year-olds.

This pattern of results was confirmed with a mixed 3x2x2 ANOVA with *condition* (matched adaptation, mismatched adaptation, or baseline trials) and

[2] Due to a coding error, there was half the number of mismatched adaptation trials at the 0% identity strength than at the other identity strengths.

identity strength (0% or 30%)[3] as within-subjects variables, and *age* (8-year-olds vs. adults) as the between-subjects variable. There was a significant main effect of *condition*, $F(2, 124) = 62.88$, $p < .001$, indicating that performance differed across the three types of trials. Critically, however, the *condition* x *age* interaction was not significant, $F(2, 124) = .36$, $p = .70$, indicating that the differences between conditions did not vary with age. There were no other interactions with the variable *condition* (*condition* x *identity strength*, $F(2, 124) = .31$, $p = .74$, and *condition* x *identity strength* x *age*, $F(2, 124) = 1.43$, $p = .24$). There was also a main effect of *age*, $F(1, 62) = 5.39$, $p = .02$, indicating overall better performance by adults than 8-year-olds.

Because norm-based coding predicts different shifts in the perception of facial identity after adapting to matched (opposite) and mismatched (non-opposite) anti-faces, the main effect of *condition* was further analyzed by comparing the means for baseline to those for matched trials and to those for mismatched trials, with a Bonferroni correction for multiple comparisons. As predicted by norm-based coding, mean accuracy on matched trials (75.4%, SE = 1.4%) was significantly higher than on baseline trials (61.9%, SE = 1.2%), $p < .001$. In contrast, accuracy was lower on mismatched trials (M = 50.4%, SE = 2.1%) than on baseline trials (M = 61.9%, SE = 1.2%), $p < .001$[4].

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[3] The analysis was restricted to identity strengths 0% and 30% because baseline accuracy was high at identity strengths 60% and 90%, masking any aftereffect (see Figure 4).

[4] On mismatched trials (e.g., adapting to anti-Jim and then identifying Dan), the perception of facial identity shifts along a trajectory different from that of the target face (Dan) and hence the target face is *less* likely to be correctly identified (e.g., all faces look less like Dan because they look more like Jim).

The ANOVA also revealed a main effect of *identity strength*, $F(1, 62) = 157.54$, $p < .001$, indicating better performance at 30% identity strength than 0% identity strength, as expected because faces at higher identity strengths should be easier to identify (stronger identity strengths are created by morphing the face towards the original identity and away from average), and because baseline performance at 0% identity strength should be at chance. The *identity strength* x *age* interaction was non-significant, $F(1, 62) = 1.16$, $p = .29$.

Because adaptation trials differed from baseline trials in that observers adapted to a face before responding to the target face, we also directly compared performance between matched and mismatched adaptation trials. There was a significant main effect of *condition*, $F(1, 62) = 96.08$, $p < .01$, and a main effect of *age*, $F(1, 62) = 4.86$, $p = .03$, but no *condition* x *age* interaction, $F(1, 62) = 0.00$, $p = .96$, indicating that the size of the identity aftereffect was similar for both 8-year-olds and adults.

Discussion

These results demonstrate that in a child-friendly two-alternative forced-choice paradigm, 8-year-olds and adults show the same facial identity aftereffect. This is the first demonstration of a face aftereffect in children, and it suggests that the mental representation of faces is organized similarly in 8-year-olds and adults.

The results are consistent with the hypothesis that, for both 8-year-olds and adults, faces are coded in a multi-dimensional face-space centered on an average face (Valentine 1991). The anti-faces in the current study were computationally derived to differ maximally from the original faces along a vector passing through the origin (i.e., the average face). The results are as would be expected if adapting to these anti-faces (matched trials) shifted the mental representation of the average face towards the adapting face, such that perception of subsequent faces was biased toward the original identity. Adapting to a face on another vector (mismatched trials) did not bias perception towards the original identity. The results suggest that, like adults, 8-year-old children represent individual faces along vectors in a multi-dimensional face-space passing through the norm. Norm-based coding of facial identity is supported by evidence that faces further away from average generate a stronger neural response in face-selective areas of the human brain (Loffler et al., 2005) and the monkey brain (Leopold et al., 2006). The special role of the average face in encoding facial identity may be established early in development, as evidenced by the fact that beginning just a few months after birth, both human and monkey infants respond to an average face as if it is familiar (de Haan, Johnson, Maurer, & Perrett, 2001; Kelly et al., 2005; Myowa-Yamakoshi, Yamaguchi, Tomonaga, Tanaka, & Matsuzawa, 2005).

The facial identity aftereffect is selective for pairs of opposite faces, such as Dan and anti-Dan (Leopold et al., 2001; Rhodes & Jeffery, 2006; this study), suggesting that the neural mechanisms underlying face processing utilize opponent-based coding, accomplished by pairs of neural populations that are adaptively tuned to above-average and below-average values for each dimension of face-space. The relative activation of the two neural populations signals the value for each face on that dimension, and equal activation signals the average value (Rhodes & Jeffery, 2006; Rhodes et al., 2005). For example, since Dan has a larger-than-average forehead (see Figure 1), seeing Dan's face will more strongly activate the neural populations encoding larger-than-average forehead size (relative to those responsive to smaller foreheads), thereby temporarily suppressing the activity of those neurons. This temporary suppression is manifested as a bias in the perception of a subsequently viewed face towards having a smaller-than-average forehead. Similar mechanisms will occur simultaneously for all dimensions of face-space, thereby shifting the position of average in face-space temporarily, leading to an identity aftereffect.

In adults, this process has been shown to be dynamic with the strength of the facial identity aftereffect increasing logarithmically with increasing adaptation duration, and decaying exponentially with time following adaptation (Leopold, Rhodes, Muller, & Jeffery, 2005; Rhodes, Jeffery, Clifford, & Leopold, 2007a). Therefore, brief adaptation, as in the current paradigm, only temporarily shifts the representation of the average face. However, the same adaptive coding mechanism may be involved in real-world face processing that dynamically calibrates neuronal responses to the range of faces most commonly experienced (Rhodes, Maloney, Turner, & Ewing, 2007b). By continuously updating the central tendency of faces experienced, and by encoding each face in terms of deviations from the average, neural efficiency is maximized because the most commonly experienced faces activate the least response (Leopold et al., 2001, 2006; Rhodes & Jeffery, 2006). The present findings suggest that such an adaptive coding mechanism for facial identity is functional by 8 years of age.

The neural locus of the face identity aftereffect appears to be in high-level visual areas, as suggested by its robustness to changes in size, position, and angle of the adapting and test stimuli (Leopold et al., 2001; Rhodes et al., 2003; Watson & Clifford, 2003; Zhao & Chubb, 2001), as well as the time-course of the aftereffects (Rhodes et al., 2007a). In adults, fMRI activation reveals neural adaptation in the FFA that parallels face identity aftereffects: repeated presentation of faces on a single identity vector relative to average leads to adaptation of the BOLD signal, unlike repeated presentation of faces on different identity vectors (Loffler et al., 2005). In the current study, we found adult-like identity aftereffects at age 8 years, the age at which previous fMRI studies indicate that the fusiform face area is not yet more responsive to faces than objects (Aylward et al., 2005; Gathers et al., 2004), or at least not at adult levels (Golari et al., 2007; Scherf, Berhmann, Humphreys, & Luna, 2007). Together, the results suggest that children can develop adaptive coding of faces independent of a large face-selective FFA.

Despite the presence of adult-like adaptive face-coding processes indicative of norm-based coding in 8-year-olds, face processing continues to improve after 8 years of age. Indeed, in the current study, adults were more accurate overall in identifying faces than 8-year-olds. Previous studies have shown that 8-year-olds perform poorly when recognizing facial identity across changes in point of view or based on the spatial relations of facial features (Mondloch et al., 2003; Mondloch et al., 2002). Accordingly, children may not show adult-like aftereffects when there are manipulations in point of view (Anderson & Wilson, 2005; Jeffery, Rhodes, & Busey, 2006; Jiang, Blanz, & O'Toole, 2006; Jiang, Blanz, & O'Toole, 2007) or the spatial relations of facial features (Robbins, McKone, & Edwards, in press; Watson & Clifford, 2003; Webster & MacLin, 1999). Future studies should therefore examine the nature of the changes in face-space that occur with development. Perhaps with increased expertise, children become better at adjusting the weights given to each dimension within face-space to reflect the utility of that dimension as a cue to identity. Alternatively, children may develop additional dimensions, and/or become better at making finer discriminations within the dimensions (Burton, Jenkins, Hancock, & White, 2005). An additional possibility is that the norm for children is less stable and shifts more easily and permanently by exposure to new faces, as suggested by the reversal of the other-race bias in Korean adults adopted into European families before age 9, such that they were better at identifying Caucasian faces than Asian faces, much like the Caucasian control group (Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2006). This hypothesis could be tested directly by comparing the timecourse of the identity aftereffect for children and adults using the technique developed for this study.

In summary, this is the first study to demonstrate adaptive coding of facial identity in children, consistent with children's use of norm-based coding of facial identity. Like adults, 8-year-olds' perception of identity shifts towards the opposite identity after viewing a face. These results suggest that adaptive coding of identity is developed by 8 years of age. The technique developed here is suitable for exploring the mental representation of faces in special populations with deficits in face processing such as children with autism and adults with prosopagnosia.

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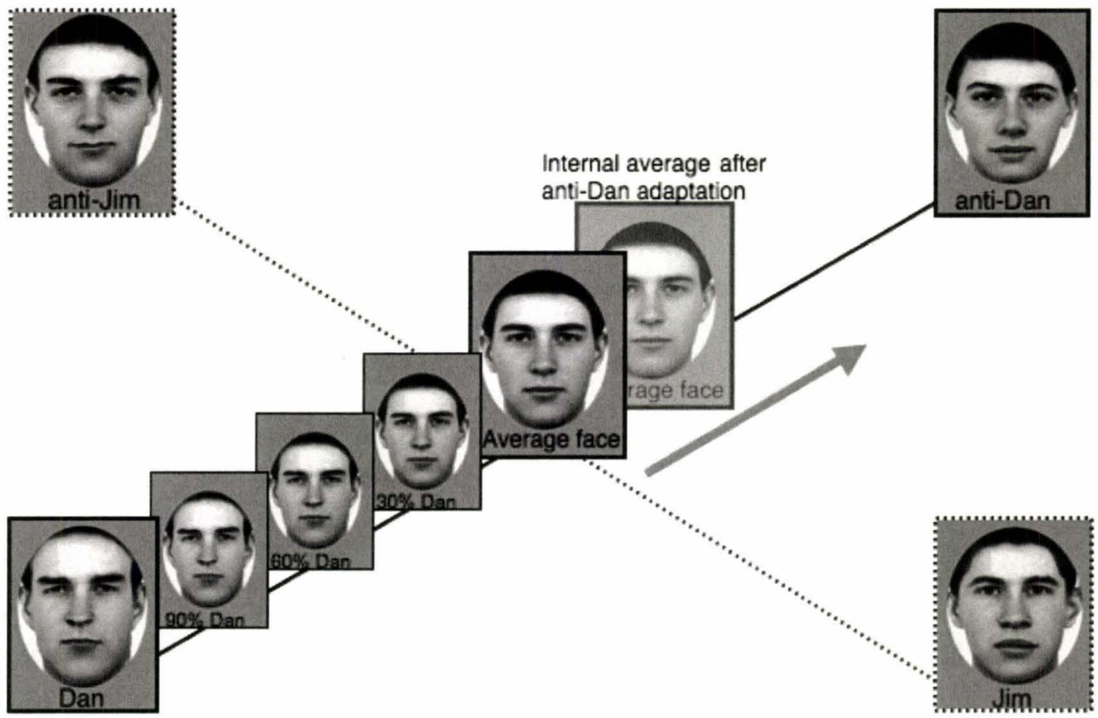


Figure 1. The centre face represents the average face morphed from 20 adult male faces. Dan and anti-Dan lie on opposite sides of the average face along an identity trajectory (solid line), whereas Jim and anti-Jim lie on a different identity trajectory (dotted line). Faces of varying identity strengths can be created by morphing the average face with Dan's original face (30, 60, & 90% Dan). Adapting to anti-Dan pulls the observer's internal representation of an average face towards anti-Dan, as indicated by the solid grey arrow and faded average face, such that the physically average face stimulus will now *look* more like Dan to the observer.

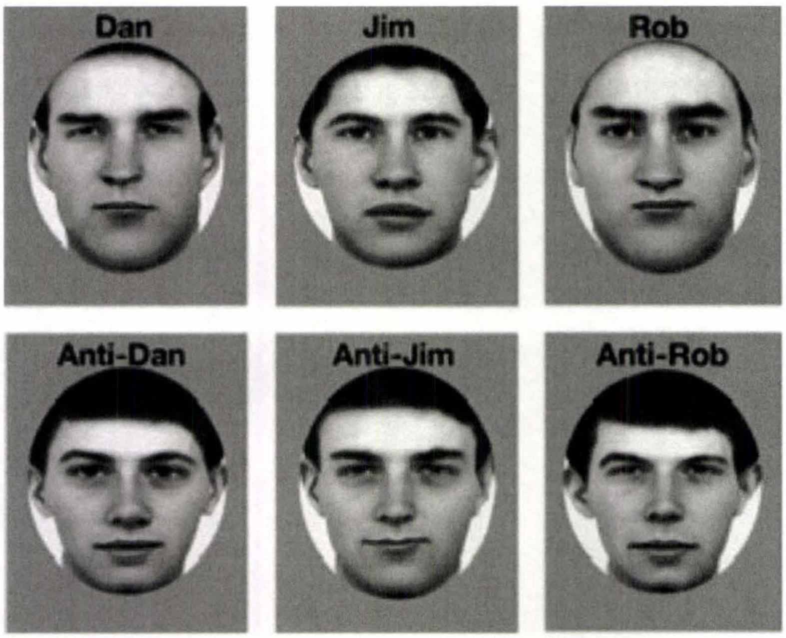


Figure 2. Top row: Team captains are shown at 100% identity strength. Observers were trained to identify two faces (half were trained to discriminate Dan vs. Jim; half were trained to discriminate Dan vs. Rob). Bottom row: Anti-faces were created by caricaturing the structure of the average face away from the original faces (team captains) by 80% using Gryphon Morph.

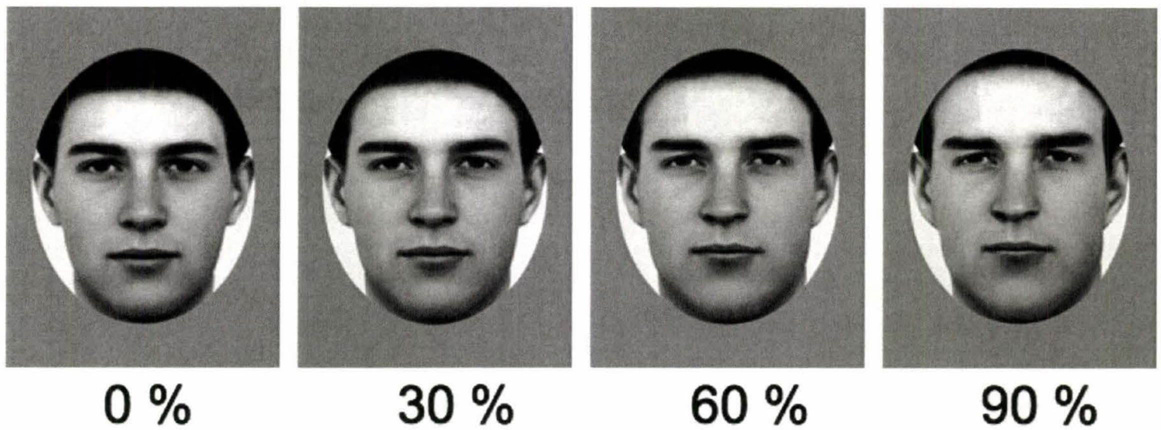
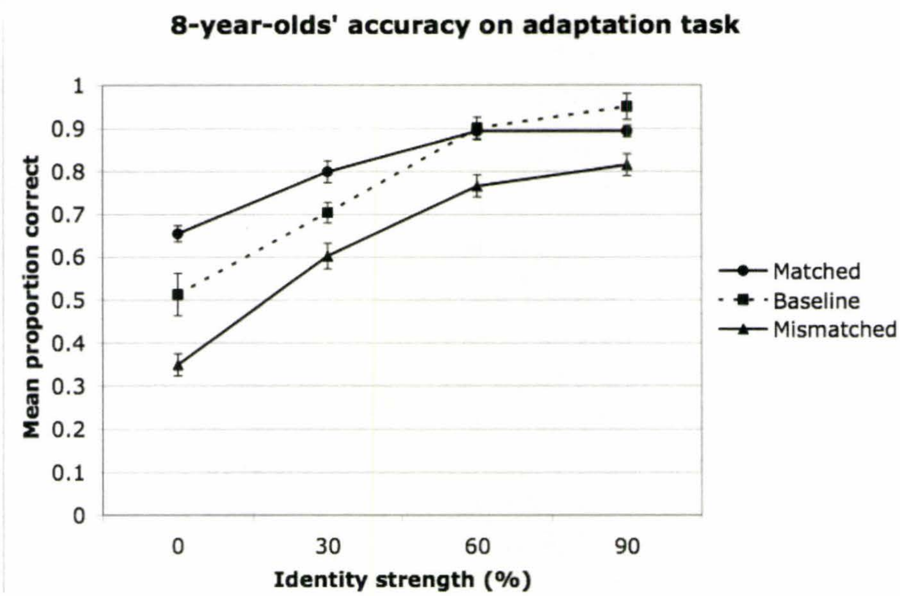


Figure 3. An example of the four identity strengths (Dan) used in the baseline phase, and as the target faces in the adaptation phase. 0% identity represents the average face created from a pool of 20 male faces. 30, 60, and 90% identity strengths were created by morphing the original face (team captains) with the average face.



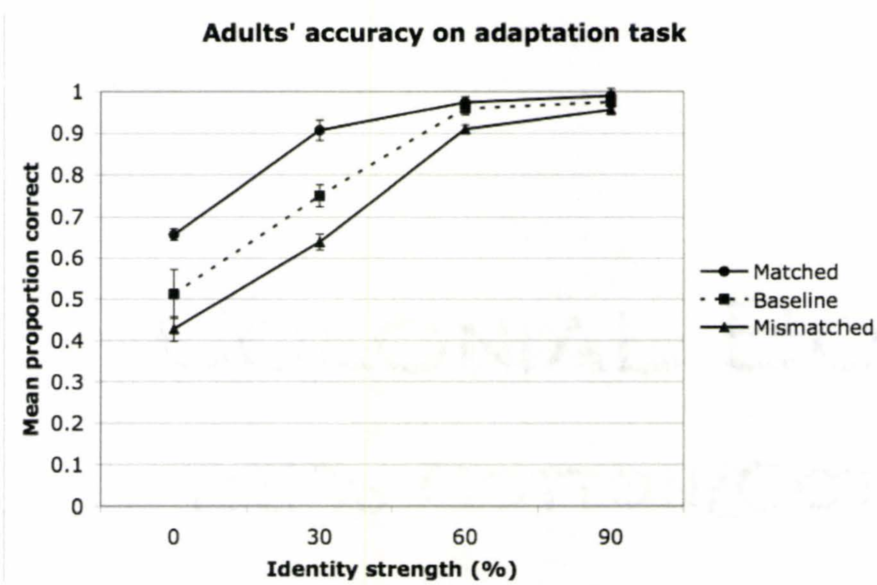


Figure 4. Accuracy on baseline and adaptation trials for *a)* 8-year-olds and *b)* adults (mean +/- one standard error). On matched adaptation trials, observers adapted to the anti-face opposite the target face. On mismatched adaptation trials, observers adapted to a non-opposite anti-face before viewing the target face (e.g., anti-Jim followed by 30% Dan).

Chapter 3

Preface

The study described in this chapter has been written as a manuscript to be submitted to *Vision Research,* entitled "*A comparison of children's and adults' face-space using multi-dimensional scaling*" by Mayu Nishimura, Daphne Maurer, and Xiaoqing Gao.

The study examines the development of face recognition by exploring children's mental representation of facial identity as predicted by the face-space model (Valentine, 1991). The findings reported in Chapter 2 revealed that 8-year-olds show evidence of norm-based coding of facial identity, which is a key assumption of the face-space model. The present study extends this finding by exploring the dimensions of children's face-space. Similarity judgments from 8-year-olds and adults were collected using a novel child-friendly paradigm, and were submitted to multi-dimensional scaling (MDS) analysis. This exploratory method allows visual inspection of multiple similarity judgments in a spatial representation, which can then be tested against the predictions of the face-space model. The findings revealed several similarities in the MDS solutions of children and adults, a pattern that is consistent with the findings from Chapter 2 that by 8 years of age, the fundamental architecture supporting the mental representation of facial identity is adult-like. However, the results also revealed greater variability in children's similarity judgments, which may contribute to behavioral immaturities observed in some face processing tasks at this age.

A comparison of children's and adults' face-space using multi-dimensional scaling.

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Abstract

Children can identify faces in everyday life, but some face processing abilities are not adult-like until late adolescence. In the current study, we explored differences in the mental representation of facial identity between children and adults by asking 8-year-olds and adults to make similarity judgments of a homogeneous set of female Caucasian faces using an odd-man-out paradigm. Hair cues to identity were removed to encourage judgments based on internal facial characteristics. There was a significant correlation between the raw similarity judgments made by 8-year-olds and adults. The fit of the solutions from multi-dimensional scaling (MDS) was better for adults, in part because children made more variable responses, both between and within individuals. Five dimensions accounted optimally for the similarity data for both children and adults, and the dimensions appeared to code for similar facial characteristics. However, the weighting of the dimensions differed between children and adults: more children relied on a single dimension, namely eye colour, whereas adults appeared to utilize multiple dimensions for each judgment. Nonetheless, a comparison of the MDS solutions for 8-year-olds and adults revealed that similar faces clustered together locally. This pattern of findings suggests that by 8 years of age, children's face-space has a similar layout to adults' face-space, but that the use of the dimensions differs between children and adults.

Adults have a remarkable ability to remember and recognize many faces in their everyday life. Adults' recognition of faces is impaired when faces are inverted, and this "inversion effect" is greater for faces than non-face objects, such as houses and airplanes (e.g., Yin, 1969). Adults demonstrate holistic processing of faces: processing the individual features, such as the eyes or mouth, together as a unitary whole or Gestalt percept (e.g., Tanaka & Farah, 1993; Young, Hellawell, & Hay, 1987). Adults also demonstrate acute sensitivity to changes in feature shape and in second-order relations, which refer to the spatial relations among internal facial features, such as the distance between the two eyes, but more for upright faces than inverted faces (e.g., Brooks & Kemp, 2007; Collishaw & Hole, 2000; Freire & Lee, 2000; Mondloch, Le Grand, & Maurer, 2002).

Like adults, children (and to a certain extent even infants) demonstrate a face inversion effect (e.g., Brace et al., 2001; Itier & Taylor, 2004a; Mondloch et al., 2002; Schwarzer, 2000; Turati, Sangrigoli, Ruel, & de Schonen, 2004). Children as young as 4 to 6 years of age also demonstrate holistic processing of faces (Carey & Diamond, 1994; de Heering, Houthuys, & Rossion, 2007; Mondloch, Pathman, Maurer, Le Grand, & de Schonen, 2007; Pellicano & Rhodes, 2003; Tanaka, Kay, Grinnell, Stansfield, & Szechter, 1998). Additionally, six-year-olds can recognize the identity of faces based on changes in external contour as accurately as adults and 8-year-olds are almost as good as adults in detecting changes in the shapes of internal features, such as eyes and mouth (Mondloch et al., 2002).

However, it takes many years for children's face processing abilities to reach adult levels. 8-year-olds are worse than adults at recognizing facial identity across changes in point of view (Mondloch, Geldart, Maurer, & Le Grand, 2003) or noticing subtle changes in the second-order relations (Mondloch et al., 2002). Their immaturity in processing the second-order relations of upright faces is evident even when memory demands are eliminated, as well as when the salience of feature shapes is reduced (Mondloch, Dobson, Parson, & Maurer, 2004). Improvements with age in sensitivity to second-order relations continue into adolescence (Mondloch, Le Grand, & Maurer, 2003). These behavioral immaturities are consistent with neuroimaging data. Adults demonstrate face-selective activation in the right anterior fusiform gyrus, an area referred to as the face fusiform area or the FFA (e.g., Kanwisher, McDermott, & Chun, 1997). Under many conditions, such FFA activation is not observed in children until 12-16 years of age (Aylward et al., 2005; Gathers, Bhatt, Corbly, Farley, & Joseph, 2004; Scherf, Berhmann, Humphreys, & Luna, 2007). However, when age-related differences in BOLD signals are controlled carefully, face-selective right FFA activation has been shown in children as young as 7-11 years, but in an area that is significantly smaller than adults (Golari et al., 2007). Similarly, the responsiveness of the face-selective negative event-related potential (ERP) component N170 (Bentin, Allison, Puce, Perez, & McCarthy, 1996) to different types of facial stimuli (e.g., inverted vs. upright faces) changes with age in both latency and amplitude, with these changes continuing into adolescence. For example, the latency of the N170 to upright faces decreases with age and the amplitude increases with age, even after age 14-16 years (Itier & Taylor, 2004b; Taylor, Edmonds, McCarthy, & Allison, 2001). Unlike adults, children aged 8-16 years do not show larger N170 amplitudes to inverted faces, although longer N170 latencies are observed in response to inverted faces in adults and children as young as 8 years old (Itier & Taylor, 2004b; Taylor et al., 2001).

The source of the immaturities in face processing that are still observed at 8 years of age may lie in children's mental representation of faces. A useful framework that describes adults' mental representation of faces is face-space: a multidimensional space in which individual faces are represented by unique multidimensional vectors from the origin (Valentine, 1991). The origin of face-space represents the average of previously encountered faces, such that individual faces are encoded as deviations from the average (Valentine, 1991). This average is updated continuously with experience, and there may be separate averages for different populations of faces, such as male versus female faces, or faces of different races (e.g., Baudouin & Gallay, 2006; Byatt & Rhodes, 1998; Levin, 1996; Little, De Bruine, & Jones, 2005; Watson, Rhodes, & Clifford, 2006; Valentine, 1991). Adaptation paradigms provide supporting evidence that adults indeed encode faces relative to an average. For example, when an observer adapts for several seconds to a face that has been digitally compressed, he/she judges a previously normal face as being expanded (Rhodes, Jeffery, Watson, Clifford, & Nakayama, 2003; Watson & Clifford, 2003; Webster & MacLin, 1999). Presumably, adaptation has shifted the observers' perception of normality towards the adapting face (i.e., the observer's cognitive "average" is more compressed than prior to adaptation), so that relative to the updated cognitive "average", a previously "normal" face looks "expanded". Such aftereffects are consistent with a model of norm-based coding of faces (for a review see Tsao & Freiwald, 2006).

Adaptation paradigms reveal that not just information about external face shape, but also information about facial identity is likely encoded relative to an average. To assess a facial identity aftereffect, pairs of computationally opposite faces are created by measuring the differences in the position of pre-specified landmarks between a given face (e.g., Dan) and a computer-averaged face (e.g., a morph of 20 male faces), and then morphing these differences in the opposite direction, thereby creating an anti-face (e.g., anti-Dan). When an observer adapts to anti-Dan for several seconds, the computer-averaged face (i.e., an identity-neutral face) is more likely to be perceived as Dan, presumably because it is being compared to the observer's cognitive "average" in face-space that has shifted towards anti-Dan (e.g., Leopold, O'Toole, Vetter, & Blanz, 2001; Rhodes & Jeffery, 2006). This aftereffect is limited to pairs of faces that have been morphed to be on opposite sides of the average face, supporting the model of norm-based coding. Norm-based face coding mechanisms appear to be dynamic and updated continuously with experience, as aftereffects increase logarithmically with longer adaptation durations and decay exponentially with longer test durations (e.g., Clifford & Rhodes, 2005; Leopold, Rhodes, Muller, & Jeffery, 2005; Rhodes, Jeffery, Clifford, & Leopold, 2007).

In the face-space model, the distance from the norm represents the typicality or distinctiveness of the face (Valentine, 1991). Additionally, the spatial distance among individual faces corresponds to the perceptual similarity of those faces, such that similar faces are closer to each other in face-space than faces that are perceived to be different (Valentine, 1991). The resulting effect is a non-uniform spatial gradient in face-space, such that typical faces cluster closer together around the origin, whereas distinctive faces are dispersed around the periphery. This characteristic of face-space has been useful in explaining the apparent paradoxical effect of typicality (or distinctiveness) on face perception. Adults are faster at *classifying* an image as a face rather than a non-face image, if it is rated independently as being more typical, but are faster at *identifying* an individual face if it is rated independently as being more distinctive (e.g., Johnston & Ellis, 1995; Rhodes, Byatt, Tremewan, & Kennedy, 1997; Valentine, 1991; Valentine & Bruce, 1986). According to the face-space framework, classification of a typical face is easier because more faces are available in close proximity to act as a matching reference (i.e., that it *is* a face). However, the close proximity of other faces interferes with correct identification because it increases the likelihood of misidentification errors. By the same logic, it should be possible to make a face more distinctive and thereby improve adults' recognition memory of that face. This prediction is supported by evidence of caricature effects: digitally exaggerating the difference between an individual face and an average face creates a caricature that is perceived as more distinctive, and that is easier to recognize than the original face (e.g., Blanz, O'Toole, Vetter, & Wild, 2000; Lee, Byatt, & Rhodes, 2000; Rhodes & Tremewan, 1994; Rhodes, Brennan, & Carey,1987).

Very little research has examined the utility of the face-space model in describing children's face processing. However, Chang, Levine, and Benson (2002) have shown that 6-year-olds, like older children (8- and 10-year-olds) and adults, chose caricatures as being more distinctive and anti-caricatures as being more typical than their original faces. These findings suggest that, like adults, children have a face-space layout that is centered on the average with a non-uniform spatial gradient. However, the magnitude of the caricature effect was much smaller in 6-year-olds than in older children and adults. One possible explanation for this age effect is that fewer faces are represented in the face-space of younger children, such that the spatial gradient is weaker, producing weaker caricature effects. Consistent with this interpretation, 5- to 7-year-olds demonstrated weaker effects of typicality, because they did not identify distinctive faces better than typical faces, although like adults, they were faster at classifying typical than distinctive faces (Johnston & Ellis, 1995). However, children 9 years and older showed typicality effects like those of adults in both identification and classification tasks (Johnston & Ellis, 1995). Similarly, eight-year-olds demonstrate an identity aftereffect that is of similar magnitude to adults, a finding that suggests that by 8 years of age, children, like adults, represent facial identity in a face-space centered on an average face, and that individual faces are coded as deviations from the average (Nishimura, Maurer, Jeffery, Pellicano, & Rhodes, in press).

Studies examining face identity aftereffects and the effects of typicality or distinctiveness provide some information about face-space, but cannot elucidate whether children and adults utilize different dimensions of face-space. The theory of face-space, as originally proposed by Valentine (1991), did not specify what the dimensions of face-space are; rather, he proposed only that the dimensions represent cues to identity that are important for discriminating faces. For example, a dimension may represent an easily identifiable feature, such as eye colour, or a more complex combination of cues that cannot be easily verbalized (e.g., combined surface area of forehead, cheeks, and chin). One approach to describing the dimensions of face-space is to use multidimensional scaling (MDS), a statistical procedure that represents measurements of similarity among pairs of objects as distances between points in a multi-dimensional space. MDS can often show regularities that remain hidden if the raw similarity judgments are examined directly (Borg & Groenen, 2005).

Using Caucasian male faces aged 20-25 years, Johnston, Milne, Williams, and Hosie (1997) applied MDS to adults' similarity ratings to examine adults' face-space. The MDS solution revealed that faces that were rated independently as being more typical were located around the origin, and faces that were rated independently as being more distinctive were located farther away from the origin, a pattern consistent with the model of face-space. Additionally, Johnston and colleagues (1997) found that three to four dimensions accounted well for adults' similarity ratings. For male Caucasian faces, these dimensions appeared to represent face width, perceived age, facial hair (male faces only), and forehead size (Busey 1998; Johnston et al., 1997).

In the current study, we used multi-dimensional scaling to examine the characteristics of 8-year-olds' face space. Previous reports of 8-year-olds' immaturities in face processing may reflect differences between children's and adults' face-space in the number of dimensions, the nature and utility of those dimensions (e.g., children may have dimensions that represent unreliable cues to facial identity, such as presence of glasses), the weights placed on each dimension, and/or the tuning of the dimensions (i.e., children's dimensions may not be well-defined). One previous study by Pedelty, Levine, and Shevell (1985) used MDS to examine the representation of unfamiliar faces by 7-, 9-, 12-year-olds and adults. Using 12 face stimuli and a child-friendly rating scale, they found no age differences in the number of dimensions needed to adequately account for the observed similarity ratings. A 3-dimensional solution was sufficient, with the dimensions likely representing hair colour, face width, and hairstyle. The results suggest that hair cues play an important role in how children and adults perceive facial identity, and that children's and adults' face-space are organized in a similar manner. However, individual results revealed that the younger children tended to rely more heavily on one or two of the dimensions, whereas adults tended to use the three dimensions equally.

One limitation to the study by Pedelty and colleagues (1985) is the availability of hair colour and hairstyle as a major cue to identity in their small stimulus set, which may have led to an overestimation of the similarity between children's and adults' face-space. Already by 5 years of age, children are able to use the outer contour of faces to recognize unfamiliar faces in a manner similar to adults (Want, Pascalis, Coleman, & Blades, 2003), whereas processing identity based on the spatial relations among the internal features of a face appears to improve into adolescence (Mondloch et al., 2002, 2003). Additionally, children under the age of 10 years are more likely to make errors in recognizing unfamiliar faces by basing their judgments on misleading cues from paraphernalia (Baenninger, 1994; Diamond & Carey, 1977; Freire, Lee, & Symons, 2000). The salience of the external hair cues in the faces used by Pedelty and colleagues (1985) may have led children to rely on that feature alone, exaggerating their reliance on a single dimension. Adults also use external features, such as hairstyle and contour shape, as cues to identity when they are available (e.g., Johnston et al., 1997; Pedelty et al., 1985), but, unlike children, they are also able to discriminate faces reliably when these features are not available (e.g., Collishaw & Hole, 2000; Haig, 1984; Mondloch et al., 2002; Rhodes, Brake, & Atkinson, 1993). In this study, we examined whether 8-year-olds' face-space resembles that of adults when salient external features such as hair colour and hairstyle are not available as cues to identity.

We developed a child-friendly paradigm to measure children's face-space using multi-dimensional scaling. Although traditional MDS paradigms use rating scales to measure adults' perception of object similarity (e.g., Busey, 1998; Johnston et al., 1997; Lee et al., 2000; Pedelty et al., 1985), this method assumes that the observer uses the scale consistently across trials, which may be difficult for children. An odd-man-out paradigm can circumvent this problem because on each trial the observer simply has to choose the stimulus that appears most different from the rest, requiring no reference to an internal rating scale and no memory of the values assigned to previous faces. The odd-man-out method has been used reliably to collect similarity judgments from adults (Kahana & Bennett, 1994; Romney, Brewer, & Batchelder, 1993; Weller & Romney, 1988, Yotsumoto, Kahana, Wilson, & Sekuler, 2007) and children (Miller & Gelman, 1983). We compared the face-space of adults and 8-year-olds, because 8-year-olds already demonstrate norm-based coding of facial identity and adult-like caricature effects (e.g., Nishimura et al., in press; Johnston & Ellis, 1995), yet they also demonstrate immaturities in some perceptual discriminations of faces (e.g., Mondloch et al., 2002) as well as in the neural markers of face processing (e.g., Golari et al., 2007; Itier & Taylor, 2004b; Scherf et al., 2007).

The purpose of Experiment 1 was to determine the smallest number of face stimuli that would be necessary to produce an adequate representation of adults' face-space, because we wanted to minimize the number of trials for children. Specifically, we asked adults to rate the similarity of 630 pairs of faces from university-aged Caucasian women. We limited our face stimuli to female faces because it is unclear whether sex of face is one dimension of a single face-space or whether there are different face-spaces for the two sexes (Baudouin & Gallay, 2006; Bruce, Burton, & Dench, 1994; Johnston et al., 1997; Little et al., 2005). We also used the same hair for all faces, in order to tap into more subtle differences between children and adults' face-space than those examined in the study by Pedelty et al. (1985), in which the 12 faces differed markedly in hairstyle and hair colour. From the MDS solutions based on adults' similarity ratings, we determined the smallest number of faces that were necessary to produce solutions comparable to those produced from the full stimulus set. Using this subset, we obtained similarity judgments from another group of adults using the odd-man-out method (Experiment 2a). Once the convergence of the two methods was confirmed, we used the odd-man-out paradigm to examine 8-year-olds' face-space (Experiment 2b).

Experiment 1

The purpose of Experiment 1 was two-fold: to obtain similarity data from adults using a rating scale, and to determine the smallest number of face stimuli that would produce a reliable MDS solution. Additionally, according to the face-space hypothesis (Valentine, 1991) and previous findings (e.g., Johnston & Ellis, 1995; Rhodes et al., 1997; Valentine & Bruce, 1986), typical faces should cluster around the origin of face-space (i.e., the norm) and distinctive faces should be located in the periphery. So that we could test this hypothesis in the similarity data, a separate group of adults rated the distinctiveness of the faces.

Experiment 1 – Methods

Subjects

Subjects were 24 Caucasian undergraduate students (18 female; age 18-20 years, mean age = 18.13 years) participating for bonus credit in an introductory psychology course. All had normal or corrected-to-normal vision.

Stimuli

The test stimuli consisted of 36 coloured photographs of female Caucasian faces, chosen from a larger set of 97 female faces that were rated previously on attractiveness. The 18 most attractive and the 18 least attractive faces with minimal make-up were chosen, to ensure a diverse sample of faces. To eliminate hair colour and hairstyle as diagnostic cues to identity, the hair (including small parts of the forehead and cheeks) from one female was cropped and copied onto the faces of the remaining 35 women using Adobe Photoshop, such that all 36 faces had the same hair (see Figure 1). The skin tones of all faces were adjusted slightly in order to smooth the transition between the new hair outline and the original face. Pilot testing confirmed that the digital modifications did not result in artifacts that made the faces appear unusual.

In addition to the 36 test stimuli, a set of 6 male faces were created in an analogous manner, to serve as the practice set. All stimuli were 10.5 cm x 15.3 cm, and were viewed from a distance of 100 cm (6.00° x 8.74° of visual angle).

Apparatus

Stimuli were presented on a 22-inch Macintosh monitor using Superlab software, running in OS 9 on a Macintosh Cube computer.

Procedure

This study was approved by the research ethics board of McMaster University. After being informed about the nature of the task, all participants provided written consent at the beginning of the session. Each participant was tested individually in a dimly lit room.

In the practice session the experimenter explained the use of the rating scale from 1 to 7 (1 = not very similar, 7 = very similar). The practice session began by presenting six male faces sequentially (1000 ms per face), and then presenting all six faces on the screen simultaneously. The observer was asked to choose the pair that appeared most similar, and was instructed that such a pair should receive a 6 or 7 on the rating scale. The observer then chose the pair that appeared most different, and was instructed that such a pair should receive a 1 or 2 on the rating scale. The practice session was used to explain the range of variability in the face stimuli, and to encourage the full use of the scale.

The testing session began by first showing all 36 female test faces sequentially (1000 ms per face) to demonstrate the range of variability in the face stimuli. Following this presentation, pairs of faces were presented side-by-side on the screen on every trial, and subjects were asked to rate the similarity of the two faces on a scale from 1 to 7 (1 = not very similar, 7 = very similar). All possible pairings and orderings (i.e., pairs A-B and B-A) of the 36 faces produce 1260 trials. We divided the 1260 trials pseudorandomly into two groups (Orders 1 & 2), so that for each order, there were 630 trials during which each face *pair* was shown only once, and each *face* was shown approximately equally often on the left and right sides. Each participant saw either Order 1 or 2.

Separately, the 36 face stimuli were rated on distinctiveness by a different group of 24 adult Caucasian subjects (20 female; age 18-25 years, mean age = 19.2 years). Each face was printed out on a 4 x 6 photo postcard using a Canon printer. Six poster boards were constructed with each poster board showing 6 photographs attached with Velcro. The assignment of each photo to a particular poster board, as well as the position of the photos within each poster board, was randomized across subjects. Poster boards were used as a fun and interactive method that would be suitable for children if it became necessary to collect distinctiveness ratings for children and adults separately. Each adult observer was asked to stand 100 cm from the poster board, and to select the most distinctive face (i.e., "The face that would stand out the most in a crowd") on the poster board. The chosen face was then removed, and the observer was asked to choose the next most distinctive face. This process continued until all 6 faces had been removed from the poster board, and was repeated for the remaining 5 poster boards until all 36 faces had been judged. The first face to be removed from each poster board (i.e., the most distinctive) was given a distinctiveness score of 6, followed by 5, 4, 3, 2, and 1 for subsequently chosen faces. These distinctiveness scores were averaged across subjects to obtain a mean distinctiveness score for each face. The mean ratings ranged from 4.71 to 1.83 (SD = 0.74; greater values indicate greater distinctiveness). The faces were then ranked based on their distinctiveness scores and divided into two categories, such that the top 18 faces were categorized as distinctive (most distinctive = D1, least distinctive = D18, mean rating = 4.11), and the bottom 18 faces were categorized as typical (most typical = T1, least typical = T18, mean rating = 2.89).

Data Analysis

The similarity ratings were recoded into distances such that pairs of faces given the highest similarity rating (7 on the rating scale) had a distance of 1, and pairs of faces with the lowest similarity rating (1 on the rating scale) had a distance of 7. Using these distance values from each participant, multi-dimensional scaling was performed using the INDSCAL procedure in SPSS software version 13.0 for Mac OS X. INDSCAL is a MDS procedure that produces a group solution and also provides a measure that characterizes the individual differences within the group (Martens & Zacharov, 2000). The Euclidean distance model was selected, with the measurement level specified as ordinal and the matrix shape as symmetric, as in previous studies (Johnston et al., 1997; Yotsumoto et al., 2007). Five analyses were performed to assess the fit of solutions with two to six dimensions, as in previous studies (e.g., Busey, 1998; Johnston et al., 1997; Lee et al., 1998). We then examined the layout of the solution to assess whether typical faces were located closer to the origin than distinctive faces. After the validity of the MDS solution was confirmed based on the typicality effect, we examined the fit of the solutions using data from fewer stimuli by systematically removing the least distinctive faces and the least typical faces from the two categories, to determine the minimum number of faces that were necessary to produce a MDS solution comparable to that based on all 36 faces.

Results

The goodness-of-fit for the 2- to 6-dimensional MDS solutions, measured by Kruskal's Stress 1 formula (Kruskal & Wish, 1978), are shown in Figure 2. Although there are no guidelines for assessing Kruskal's Stress values (Giguere, 2006), the fit of the 5-dimensional solution (Stress = 0.21) and 6-dimensional solution (0.18) are comparable to those reported previously as good fits in studies of face-space (e.g., Stress = 0.14 in Johnston et al, 1997; 0.19 in Lee et al., 2000; 0.26 in Yotsumoto et al., 2007). We also examined whether the MDS solutions corresponded to the independent ratings of typicality. t-tests revealed that the distance to the origin for typical faces in each of the 2- to 6-dimensional MDS solutions was smaller than the distance for distinctive faces (Table 1). The effect sizes (Table 1) were large and comparable to those reported previously by Johnston and colleagues (1997) who used a set of 36 male faces with hair cues.

Thus, these MDS solutions appeared to correspond well to adults' perceptions of similarity and typicality, even though we had increased the homogeneity of our stimulus set by using the same hair on all faces.

To determine the smallest number of faces that would adequately produce a comparable MDS representation of adults' similarity judgments, we conducted four additional sets of MDS analyses with smaller subsets of the face stimuli: 30, 24, 18, and 12 faces. The three least typical and three least distinctive faces were removed each time, so that in each subset, half of the faces were the most typical and half were the most distinctive faces. The goodness-of-fit of the 2- to 6-dimensional solutions for each subset are shown in Figure 2. As can be seen from the figure, using a minimum of 18 or 24 faces produced a solution comparable to the solution using the full set of 36 face stimuli.

Discussion

The results showed that with additional dimensions, the fit of the multi-dimensional scaling solution to adults' raw similarity data improved, however, with each additional dimension the interpretability of the solutions decreases. The fit of the 5- and 6-dimensional solutions were comparable to those reported previously in studies of face-space (e.g., Johnston et al, 1997; Lee et al., 2000; Yotsumoto et al., 2007). An examination of the position of the faces in the MDS solutions revealed that independently rated typical faces were closer to the origin than distinctive faces, as predicted by the face-space model and previous findings (e.g., Johnston et al., 1997). This result confirms that MDS is a useful method of analysis, even when the homogeneity of the stimulus set is increased because all faces share the same hair. The results also suggested that using 18-24 face stimuli would be sufficient to produce comparable MDS solutions as using the full set of 36 faces. Because the fit of any MDS solution will improve with more dimensions relative to the number of stimuli used, we chose the more conservative method of using a minimum of 24 faces. The nature of what the 5-6 dimensions represent in the MDS solutions of Experiment 1 will be discussed together with the results from Experiment 2.

Experiment 2

The goal of Experiment 2 was to examine whether comparable similarity judgments to those obtained in Experiment 1 could be collected through the use of an odd-man-out paradigm rather than a rating scale, and if so, to compare 8-year-olds' and adults' face-space using multi-dimensional scaling. In an odd-man-out paradigm, observers are asked to choose the one item that looks most different from the rest of the array on each trial. No reference to a rating scale is required, so the method should be more suitable for children. MDS has been applied successfully to adults' similarity judgments obtained through the odd-man-out paradigm (e.g., Romney et al., 1993), including similarity judgments of face stimuli (Yotsumoto et al., 2007). We minimized working memory load by presenting only 3 faces simultaneously, and the observer's task was to choose the face that looked most different from the other two faces in the array. Given the results of Experiment 1, we chose to use 25 face stimuli to have a balanced incomplete block design (Weller & Romney, 1988; Yotsumoto et al., 2007). This design allowed us to present the minimal number of necessary *triads* (arrays of 3 faces) to observers while ensuring that each face *pair* was presented an equal number of times (a balanced incomplete block design is not possible with 24 stimuli). The 13 most distinctive faces and the 12 most typical faces were chosen as the face stimuli because we aimed to provide sufficient variability in the internal facial characteristics among faces to reveal differences, if any, between children and adults' similarity judgments and to evaluate the influence of typicality/distinctiveness on those judgments.

We first collected similarity judgments from adults using the odd-man-out method (Experiment 2a), and verified the convergence of the MDS solutions between Experiments 1 and 2a. We then collected similarity judgments from 8-year-olds using the odd-man-out method to compare children's and adults' similarity judgments and the resulting MDS solutions (Experiment 2b).

Methods – Experiment 2a

Participants

Participants were 24 Caucasian undergraduate students (17 female; age 18-22 years, M = 19.9 years) participating for bonus credit in an introductory psychology course. All had normal or corrected-to-normal vision.

Stimuli

The 13 most distinctive and 12 most typical faces from Experiment 1 were chosen to form a balanced incomplete block design, which allows for the minimal number of *triad* presentations (A-B-C) while ensuring equal presentation of face *pairs* (a single triad results in three face pairs: A-B, A-C, B-C). Stimuli were 10.3 cm x 15.0 cm viewed from a distance of 100 cm (5.90° x 8.74° of visual angle).

Apparatus

Stimuli were presented on a 19-inch Trinitron monitor using XScope software, on a Mac mini computer running on OS X.

Procedure

This study was approved by the research ethics board of McMaster University. All participants were informed of the nature of the task and provided written consent at the beginning of the session. Each participant was tested individually in a dimly lit room.

The procedure began by introducing the purpose of the study as a game in which "*many women are looking for a partner to join a race*". The observer's task was to help these women find their best partners "*because partners who look alike are going to do the best in this race*". To clarify the task, a demonstration trial showed three schematic faces on the screen (two smiling faces and one frowning face) and the participant was asked to choose the face that looked "*the most different*".

Participants then performed six validity trials with photographs of vehicles of transportation, to verify that they had understood the task of choosing the stimulus that was most different (i.e., odd-man-out). On each trial, two photographs of the same vehicle type were shown (e.g., two transport trucks) and one photograph of a different vehicle (e.g., an airplane). Participants were asked to choose the object that was most different, and were required to answer all six validity trials correctly to proceed to the next practice block. All participants passed this criterion on their first attempt.

Participants then completed six practice trials with faces. Face stimuli were chosen such that there was one obviously different face in each triad (e.g., two women's faces and one man's face), although participants were free to choose the face that appeared most different to them (i.e., no feedback from the experimenter was given other than words of encouragement). On each trial, after the observer had chosen the most different face, the remaining two faces were shown in an animation with two people holding hands and forming a team, to emphasize the purpose of the game.

Participants then completed 200 test trials. On each trial, three faces were shown in the same layout as practice trials and subjects were encouraged to look carefully at all three faces before choosing the face that appeared most different, either by a verbal response or a mouse click (see Figure 3). The formation of the triads was randomized across subjects, with the constraint that each face pair was presented twice for every subject, because collecting similarity judgments from only a single presentation of each pair has been shown to produce unreliable results in a balanced incomplete block design (Burton & Nerlove, 1976). After approximately every 15-30 trials there was a "bonus" trial in which the observer was free to take a break as needed.

Data Analysis

Data from the odd-man-out judgments were recoded such that given a triad A-B-C, if face A was chosen as most different, face pairs A-B and A-C were given a distance score of 1, and face pair B-C was given a score of 0, because similar faces should be closer together in face-space. The average distance for each face pair was calculated for each subject. Before performing multi-dimensional scaling, we compared these distance values for each face pair to the raw similarity ratings from Experiment 1.

Using the distance values from each participant, multi-dimensional scaling was performed using the INDSCAL procedure in SPSS software (as in Experiment 1). Additionally, pairwise distance in the MDS solutions, equal to the square root of the sum of the intradimensional differences (Borg & Groenen, 2005), was calculated between all possible pairs of faces for the 2- to 6-dimensional solutions. These distances were compared to pairwise distances in the MDS solutions from Experiment 1 and to the raw similarity judgments from Experiment 1.

To interpret what the MDS dimensions represent psychologically, for each MDS solution, the faces were ranked in terms of their position along each dimension. For each dimension, the four most extreme faces at the positive end were morphed together and the four most extreme faces at the negative end were morphed together, in an attempt to cancel out cues that were not diagnostic of that dimension. These morphed faces were then compared to each other and to the average face (a morph of all 25 faces) to infer the facial characteristic(s) represented by that dimension. The interpretability of these dimensions and the goodness-of-fit of the MDS solutions were used to choose the best MDS solution that captured adults' similarity judgments, which appeared to be the 5-dimensional solutions. Subsequently, cluster analysis (Sireci & Geisinger, 1992) was performed using SPSS version 16.0 for Mac OSX on the position of the faces in the 5-dimensional MDS solutions to compare local clustering of faces in Experiments 1 and 2a.

Results

The correlation between the distance values from odd-man-out judgments and the raw similarity ratings from Experiment 1 was very high, $r(298) = 0.797$, $p < .001$. The goodness-of-fit measured by Kruskal's Stress 1 Formula (Kruskal & Wish, 1978) for the multi-dimensional scaling solutions with 2 to 6 dimensions are shown in Figure 4, along with the goodness-of-fit for the solutions from Experiment 1 (using only the same subset of 25 faces used in Experiment 2). The fit of the MDS solutions from the two experiments appear very similar (see overlapping lines in Figure 4), a pattern again suggesting that similarity judgments collected through the use of a rating scale and through odd-man-out judgments are comparable. Five or six dimensions appear to account for the similarity data well.

The pairwise distances in the MDS solutions of Experiment 2 (odd-man-out method) correlated highly with the pairwise distances in the corresponding

MDS solutions of Experiment 1 (rating scale method; see Table 2). The layout of the two-dimensional solutions (for ease of representation) from Experiments 1 and 2 are shown in Figure 5. They also correlate well with the raw similarity ratings from Experiment 1 and the raw odd-man-out (Table 3). The pattern of correlations, along with Kruskal's Stress values, suggest that four to six dimensions optimally account for adults' similarity judgments.

As in Experiment 1, we also compared the distance to the origin for typical versus distinctive faces, for each of the 2- to 6-dimensional MDS solutions. For every solution, typical faces were closer to the origin than the distinctive faces (Table 4). Although the effect sizes were smaller than those observed in Experiment 1 and in a previous study (Johnston et al., 1997), they were still large by conventional standards (Cohen's $d > 0.7$). This finding suggests that a 7-point rating scale (Experiment 1) is more sensitive than the odd-man-out method (distances range only from 0 to 1), but that the odd-man-out judgments can still reveal robust typicality effects in the MDS solutions.

Another method of comparing the MDS solutions based on adults' similarity ratings and odd-man-out judgments is to examine how the faces cluster together locally in the MDS solutions. Because it is impossible to visually inspect local clusters of faces in a 5-dimensional solution, we conducted cluster analyses (e.g., Johnson, 1967; Sireci & Geisinger, 1992) to first determine which faces cluster together locally in the solutions from each of the two experiments. When faces were grouped so that single clusters contained no more than 4 faces (producing 8 or 9 clusters), 19/25 faces in the solution from Experiment 1 fell into the same clusters in Experiment 2 (Figures 7a & b). This pattern of results suggests that the local clustering of faces (i.e., perceived similarity of groups of faces) was similar in the MDS solutions produced from adults' similarity ratings (Experiment 1) and odd-man-out judgments (Experiment 2).

To examine what the MDS dimensions represent, and to determine the best solution, we morphed the faces located at the ends of each dimension in the 4-, 5- and 6-dimensional MDS solutions from Experiments 1 and 2a. The 4- and 6-dimensional solutions were less interpretable than the five-dimensional solution, and therefore subsequent analyses are based on the 5-dimensional solutions. Subjective visual inspection of the face morphs (Figures 6a and b) suggests that the dimensions do not represent a single feature cue, but rather that each dimension represents multiple facial characteristics. A subjective interpretation of the most salient characteristics, as judged by the authors' inspection of the face morphs (see Figures 6a and b), is summarized in Table 5, as well as the relative weighting of that dimension in the MDS solutions. A comparison of the morphed faces in Figures 6a and b, as well as the summary in Table 5, reveals some overlap in the characteristics revealed through the MDS solutions in Experiments 1 and 2a, but they were not identical. For example, the first two dimensions can be interpreted as coding face length, perceived age of face, and eye colour, yet the morphed faces representing the most extreme values along the dimensions are not identical between Experiments 1 and 2a.

Discussion

The pattern of findings based on adults' odd-man-out judgments was consistent with the pattern from adults' similarity ratings collected in Experiment 1, verifying the validity of the odd-man-out method to obtain similarity data suitable for multi-dimensional scaling. The raw similarity judgments collected through the two methods, as well as the pairwise distances based on the MDS solutions, were all highly correlated. The results from the cluster analysis revealed that similar faces clustered together in the MDS solutions from the two methods. Larger effects of typicality on the MDS solutions were observed for the similarity ratings, but robust effects were still observed in the odd-man-out data. These results suggest that the odd-man-out method is a suitable method for collecting similarity judgments of facial identity. In Experiment 2b we used the same method to collect similarity judgments from 8-year-olds.

Methods – Experiment 2b

Participants

Twenty-four Caucasian 8-year-old children (+/- 3 months; 12 female) with normal or corrected-to-normal vision participated in the study. Children were recruited from a database of names of mothers who had volunteered for developmental studies at the time of the child's birth. Children were given snacks (cookies and/or juice) and stickers during breaks, and a toy from the toy box ($1-2 value) to take home as a token of our appreciation at the end of the experiment.

Parents did not receive any compensation, other than free parking on campus during the experiment.

Stimuli & Procedure

This study was approved by the research ethics board of McMaster University. Children provided informed verbal assent, and their parents provided informed written consent. The stimuli and procedure were identical to Experiment 2a, except for the stickers and a snack break half way through the session. All participants passed criterion on their first block (i.e., choosing the most different vehicle correctly on all six validity trials).

Data Analysis

Data analyses were performed in the same manner as in Experiment 2a.

Results

A comparison of the raw distance values from the odd-man-out judgments made by 8-year-olds and adults revealed a significant correlation, $r(298) = 0.721$, $p < 0.01$. From the INDSCAL method, the goodness-of-fit of the 2- to 6-dimensional solutions was assessed through Kruskal's Stress Formula (Kruskal & Wish, 1978), and is shown in Figure 4. Similar to the adult data, five or six dimensions appeared to best account for children's similarity judgments. However, the stress values for 8-year-olds' solutions were relatively high: higher than any of the 2- to 6-dimensional MDS solutions for adults tested with the same method (Experiment 2a) and higher than what have been reported for adults in previous studies of face perception (e.g., Johnston et al., 1997; Lee et al., 2000; Yotsumoto et al., 1997).

Despite children's higher stress values, the correlations between the pairwise distances in the MDS solutions and raw similarity judgments were comparable to those of adults (Table 3) and to previous reports (Busey, 1998). Furthermore, the pairwise distances in the MDS solutions were all highly correlated with those of the adult MDS solutions (Table 6). The distance to the origin in children's MDS solutions was smaller for typical faces than distinctive faces, similar to the results from adults' odd-man-out judgments in Experiment 2a, with comparable effect sizes (cf. Tables 4 and 7). However, the standard variations of the distances to the origin appear higher (Table 7) than those observed in the adult MDS solutions (Table 4), a result which suggests greater variability in the location of typical and distinctive faces in the MDS solutions of children than adults.

The results of the cluster analysis based on the 5-dimensional MDS solution revealed that 16/25 faces in the 8-year-olds' solution fell into the same clusters as in the adult solution from Experiment 2a (Figure 7c). This finding is similar to the comparison of the clusters between the two adult groups, and reveals that local clustering of faces in the MDS solution from 8-year-olds was similar to that of adults.

Figure 6c shows the morphed faces representing the dimensions of the 5D MDS solution (face morphs based on 4- and 6-dimensional solutions were less interpretable, similar to the adult data). As in the adult data, the dimensions do not appear to code for single features that can be easily verbalized. Nonetheless, a comparison of the most salient characteristics (judged subjectively by the authors looking at the face morphs) reveals some similarity to the adults tested with the same odd-man-out method, but fewer correspondences than between the two adult groups (Table 5). Importantly, the average weightings of the dimensions reveal that children relied very heavily on the first dimension, which likely represents eye colour (among other cues), and relied much less on the other dimensions, whereas adults' use of various dimensions was more equally distributed. To examine this age difference further, we compared individual children and adults' use of the dimensions when only two dimensions were imposed on the similarity data. Figure 8 reveals that adults' weightings cluster around the diagonal, which represents roughly equal use of the two dimensions by all adults. However, the weightings of roughly half of the 8-year-olds are biased heavily towards a single dimension, and for many 8-year-olds, the weightings are close to the origin. The clustering around the origin likely represents children switching their use of the dimensions across trials, and/or relying on a different dimension(s) that was not captured in the group solution (especially the one child whose weightings for both dimensions are near zero). The variability and the low weightings of the 8-year-olds confirm the poor fit of the MDS solutions to the raw data indicated by Kruskal's Stress values (Figure 4).

If the low weightings of the MDS dimensions demonstrated by roughly half of the 8-year-olds (Figure 8) represent inconsistencies in children's use of the dimensions across trials, we should observe greater variability in children than in adults, both across individuals and within individuals. Inter-individual variability was assessed by calculating the standard deviation of all pairwise similarity distances in the raw odd-man-out judgments from 8-year-olds and adults (each individual rated every pair twice). A paired samples t-test revealed that adults' standard deviations were smaller than those of 8-year-olds, $t(299) = 4.75$, $p < 0.001$, a finding that suggests that there was more variability between 8-year-olds than between adults in the similarity judgments. Intra-individual variability was assessed by comparing how often 8-year-olds and adults chose the same pair as being most different when it was presented a second time with a different third face. As a group, 8-year-olds were more likely to change their answer on the second presentation than adults, $t(46) = 2.83$, $p < 0.01$[5]. This finding suggests that children were more variable in their odd-man-out choices than adults, a finding which is consistent with the interpretation that children with low weightings on the MDS dimensions were using different dimensions on different trials.

Discussion

[5] Consistency in responses at the individual level cannot be assessed adequately with the current method, because although all observers saw each face pair twice, the third face forming the triad differed for every individual. That is, we cannot meaningfully compare whether Subject 1 was more consistent than Subject 2 because the two subjects did not observe face pair A-B relative to the same third face. However, if adults and 8-year-olds were responding in a similar manner, we should not observe any difference at the group level because triads were formed randomly across subjects.

The results from Experiment 2 demonstrate a number of similarities between the judgments of children and adults. First, children's similarity judgments from an odd-man-out paradigm were highly correlated with adults' judgments using the same method. Second, a comparison of the clustering of faces in the MDS solutions revealed that 8-year-olds perceived the similarity of facial identity in a manner similar to adults, even when salient hair cues could not be used. These findings are consistent with previous reports suggesting that by 7 years of age children have a face-space that is similar to adults (Pedelty et al., 1985), and that by 8 years of age face-space is centered on an average face or norm (Nishimura et al., in press). Third, the MDS solutions based on children's and adults' odd-man-out judgments revealed that typical faces, rated by an independent group of adult observers, were located closer to the origin than distinctive faces, a finding that is also consistent with previous research (e.g., Johnston et al., 1997) and suggests that by 8 years of age children perceive the typicality/distinctiveness of faces in a manner similar to adults (e.g., Johnston & Ellis, 1995; Chang et al., 2002). These findings suggest that the spatial layout of children's psychological face-space is similar to that of adults in some respects.

The most striking difference between the MDS solutions of 8-year-olds and adults was the fact that no MDS solution fit the raw data of 8-year-olds as well as those of adults (see Figure 4). The poor fit may, in part, be accounted for by the greater variability in the odd-man-out choices made by 8-year-olds than adults, which was revealed in the analyses of within- and between-subjects variability. This pattern of findings suggests that children's immaturities on face processing tasks (e.g., Johnston & Ellis, 1995; Mondloch et al., 2002, 2003, 2004) may reflect, in part, greater variability among 8-year-olds. One possible explanation for this variability is that children use a different dimension depending on the particular faces to be encoded. Whereas adults may consistently use the same (five) dimensions simultaneously to code facial identity and thereby make similarity judgments, children may utilize a single dimension that is guided by the most salient cue in the face to be coded. For example, when shown two faces with brown eyes and one face with blue eyes, children may rely solely on eye colour to choose the odd-man-out, but given three faces with blue eyes, they may rely solely on another chacteristic, such as face width. In contrast, adults may use the same amalgam of characteristics for every trial. However, across trials, both strategies may converge to reveal similar dimensions, as was the case in this study (see Table 5 and Figure 6). One method to examine this possibility in future studies would be to use the same triads for all observers to examine inter-individual differences, and to repeat the triads to assess intra-individual differences.

The variability in children's responses suggest that children are utilizing different dimensions on a trial-by-trial basis to make similarity judgments whereas adults use the same dimensions more equally and consistently. One consequence is that children's MDS solutions will vary more than adults' solutions depending on the stimulus set they are asked to judge and will, in turn, make them appear more or less mature. For example, the MDS solutions from children 7-11 years appeared to be more similar to those of adults when hair cues were present (Pedelty et al., 1985) than when they were removed as in the current study, a pattern that suggests that the saliency of available facial characteristics affects the nature of the MDS solutions and the interpretation of developmental differences. A recent study by Yotsumoto, Kahana, Wilson, & Sekuler (2007) found that adults' recognition memory of unfamiliar faces is affected independently by both the similarity of the target face to the study faces and the similarity among the study faces themselves. Although Yotsumoto et al. examined recognition memory, similarity judgments will also likely be influenced by the homogeneity of the stimulus set. Future studies could compare consistencies in the MDS solutions for children and adults across face sets differing systematically in homogeneity. The tendency of children to rely heavily on a single dimension (see Table 5 and Figure 8) suggests that varying the homogeneity of the test stimuli would have a greater effect on children than adults, because presumably it will become increasingly more difficult to capture subtle differences among increasingly homogeneous face stimuli. For example, using only typical faces (presumably sampling a small area of face-space) or only distinctive faces (presumably sampling a wide area of face-space) should have a larger effect on children's similarity judgments than on adults' judgments. It is unclear, however, whether children would appear more like adults when judging only typical or only distinctive faces, because not all distinctive faces differ from the average in the same way, making different facial characteristics salient on different trials.

The average weightings (Table 5) of 8-year-olds' MDS dimensions revealed that children relied heavily on a single dimension, likely eye colour, when making similarity judgments, whereas adults used all five dimensions more equally. This age difference was not revealed by simply correlating the similarity judgments of 8-year-olds and adults and demonstrates the utility of MDS in examining subtle developmental differences. The interpretation that children relied heavily on eye colour as a cue when making similarity judgments is consistent with previous research showing children's reliance on a single face attribute when categorizing faces (Schwarzer, 2000) and children's nearly adult-like sensitivity to changes in feature shapes by 8 years of age (Mondloch et al., 2002). Conversely, there was no clear indication of a dimension in children's 5D solution that coded eye-to-eyebrow distance, unlike adults' dimensions, which is consistent with the slow development of sensitivity to the spatial relations among internal facial features (Mondloch et al., 2002, 2003).

The interpretation of what the MDS dimensions represent psychologically proved difficult, because each dimension for adults, and to some extent children, appeared to represent multiple facial characteristics that cannot be easily verbalized. However, some of the most salient facial features representing the dimensions appeared to be face length, eye colour, and perceived age of the face, as judged by the experimenters. The difficulty in interpreting these dimensions suggests that adults use multiple cues to make similarity judgments of facial identity, which is consistent with previous reports of adults' use of an amalgam of facial features in judging facial identity (e.g., Schwarzer, 2000). One limitation of the present study is that the interpretation of what the MDS dimensions represented psychologically was subjective, as are all psychological interpretations of multi-dimensional scaling dimensions. To obtain a more objective interpretation of the dimensions, an extension of the current study would be to have independent observers describe the perceptual characteristics that the MDS dimensions represent, although this method still assumes that the MDS dimensions capture characteristics that can be verbalized. The degree of agreement among independent raters would provide a measure of objectivity in interpreting what the dimensions represent psychologically, and also reveal the extent to which different dimensions capture easily verbalizable facial characteristics. One hypothesis is that there would be more agreement in the interpretation of children's dimensions, given their greater reliance on a single dimension and their sensitivity to local feature cues. Such a finding would extend our understanding of the development of children's face-space.

In summary, the present study used a novel child-friendly paradigm to compare children's and adults' face-space. By creating a homogeneous set of face stimuli with the same hair, subtle differences between children's and adults' processing of facial identity could be examined, because salient hair cues that could lead to an overestimation of the similarity between children's and adults' judgments were removed. Additionally, we provide evidence to support the utility of an odd-man-out paradigm in obtaining similarity judgments, instead of a rating scale that must be interpreted. The findings from this novel paradigm suggest that the layout of 8-year-olds' face-space is similar to that of adults, but that children are more variable than adults in their use of the dimensions. This variability may contribute to immature performance on face processing tasks at 8 years of age.

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	Number of Dimensions				
	2	3	4	5	6
Mean distance to origin of distinctive faces (SD)	1.48 (0.13)	1.81 (0.11)	2.09 (0.09)	2.31 (0.09)	2.52 (0.09)
Mean distance to origin of typical faces (SD)	1.32 (0.09)	1.63 (0.08)	1.90 (0.07)	2.15 (0.08)	2.37 (0.06)
$t(23) =$ ($p <$)	3.56 (.01)	4.56 (.001)	5.60 (.001)	5.03 (.001)	5.05 (.001)
Effect size (Cohen's d)	1.48	1.90	2.34	2.10	2.11
Effect size (Cohen's d) from data reported by Johnston et al. (1997)	1.84	2.05	2.06	1.64	1.97

Table 1. A comparison of the mean distance to the origin (standard deviation) for distinctive faces versus typical faces for 2- to 6-dimensional MDS solutions based on adults' similarity ratings using a 7-point rating scale (Experiment 1). Effect sizes (Cohen's d) are shown for the data from the current study, as well as the data reported by Johnston et al. (1997) in a previous study using 36 male faces with individuating hair cues.

	Number of Dimensions				
	2	3	4	5	6
Correlation coefficient	.582	.774	.765	.752	.743
$p =$	.000	.000	.000	.000	.000

Table 2. Correlation coefficients (Pearson's r) for the pairwise distances obtained from solutions using the rating scale method (Experiment 1) and the odd-man-out method (Experiment 2a).

	Number of Dimensions				
	2	3	4	5	6
Adults Rating Method	.607	.680	.718	.701	.699
Adults Odd-man-out Method	.655	.745	.775	.784	.794
Eight-year-olds Odd-man-out Method	.674	.754	.782	.810	.809

Table 3. Correlation coefficients (Pearson's r) for the pairwise distances based on MDS solutions and raw similarity judgments (all *p*s < 0.001).

	Number of Dimensions				
	2	3	4	5	6
Mean distance to origin of distinctive faces (SD)	1.45 (0.12)	1.75 (0.07)	2.04 (0.05)	2.27 (0.04)	2.48 (0.03)
Mean distance to origin of typical faces (SD)	1.37 (0.08)	1.71 (0.05)	1.96 (0.05)	2.20 (0.05)	2.42 (0.04)
$t(23) =$ (p-values)	1.88 (.07)	2.00 (.06)	3.67 (.001)	4.06 (.0001)	3.89 (.001)
Effect size (Cohen's d)	0.78	0.83	1.53	1.69	1.62

Table 4. A comparison of the mean distance (standard deviations) to the origin for distinctive faces versus typical faces for 2- to 6-dimensional MDS solutions based on adults' similarity judgments made using the odd-man-out method (Experiment 2a).

	Dimension 1	Dimension 2	Dimension 3	Dimension 4	Dimension 5
Adults Rating	Face length & age	Eye colour	Nose size, eye to eyebrow distance	Face width & eye size	Face length
	.051	.048	.043	.040	.039
Adults Odd-man-out	Face length, age, eye colour	Eye colour	Face width	Eye to eyebrow distance	Eye size & lip thickness
	.045	.043	.041	.036	.035
8-year-olds Odd-man-out	Eye colour	Cheek & eye size	Age & skin tone	Face length	Eye size
	.073	.037	.021	.018	.019

Table 5. Facial characteristics judged subjectively as representing the dimensions of the 5-dimensional MDS solutions, and their corresponding average weights, representing the relative use of each dimension in adults' similarity ratings (Experiment 1) and odd-man-out judgments (Experiment 2a), as well as 8-year-olds' odd-man-out judgments (Experiment 2b).

	Number of Dimensions				
	2	3	4	5	6
Correlation coefficient	.623	.681	.539	.606	.581
$p =$	.000	.000	.000	.000	.000

Table 6. Correlation coefficients for the pairwise distances from MDS solutions based on odd-man-out judgments by adults and 8-year-olds (Experiment 2).

	Number of Dimensions				
	2	3	4	5	6
Mean distance to origin of distinctive faces (SD)	1.47 (0.18)	1.80 (0.20)	2.09 (0.26)	2.33 (0.26)	2.57 (0.26)
Mean distance to origin of typical faces (SD)	1.34 (0.10)	1.65 (0.10)	1.87 (0.13)	2.11 (0.14)	2.29 (0.15)
$t(23) =$ ($p <$)	2.27 (.05)	2.35 (.05)	2.58 (.05)	2.59 (.05)	3.19 (.01)
Effect size (Cohen's d)	0.94	0.98	1.08	1.08	1.33

Table 7. A comparison of the mean distance (standard deviations) to the origin for distinctive faces versus typical faces for 2- to 6-dimensional MDS solutions based on 8-year-olds' similarity judgments.

Figure 1. An example of a typical female face (left) and a distinctive female face (right) used as test stimuli.

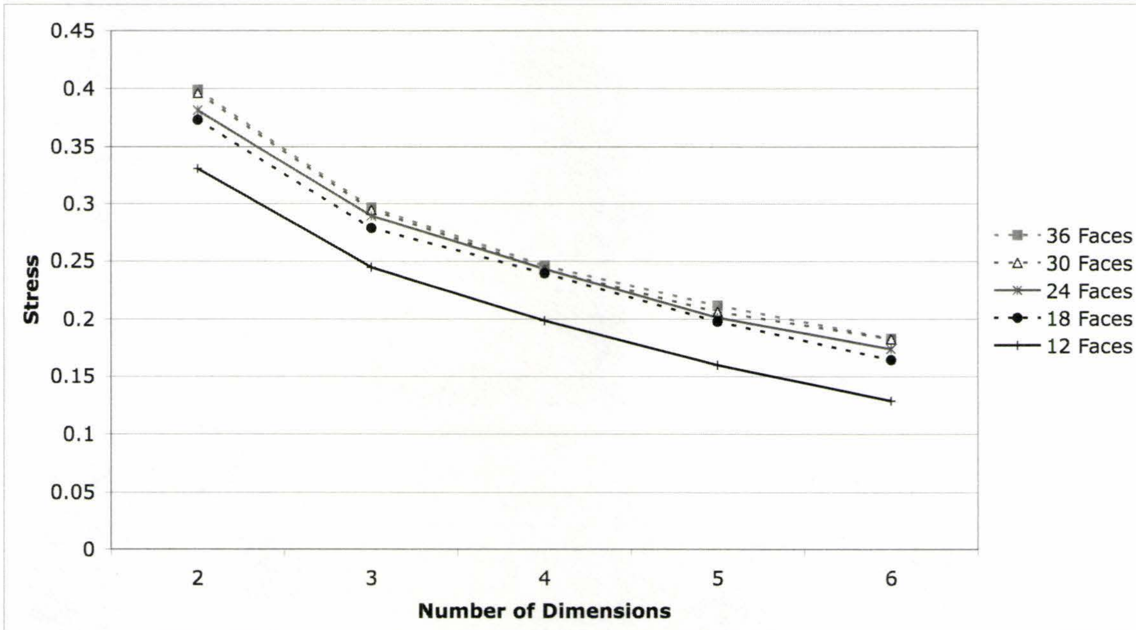

Figure 2. Goodness-of-fit (Kruskal's Stress 1; Kruskal & Wish, 1978) of 2- to 6-dimensional solutions with varying numbers of face stimuli included in MDS (Experiment 1).

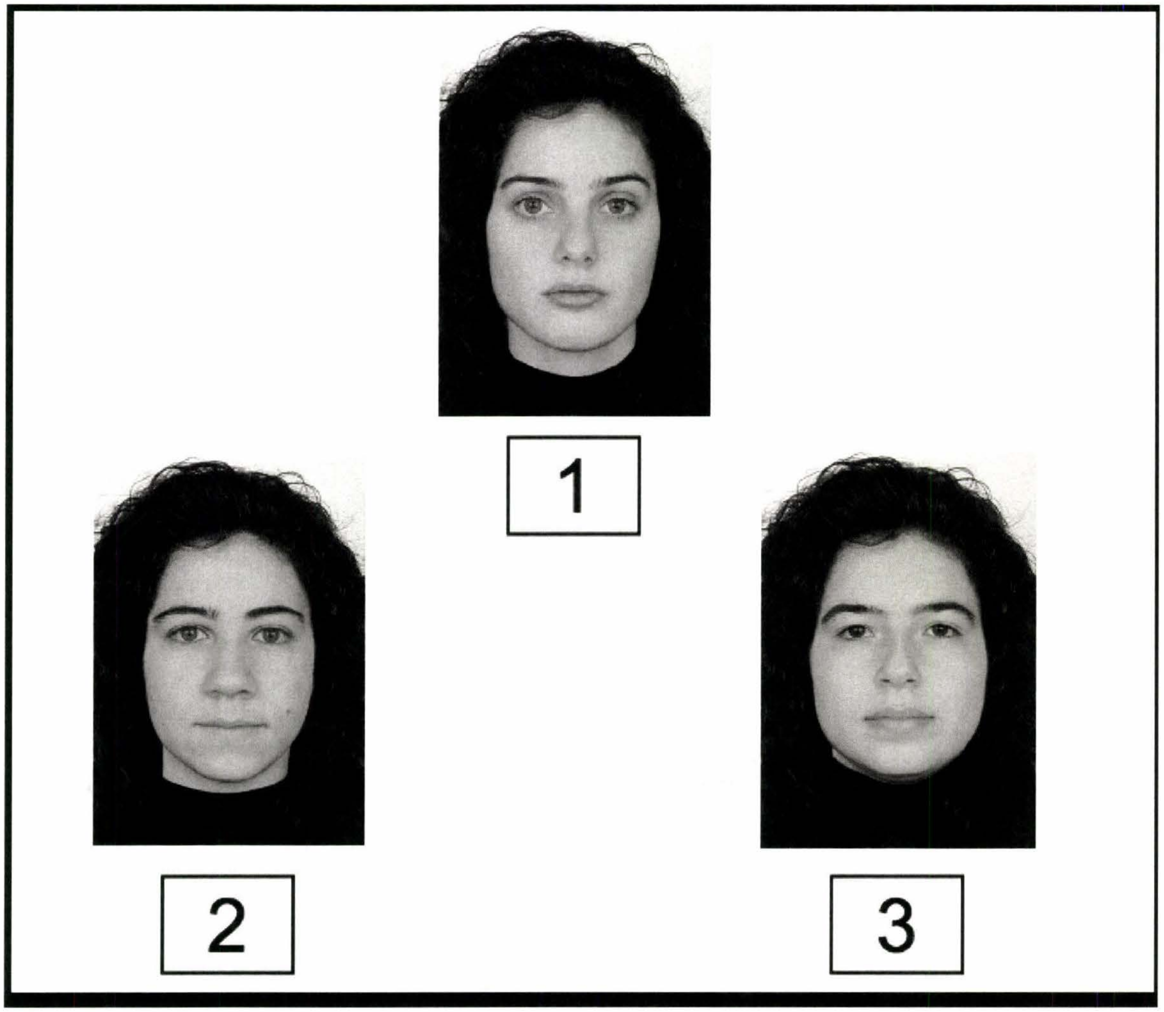

Figure 3. An example trial of the odd-man-out paradigm. Face 1 = 3rd most distinctive, Face 2 = 11th most distinctive, Face 3 = 3rd most typical.

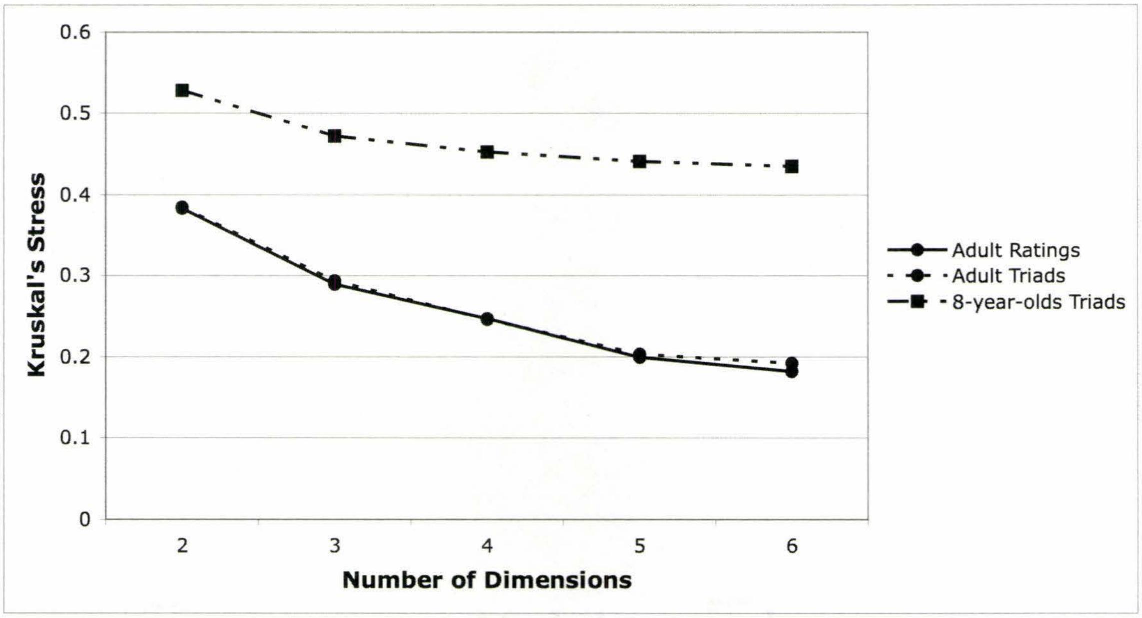

Figure 4. Goodness-of-fit of the MDS 2- to 6-dimensional solutions measured by Kruskal's Stress 1 formula (Kruskal & Wish, 1978), for which smaller values indicate better fit. The lines represent fit to similarity judgments based on adults' ratings (Experiment 1), adults' odd-man-out judgments (Experiment 2a), and 8-year-olds' odd-man-out judgments.

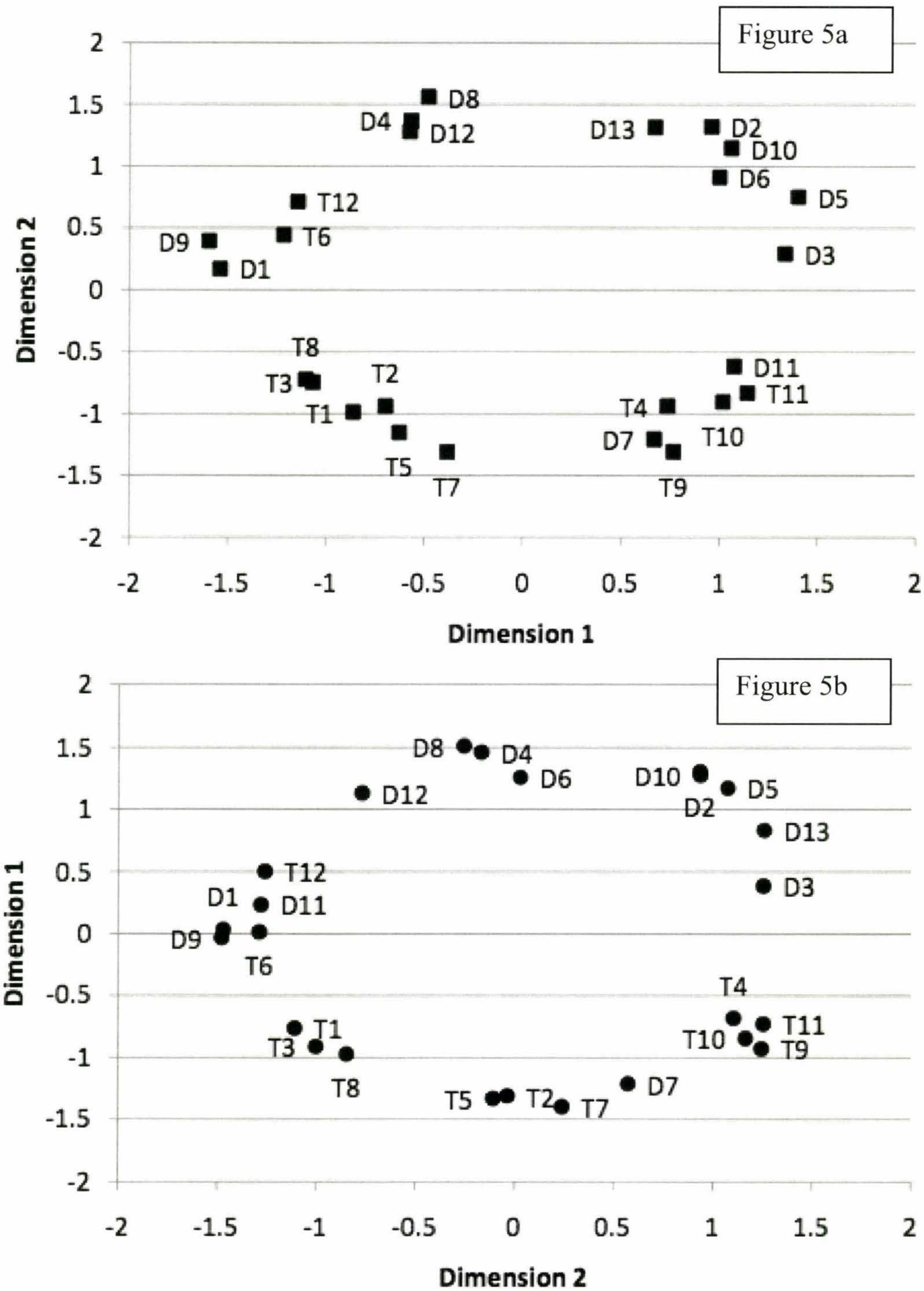

Figure 5. Two-dimensional MDS solution of adults' similarity judgments of 25 faces based on: a) pairs of faces using a 7-point rating scale (Experiment 1), and b) odd-man-out decisions (Experiment 2a).

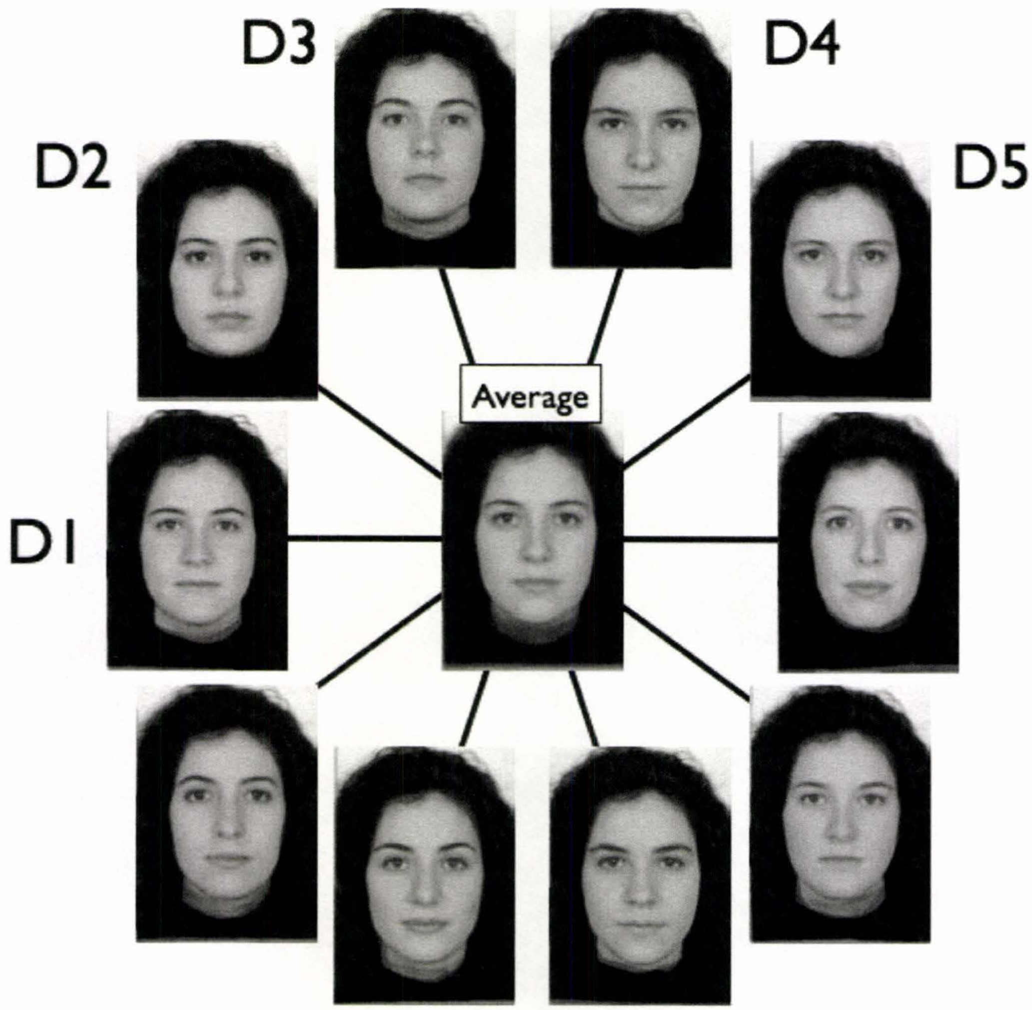

Figure 6a. A representation of the 5-dimensional MDS solution from Experiment 1 using only the subset of 25 faces used in Experiment 2.

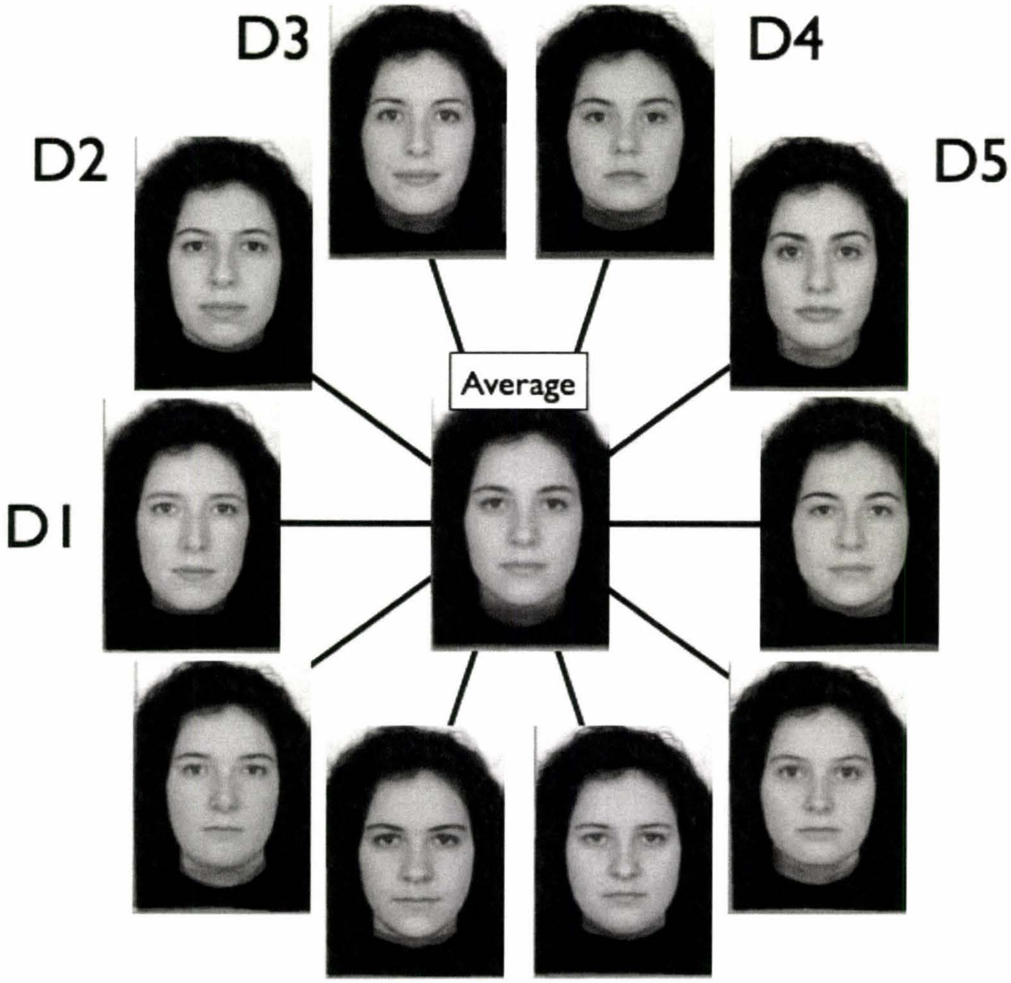

Figure 6b. A representation of the 5-dimensional MDS solution from adults' similarity judgments made in the odd-man-out task (Experiment 2a).

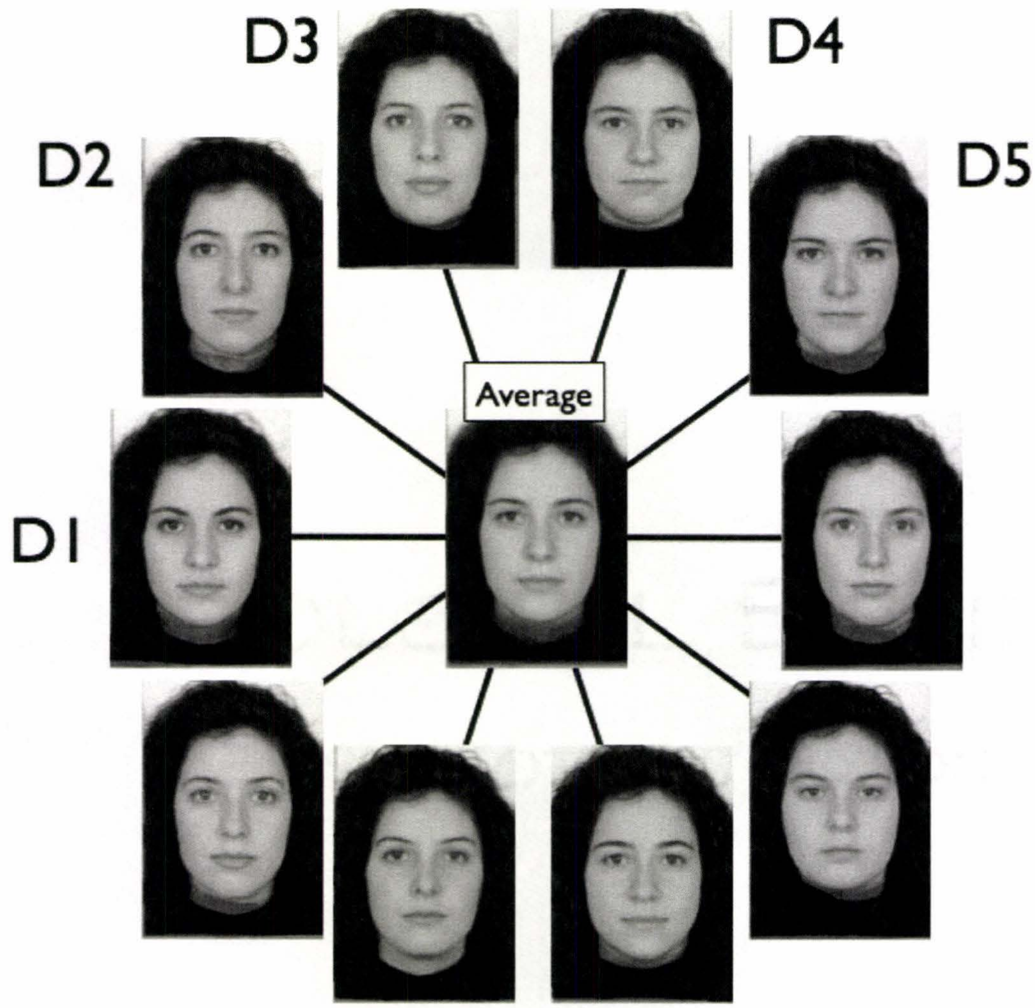

Figure 6c. A representation of the 5-dimensional MDS solution from 8-year-olds' similarity judgments made in the odd-man-out task (Experiment 2b).

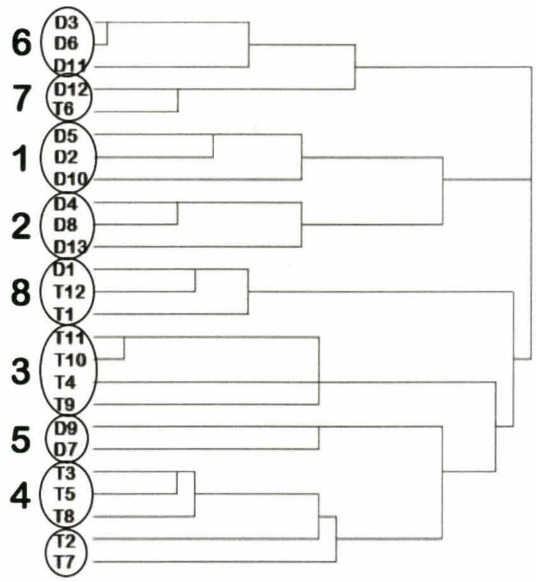

Figure 7a

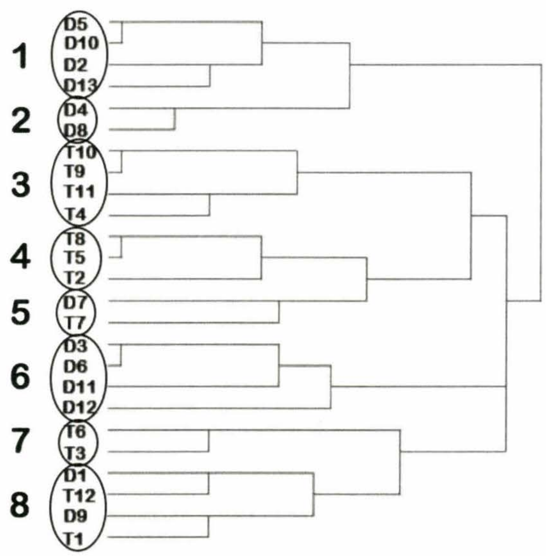

Figure 7b

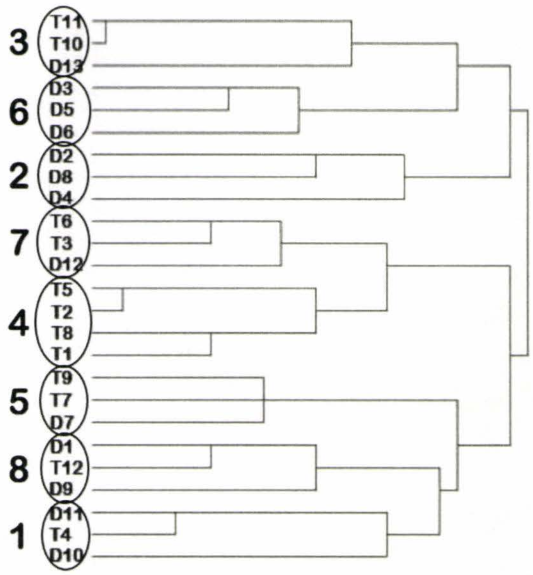

Figure 7c

Figure 7. The results of the cluster analysis using the position of faces in the 5-dimensional MDS solutions based on a) adults' similarity ratings (Experiment 1), b) adults' odd-man-out judgments (Experiment 2a), and c) 8-year-olds' odd-man-out judgments (Experiment 2b). Local clusters were created by grouping a maximum of four adjacent faces together (shown in ovals), and were numbered 1-8 in the solution from adults' odd-man-out judgments (figure 7b), and compared to the corresponding local clusters in the solution for adults' similarity ratings and 8-year-olds' odd-man-out judgments.

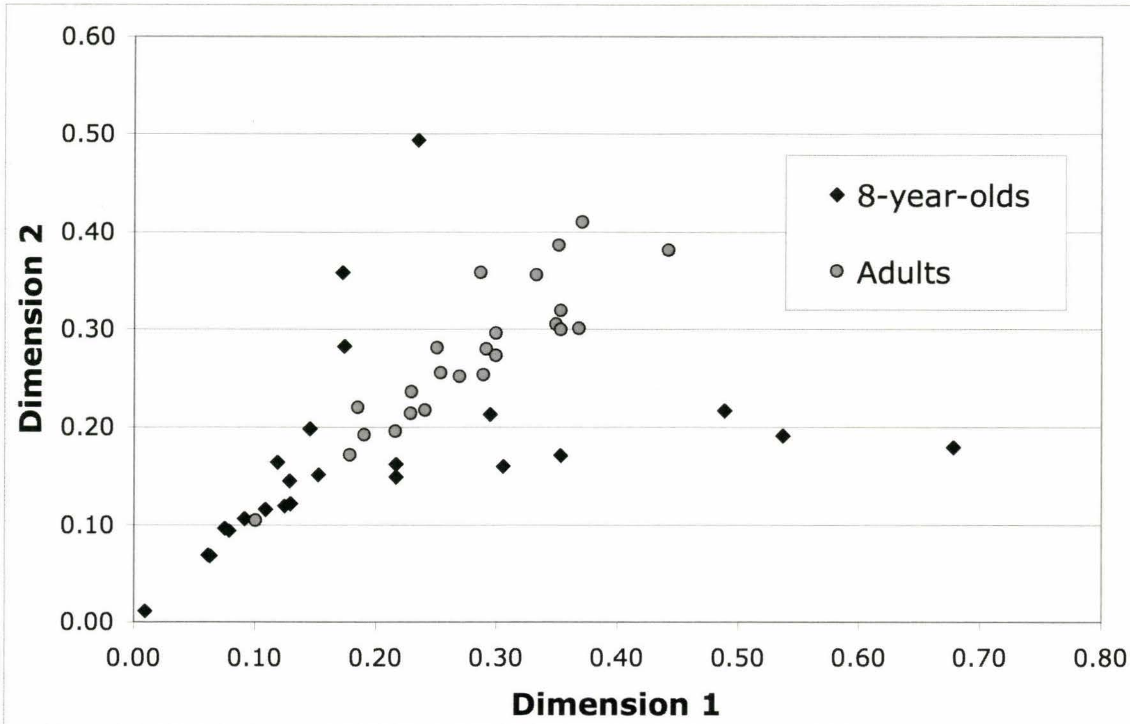

Figure 8. Individual weightings of the two dimensions produced in the group INDSCAL 2-dimensional solution for 8-year-olds and adults.

Chapter 4

Preface

The study described in this chapter has been written as a manuscript in preparation, to be submitted to a scientific journal. Authors on the manuscript will be Mayu Nishimura, Daphne Maurer, and Samidha S. Joglekar.

The study examined the development of face recognition in a complementary approach to the studies described in Chapters 2 and 3 by examining how children and adults learn to recognize facial identity of unfamiliar faces with short-term training. Specifically, the study examined improvement in 10-year-olds and adults on two face processing abilities: the ability to recognize facial identity across changes in viewpoint, and the ability to detect changes in the second-order relations (i.e., the spatial relations among internal features) of faces. These two abilities and their functional relationship are of theoretical interest because both skills are tuned to upright faces in adults, and both skills are not yet adult-like at age 10, a pattern of findings that suggests that experience plays an important role in shaping these two skills. The results from Experiment 1 showed that children and adults improved their recognition of faces across changes in viewpoint after short-term training, but the improvement failed to transfer to sensitivity to second-order relations in either age group. Children showed lower accuracy and greater variability than adults, a finding that is consistent with the variability observed in children's similarity judgments in Chapter 3. The results from Experiment 2 with adults also suggested that general memory capacities might limit short-term learning of facial identity across changes in viewpoint. The developmental implications of such capacity limits are discussed.

The effect of training on view-invariant recognition of faces and sensitivity to second-order relations.

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Abstract

Adults appear to utilize both view-independent and view-dependent information to recognize facial identity from novel viewpoints, but how this skill develops is not fully understood. In two experiments, we examined the effect of short-term training on adults' ability to recognize unfamiliar faces across changes in viewpoint, and whether any improvement correlates with improved sensitivity to second-order relations (i.e., the spatial relations among facial features), because second-order relations may be an important structural cue for view-invariant recognition. In one experiment we also trained 10-year-olds, who are not yet adult-like in all aspects of face processing, to examine whether the visual system is more malleable during development. The findings from Experiment 1 revealed that both 10-year-olds and adults improved on the training task, but that the effect of training was more robust in adults. Results from Experiment 2, with adults only, showed that the improvement transferred to one novel set of faces, but not to a third set, a pattern that suggests some memory capacity limit in short-term learning of view-dependent information that supports view-transformations for successful recognition across changes in viewpoint. Such capacity limits may have contributed to the greater variability in children's improvement scores and their lower accuracy than adults on all tasks. There was no evidence of a functional relationship between the ability to recognize facial identity across changes in viewpoint and sensitivity to second-order relations, in either age

group. The theoretical implications of the findings for the development of these two skills are discussed.

The ability to recognize faces from different viewpoints is a tremendous computational feat of the human brain. Two photographs of different faces taken from the same viewpoint share more image characteristics than two photographs of the same face taken from two different viewpoints (Hancock, Bruce, & Burton, 2000). The observer must solve the perceptual problem of distinguishing between differences in image characteristics that represent only a change in viewing angle, and additional differences that represent a simultaneous change in identity. How such processing is handled by the visual system is yet to be explained by research in face and object recognition (for a recent review see Peissig & Tarr, 2007).

With photographs of unfamiliar faces, adults' accuracy in matching facial identity decreases with increasing angles of rotation from frontal to profile view, although performance is above chance at all angles (e.g., Hill, Schyns, & Akamatzu, 1997; Lee, Matsumiya, & Wilson, 2006; McKone, 2008; Newell, Chiroro, & Valentine, 1999; O'Toole, Edelman, & Bulthoff, 1998). Even with familiar faces, adults' accuracy in recognizing the identity of the face decreases with greater deviation from frontal view (Hill & Bruce, 1996), although response times may not increase (Troje & Kersten, 1999). Even with photographs of their own faces, adults are faster to recognize photos of themselves from frontal view, which they experience in the mirror, than the profile view (Troje & Kersten, 1999). Collectively, the results suggest that adults are able to use view-invariant cues to recognize faces in unfamiliar viewpoints, but that even for highly familiar faces, recognition is best for views that are most familiar, a finding that demonstrates the view-dependence of face recognition. Overall, findings over the last three decades for both faces and objects indicate that view-invariant recognition is accomplished by an interactive process that involves both view-dependent and view-independent processes (e.g., Biederman & Bar, 1999; Burke, Taubert, & Higman, 2007; Hayward 2003; Tarr & Bulthoff, 1998). The view-dependent process is postulated to use feature- or image-based information that is specific to the viewpoint of the observer, whereas the view-independent process is thought to be based on structural properties of the stimulus that are independent of viewpoint (e.g., Fang & He, 2005; Hayward, 2003; Murray, Jolicoeur, McMullen, & Ingleton, 1993; O'Toole, Edelman, & Bulthoff, 1998; Troje & Kersten, 1999).

Adaptation studies provide evidence for both the view-dependent and structure-based processes. When an adult observer adapts to a face rotated by 15° or 30° to the *left* from frontal view, the perception of the same face in frontal view shifts in the opposite direction, such that he/she will report that the face appears to be rotated to the *right* (Fang & He, 2005; Fang, Ijichi, & He, 2007). This finding that a particular view of a face can be adapted and that adaptation can alter the perceived viewpoint of a subsequent face suggests that some neurons are tuned to specific viewpoints of faces. Additionally, when adults are adapted to a distortion of face shape (e.g., contracting or expanding the face) in one view and concurrently adapted to the opposite distortion in a second view, the two aftereffects do not cancel out, a result that suggests that different neurons are coding the two different views (Jeffery, Rhodes, & Busey, 2007).

Functional magnetic resonance imaging (fMRI) paradigms reveal that, within the area of the fusiform gyrus that is selectively responsive to faces (Kanwisher, McDermott, & Chun, 1997), different sub-regions show view-dependent versus view-independent activation (Pourtois et al., 2005). Also in the face-selective region of the lateral occipital cortex (LOC), repetition of a face decreases fMRI activation, unless the same face is presented from different viewpoints (Grill-Spector & Malach, 2001). Collectively, these findings provide strong evidence for the existence of neurons that are tuned to specific viewpoints of faces, which may play an important role in encoding view-specific representations.

Behavioral adaptation aftereffects are smaller when there is less disparity between the adapting and test viewpoints, a pattern suggesting some overlap in the views to which individual neurons are tuned (Fang & He, 2005; Jeffery et al., 2007). Moreover, when an adaptation paradigm emphasizes the identity of a face, rather than perceived viewpoint, observers can show view-invariant identity aftereffects (Jiang, Blanz, & O'Toole, 2006). An identity aftereffect is shown by a shift in the perceived identity of an average face in the direction opposite to the adapting face (e.g., Leopold, O'Toole, Vetter, & Blanz, 2001). This aftereffect has been shown to generalize across changes in viewpoint between the adapting and test faces (Jiang et al., 2006). The generalization indicates that adaptation affected view-invariant representations of faces, or at the very least, that adaptation affected representations of facial identity that support view-transformation.

The interactive process that combines both view-dependent and view-independent information likely involves a transformation process, such as normalization based on the known view-independent structural properties of the face, that is applied to view-specific representations (e.g., Hancock, Bruce, & Burton, 2000; O'Toole et al., 1998; Tarr & Bulthoff, 1998). As in any estimation, presumably this process will be more successful with more view-specific exemplars from which the view-independent structural properties can be derived. This was shown in a study that trained monkeys to recognize novel three-dimensional objects (Logothetis, Pauls, Bulthoff, & Poggio, 1994). In an old-new recognition task, monkeys first viewed a novel object in an animation from a single view (within which the object appeared to oscillate slowly by +/- 10°), and then had to discriminate the same object from a distractor when they were presented from different viewpoints. Viewpoints varied in roughly 10-15° increments about the horizontal, vertical, and +/- 45° diagonal over the full range of 360° views. Monkeys' recognition was poor when the familiar object was shown from a view rotated by more than 40° from the centre of the studied animation (Logothetis et al., 1994). However, when trained on as few as three views of a novel object 120° apart, monkeys could recognize most viewpoints well (Logothetis et al., 1994). These findings suggest that an exemplar from a single view may not be sufficient for view-invariant recognition, but that as few as three key viewpoints are sufficient to support view-independent recognition. Indeed, Perrett and colleagues (1985, 1987) have found four classes of face-selective neurons in the superior temporal sulcus of the macaque monkey that are selectively tuned to one of four characteristic views of the head: frontal view, left or right profile views, and the back of the head. These prototypical views may be sufficient to support a transformation that allows view-invariant recognition of faces.

To accomplish view transformations for accurate face recognition, the observer must have some knowledge about the structural properties of faces. The structure-based model of view-invariant recognition was proposed originally for object recognition, based on findings that if the first image contains enough diagnostic information about the structural properties of the object (e.g., presence or absence of a diagnostic part), there appears to be little or no cost of rotation about the vertical axis (Biederman & Gerhardstein, 1993). When making a classification decision (i.e., judging whether an image is a face or not a face), the first-order relations of faces (i.e., the structural property shared by all faces of having two eyes above a nose above a mouth in an oval contour) would be a relevant structural property supporting view-invariant recognition. However, to make individual identity judgments, the structural properties that support view-invariant recognition must be specific to the individual, such as the spatial relations among the facial features, or the second-order relations of the face (e.g., Carey, 1992; Maurer, Le Grand, & Mondloch, 2002). Second-order relations vary across individuals (Farkas, 1981), and even when some features are hidden from view (e.g., a mole on left cheek would not be visible from right profile), the second-order relations of the face can remain visible (e.g., eye-to-mouth distance) and/or may be inferred from the remaining information (e.g., interocular distance can be inferred from the distance between the eye and the bridge of the nose, given the bilateral symmetry of faces). These properties make second-order relations a good candidate for guiding recognition of facial identity across changes in viewpoint. Furthermore, adults are extremely sensitive to the second-order relations of upright faces, as shown by the ability to detect deviations in mouth position as small as 1 minute of visual angle, very close to the visual acuity limit (Haig, 1984). Sensitivity to mouth position does not appear to be affected by familiarity (Brooks & Kemp, 2007; Ge, Luo, Nishimura, & Lee, 2003). Memory for eye position is also very accurate, as Mainland Chinese adults can detect deviations in photographs of Chairman Mao as accurately as naïve Eastern Asian observers making same/different judgments with the photos presented simultaneously, with both groups detecting deviations as small as 10 minutes of visual angle (Ge et al., 2003). When the faces are personally familiar to observers, eye positions are easier to detect in familiar than unfamiliar faces (Brooks & Kemp, 2007).

This analysis suggests that there may be a functional relationship between sensitivity to second-order relations and view-invariant recognition of facial identity. Indirect evidence is provided by a recent study that assessed the effect of viewpoint on holistic processing of faces as measured by the composite effect: difficulty in recognizing the top (or bottom) halves of faces when they are fused with the bottom (or top) half from a different face (Young, Hellawell, & Hay, 1987). The interference from the irrelevant half of the face implies that face recognition is not supported solely by local featural cues (Young et al., 1987). McKone (2008) demonstrated recently that the magnitude of the composite effect did not change as faces were rotated from frontal view to three-quarter and profile views, but that overall reaction times increased as faces were rotated away from frontal view. The pattern of these findings suggest that changes in viewpoint disrupt local featural information but not the information provided by a holistic percept above and beyond the sum of its parts, which would presumably include the spatial relations among internal features (e.g., vertical distances among eyes, nose, and mouth). Thus, developmental increases in sensitivity to second-order relations may underlie adults' ability to recognize the identity of faces in novel viewpoints. Indeed, both skills are slow to develop and sensitive to inversion. Ten-year-olds are as accurate as adults at most face processing tasks, including same/different judgments about faces with featural differences and matching the identity of faces that differ in facial expression (e.g., Mondloch, Le Grand, & Maurer, 2002; Mondloch, Geldart, Maurer, & Le Grand, 2003). The exceptions are sensitivity to second-order relations and matching the identity of faces despite a change in point of view: on both of these tasks, 10-year-olds are much less accurate than adults. Accuracy on both tasks is also greater for upright than inverted faces, and this difference is greater in adults than 10-year-olds (e.g., Bruce et al., 2000; Ellis, 1992; Mondloch, et al., 2002, 2003).

In the current experiment, we used a training procedure to evaluate the malleability of view-invariant recognition and its relationship to sensitivity to second-order relations. We designed a training study that simulates the real-world experience of learning to recognize upright faces across changes in viewpoint and measured learning in adults, who are not perfect at view-invariant recognition, and in 10-year-olds, who are not yet as accurate as adults. We suspected that training might be more effective in children, because the visual system may be more malleable at that age. Alternatively, adults may show better improvement because they have developed exquisite sensitivity to second-order relations, and algorithms for structural transformations that could assist them in doing the task, which might be easily refined.

Faces were shown as greyscale images because obvious colour cues allow for view-invariant recognition even without training (Hayward & Williams, 2000). Face stimuli were also presented in noise because pilot testing revealed that without noise the task was so easy for adults that there was little room for improvement. The training paradigm involved a 2AFC match-to-sample task, in which observers matched the identity of faces shown from different viewpoints. Pilot testing with 10 adults showed that a single one-hour session of training was not sufficient for all participants to demonstrate improvement. Therefore, observers were trained on two consecutive days to match the identity of unfamiliar faces across changes in viewpoint. This paradigm also allowed us to assess the effect of sleep on memory consolidation (e.g., Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Mednick et al., 2002; Mednick, Nakayama, & Stickgold, 2003; Stickgold, James, & Hobson, 2000), by comparing performance at the end of Day 1 and at the beginning of Day 2.

Before and after training, we tested sensitivity to changes in the second-order relations in a different set of faces, to examine whether sensitivity to second-order relations correlated with accuracy in view-invariant recognition at the beginning of training and to examine whether improvements in view-invariant recognition lead to improvements in sensitivity to second-order relations.

Experiment 1

The first goal of the study was to examine whether adults can learn to recognize unfamiliar faces across changes in viewpoint accurately after minimal exposure and a short training session. If a short period of training were successful, the finding would suggest that a few key exemplars are sufficient to allow the transformation process that adults presumably perform in their everyday environment to be applied to novel stimuli. Our second goal was to evaluate the hypothesis that sensitivity to second-order relations would be related to training success, because second-order relations represent a structural property of faces that supports the transformation process necessary for view-invariant face recognition. We evaluated this possibility by measuring sensitivity to second-order relations before and after training on recognizing faces across different viewpoints.

Our third goal was to evaluate the success of training in children 10 years old, an age when children are not yet adult-like at either matching identity across changes in viewpoint or discriminating changes in second-order relations. We reasoned that a stronger functional relationship between view-invariant recognition and sensitivity to second-order relations may be revealed at an age when both skills are still developing, whereas both skills may be over-learned in adults, making the effects of training less salient. Alternatively, there may be some capacity limit on the ability of 10-year-olds to recognize faces across changes in viewpoint, making short-term training ineffective. Indeed, given that they have had 10 years of experience processing faces, including recognizing faces across changes in viewpoint, but that they are nevertheless worse than adults, one might predict that 10-year-olds would not show any improvements from short-term training in the laboratory.

We also tested sensitivity to second-order relations in a control group of 10 adults who did not receive any training in matching facial identity across changes in viewpoint, but rather, participated in two sessions on consecutive days of non-face visual tasks (e.g., perception of global motion). If sensitivity to second-order relations develops, in part, as a consequence of our experience recognizing faces across changes in viewpoint, improvements in sensitivity to second-order relations should be greater in the trained groups than the control group.

Methods

Participants

Ten undergraduate students (8 female; age range 17-21 years) participated for course credit towards a psychology course or $10 per session. Ten 10-year-olds (+/- 3 months; 6 female) were recruited from a database of mothers who had volunteered for developmental studies at the time of the child's birth. They received snacks (cookies and/or juice) during breaks, if they wished, and all children chose a toy ($1-2 value) from the toy box at the end of each session. Parents were not compensated, but provided with free parking on campus during the experiment. All participants were Caucasian and had normal or corrected-to-normal vision.

Training Stimuli

Training stimuli consisted of a set of greyscale digital photographs of 15 Caucasian women aged 17 to 25 years taken from seven viewpoints: frontal, turned 45° to the left and right, turned 90° to the left and right (profile views), looking up, and looking down (see Figure 1). All models had minimal make-up and neutral expressions. To encourage processing of the internal physiognomy, models wore surgical caps to conceal their hair and ears. To ensure sufficient task difficulty so that there was room for improvement in the performance of adults, we applied Gaussian noise of 50% using the filter function in Adobe Photoshop

6.0 to each image. The faces were 10.2 cm wide and 15.2 cm tall (5.7° x 9.1° of visual angle from a viewing distance of 100 cm).

Test Stimuli

Test stimuli were the set of 5 faces with different second-order relations used previously by Mondloch et al. (2002). Briefly, the stimuli were created using an original greyscale photograph of a Caucasian woman with facial features (eyes, nose, and mouth) near the anthropomorphic mean (Farkas, 1981), and moving her eyes 4 mm (0.23° visual angle from a viewing distance of 100 cm) up, down, closer, or farther apart relative to the original, while simultaneously moving the mouth 2 mm (0.12° visual angle) up or down (see Figure 2). These stimuli were also shown inverted in a separate block.

Apparatus

The stimuli were presented on a 22-inch Macintosh monitor (screen size = 47.0 cm x 30.0 cm; 25.2° x 16.7° of visual angle from a viewing distance of 100 cm), controlled by a Power Mac G4 Cube computer, running in Mac OS 9.1, using Cedrus Superlab Software.

Procedure

This study was approved by the Research Ethics Board of McMaster University. The procedure was briefly explained to adult participants, children, and their parents, and informed consent was obtained from all participants, as well as the children's parents, at the beginning of the first day of training. Participants were trained and tested individually, seated 100 cm from the monitor in a dimly lit room.

Pre-test

Adults and children first performed a pre-test that measured their initial sensitivity to changes in the second-order relations of upright and inverted faces (for further details about the methodology see Mondloch et al., 2002). All participants completed the upright block first, followed by the inverted block. In each block, 4 practice trials were followed by 30 test trials in which the observer's task was to indicate whether two sequentially presented faces were the same or different (15 same, 15 different trials). Both images were presented for 200 ms separated by a checkerboard mask shown for 390 ms. Participants were asked to respond as quickly but as accurately as possible, using a Macally iShock controller. No feedback was given. Accuracy and response times were recorded.

Training

Following the pre-test, participants completed 6 training blocks (60 trials per block) of matching identities through changes in viewpoint in a 2AFC match-to-sample task. One face was shown for 500 ms, followed by a checkerboard mask for 390 ms, and then two images shown side-by-side from different viewpoints (different from each other and also from the sample face) that remained on the screen until the observer made a response. Only one of the two images matched the identity of the first face, and the task was to indicate whether the face on the left or the right had the same identity as the first face, with the correct side counterbalanced across trials. Feedback was given on each trial by one of two tones that signaled a correct or incorrect response. Stimuli were paired pseudorandomly such that all identities and viewpoints were shown equally often across training blocks, and no trial (i.e., a particular combination of sample and test images) was repeated across the two days of training. All participants performed the training blocks in the same order.

Participants returned 23 hours later to complete a second set of 6 training blocks starting at the same time of day as the first training session, so that the effect of memory consolidation following sleep could be assessed, and because pilot training revealed that two one-hour sessions was sufficient for adults to demonstrate improvement on the training task.

Post-test

Following the training session on the second day, all participants completed the post-test, which was identical to the pre-test.

Data Analysis

Accuracy was collapsed across every 3 training blocks to yield 4 consolidated blocks of training, and statistical analyses were performed on these *consolidated* training blocks (unless specified otherwise) using SPSS software version 16.0 for Mac. To examine absolute differences between performance of 10-year-olds and adults, we conducted a repeated-measures ANOVA on accuracy with *age* as a between subjects-variable and *training block* as the repeated measure. We then assessed the pattern of improvement on the training task in 10-

year-olds and adults using improvement scores to account for baseline differences in accuracy between the two age groups. An improvement score was computed for each participant by dividing the difference in accuracy between the first block and each subsequent block by the accuracy on the first block, as in a previous study by Furmanski and Engel (2000) that examined perceptual learning of objects in adults. This calculation gives the proportional improvement relative to initial accuracy. We examined learning in two stages using the improvement scores. First, we tested for evidence of *any* learning in either age group by performing one-sample t-tests (relative to zero improvement, two-tailed) for every training block, separately for the two groups, with Bonferroni corrections. Once we had evidence of learning in both age groups, we assessed whether the *rate* of learning differed between 10-year-olds and adults, by performing a repeated-measures ANOVA, with *training block* (3 blocks) as the within-subjects variable and *age* (10-year-olds vs. adults) as the between-subjects variable. Additionally, we performed linear curve fitting to assess whether the learning was *continuous* in both age groups.

The effect of sleep on memory consolidation without any further training was assessed by paired samples t-tests (two-tailed) comparing accuracy on the final 60 trials of Day 1 and the first 60 trials of Day 2, separately for 10-year-olds and adults.

To examine whether everyday experience with recognizing faces across changes in viewpoint is correlated with sensitivity to second-order relations, we compared performance on consolidated training block with pre-test sensitivity to second-order relations for each age group. Additionally, we examined whether improvement on the training task transferred to sensitivity to second-order relations in two ways: 1) comparison of pre- and post-test, and 2) correlation between improvement on the training task and on the test of sensitivity to second-order relations. First, we compared pre-test and post-test sensitivity to second-order relations in upright faces in a 2 x 2 ANOVA with *test* (pre-test vs. post-test) as the repeated measure and *age* as the between-subjects variable, both on accuracy and median reaction times on correct trials. Additionally, because expert face processing is tuned to upright faces, we examined whether the inversion cost (i.e., drop in accuracy when faces are presented inverted relative to upright) in sensitivity to second-order relations increased after training in 10-year-olds and adults in a 2 x 2 (*test* x *age*) ANOVA. Secondly, we calculated improvement scores for sensitivity to second-order relations in upright and inverted faces, in an analogous manner as the improvement scores of the training task (i.e., difference between pre- and post-test accuracy divided by pre-test accuracy). Correlations were performed on improvement scores of the training task and the test of sensitivity to second-order relations.

Results

Training

Figure 3 shows the mean accuracies for the consolidated training blocks. A repeated measures ANOVA revealed a significant main effect of *age*, $F(1, 18)$

= 14.89, $p < 0.01$, because adults were more accurate overall than 10-year-olds. There was also a significant main effect of *training block*, $F(3, 54) = 11.78$, $p < 0.001$, a result which suggests improvement by both groups on the training task (see Figure 3). The *training block* x *age* interaction was not significant, $F(3, 54) = 1.17$, $p = 0.33$, a finding which suggests that there were no significant differences in the impact of training on the two age groups, and also that the magnitude of the age difference did not change as training progressed.

Figure 4 shows the mean improvement scores (amount of improvement relative to accuracy on the first training block) for 10-year-olds and adults. Three one-sample t-tests per group, with a Bonferroni adjusted alpha = 0.017, revealed that 10-year-olds' improvement score was significantly greater than zero in Block 3 (i.e., performance was significantly better in Block 3 than Block 1), $t(9) = 3.70$, $p < 0.01$, but not in Block 2, $t(9) = 0.54$, $p = 0.60$, or Block 4, $t(9) = 1.83$, $p = 0.10$. Adults' improvement scores were significantly greater than zero in Block 3, $t(9) = 3.44$, $p < 0.01$ and Block 4, $t(9) = 6.17$, $p < 0.01$, but not in Block 2, $t(9) = 2.24$, $p = 0.05$. These results suggest that both 10-year-olds and adults showed improvement by the third training block, but that adults' improvements were more stable than those of children. Visual inspection of Figure 4 indicates that children's mean improvement score in Block 4 was slightly higher than in Block 3, but that the increased variance makes the improvement not statistically different from zero.

The improvement scores of 10-year-olds and adults were compared directly by a repeated measures ANOVA. There was a significant main effect of *training block*, $F(2, 36) = 7.13, p < 0.01$, with a significant linear trend, $F(1, 18) = 17.66, p < 0.01$, a pattern which suggests an overall pattern of continuous improvement (see Figure 4). The main effect of *age* $F(1, 18) = 1.20, p = 0.29$ and the *training block* x *age* interaction $F(2, 36) = 0.38, p = 0.69$ were not significant, a pattern suggesting that the pattern of improvement did not differ significantly between 10-year-olds and adults. This finding appears to be inconsistent with the results of the one-sample t-test that failed to reveal a significant improvement in 10-year-olds on Block 4. To examine whether continuous improvement was observed reliably in 10-year-olds and adults, post-hoc linear curve fitting was performed on the improvement scores of the two groups separately (Figures 5a and b). The analyses revealed that the improvement scores of 10-year-olds did not fit the linear model well, $F(1, 28) = 1.79, p = 0.19$, whereas the adults' improvement scores did, $F(1, 28) = 7.45, p = 0.01$. The lack of a significant linear trend in the improvement scores of 10-year-olds appears to stem from the high variability in the improvement scores at the end of training (see Figures 4 & 5).

Paired samples t-tests revealed no difference in mean accuracy on the last 60 trials of Day 1 and first 60 trials of Day 2 for either 10-year-olds, $t(9) = 0.05, p = 0.96$, and adults, $t(9) = -1.41, p = 0.28$.

Sensitivity to Second-order Relations

Upright Faces

At the beginning of training, there was no evidence of a correlation between the ability to match facial identity across viewpoints (accuracy on Block 1) and sensitivity to second-order relations (pre-test accuracy) in 10-year-olds, r(10) = 0.02, p = 0.97, or in adults, r(10) = 0.43, p = 0.22. When we compared accuracy in matching second-order relations on the pre-test versus the post-test, a 2 x 2 repeated measures revealed a main effect of *age*, $F(1, 18) = 15.88$, $p < .001$ (see Figure 6a), because 10-year-olds were worse than adults at detecting changes in the spatial relations among facial features. However, there was no main effect of *test*, $F(1, 18) = 2.80$, $p = 0.11$, and no *age* x *test* interaction, $F(1, 18) = 0.16$, $p = 0.70$, a pattern indicating that neither group of observers demonstrated improvement in their sensitivity to second-order relations after training to identify faces across changes in viewpoint. Correlations performed on the improvement scores from training block 3 (the only block in which 10-year-olds demonstrated significant improvement) and improvement scores on sensitivity to second-order relations also failed to reveal any evidence of transfer of learning in 10-year-olds, r(8) = -0.046, p = 0.18, or in adults, r(8) = -0.60, p = 0.07 (Figure 7). There was also no significant correlation between test and improvement scores from any other training block (10-year-ods: Block 2, r(8) = 0.17, p = 0.65, Block 4, r(8) = -0.03, p = 0.94; Adults: Block 2, r(8) = -0.04, p = 0.92, Block 4, r(8) = -0.39, p = 0.26), presumably because there was very little difference between performance on the pre- and post-test measure of sensitivity to second-order relations (see Figure 6).

A 2 x 2 repeated measures ANOVA on median reaction times on correct trials (Figure 8) revealed a main effect of *age*, $F(1, 18) = 4.96$, $p < 0.05$, and a main effect of *test*, $F(1, 18) = 16.19$, $p < 0.001$. Although adults were overall faster to respond than 10-year-olds, both age groups were faster on the post-test. The *age* x *test* interaction was not statistically significant, $F(1, 18) = 1.07$, $p = 0.31$. To examine whether this improvement in reaction time was related to training, or a general practice effect, we tested sensitivity to second-order relations in an additional group of 10 undergraduate students (7 female; age range 18-24 years). They were tested on two consecutive days, both before and after they performed visual tasks that are not related to face processing (i.e., threshold measures of perception of biological motion, global motion, and/or orientation discrimination). A 2 (test vs. pre-test) x 3 (10-year-olds, trained adults, control adults) ANOVA revealed a main effect of *test*, $F(1, 27) = 14.43$, $p < 0.01$, but importantly, no *group* x *test* interaction, $F(2, 27) = 2.08$, $p = 0.15$. Therefore, improvement in reaction times shown by the trained adult group and 10-year-olds appears to represent improvement following practice with visual tasks on a computer, and/or performing the test of sensitivity to second-order relations a second time, rather than viewpoint recognition training[6].

Inversion Cost

A 2 x 2 repeated measures ANOVA was also conducted to examine the effect of *age* and *test* on the inversion cost. The main effect of *test* was not

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[6] The adult control group also failed to show any improvement in accuracy between pre-test (M = 77.0% correct) and post-test (M = 75.7%) of sensitivity to second-order relations.

significant, $F(1, 18) = 1.26$, $p = 0.28$, a result indicating that there was no significant difference in the size of the inversion effect between the pre-test and post-test. Additionally, there was no main effect of *age*, $F(1, 18) = 0.05$, $p = 0.83$, a result indicating that both 10-year-olds and adults showed a similar inversion cost (see Figure 6a). The *age* x *test* interaction was not statistically significant, $F(1, 18) = 1.27$, $p = 0.27$. Because the trained adults appeared to be more accurate on the inverted block after training (see Figure 6), we performed two additional post-hoc analyses. When the inversion costs on pre-test and post-test were compared between just the trained and control adults, there was still no group x test interaction, $F(1, 18) = 1.14$, $p = 0.30$. Additionally, a paired samples t-test on pre- and post-test inversion cost of the trained adult group revealed no effect of test, $t(9) = 1.38$, $p = 0.20$.

Because of low accuracy on inverted trials (e.g., 10-year-olds on pretest: M = 50.8%, SD = 6.6%; trained adults: M = 62.0 %, SD = 9.3%), it was not possible to obtain a meaningful measure of reaction times for "correct" trials with inverted faces.

Discussion

Adults were consistently more accurate than 10-year-olds at matching identity across changes in viewpoint and detecting changes to second-order relations, findings that are consistent with previous research (e.g., Mondloch et al., 2002, 2003). A novel finding was that adults, and some 10-year-olds, improved in matching facial identity across changes in viewpoint within two one-hour training sessions, even though the presentation of the sample face was very brief (500 ms). The improvement on the training task demonstrated by adults is consistent with a previous study with adults showing greater transfer of an identity aftereffect across changes in viewpoint with more pre-test training with the faces (Jiang, Blanz, & O'Toole, 2006).

Although 10-year-olds showed significant improvement in Block 3 and there was no significant age x block interaction in any analysis, there were some indications that improvements were not as robust in children as they were in adults. Specifically, the improvement was not significant in 10-year-olds in Block 4 because of increased variability, and the linear trend was not significant when the analysis was restricted to the data from the 10-year-olds. Visual inspection of individual performance revealed that four 10-year-olds performed at chance (< 62.5% correct on a 2AFC task) even in the final block of training, whereas this was true for only one adult (see black lines in Figure 9). The same four children also showed a drop in accuracy in the second training block of each day, a pattern which suggests that they may have been especially prone to fatigue. The remaining children showed improvements similar to those of most adults (see grey lines in Figure 9).

Fatigue may have contributed to children's less robust improvement. Alternatively, they may be using different processing strategies than adults or processing strategies that are not as precisely tuned. Another possibility is that children utilize the same processing mechanisms as adults, but that they are less efficient and/or affected by more internal noise. The greater variability in children's final improvement scores suggests that indeed there may be greater noise in children's processing mechanisms. The present paradigm cannot disambiguate between developmental differences caused by the use of different strategies and by the use of the same but more inefficient strategies. To examine developmental changes in face processing efficiency and internal noise, one possible approach for future research would be to use ideal observer analysis (e.g., Gold, Bennett, & Sekuler, 1999).

Despite evidence of some improvement on the training task, neither age group approached perfect performance (Figure 9), a limitation that indicates that two days of training is not sufficient, even for adults, to learn to recognize all 7 viewpoints of 15 unfamiliar faces, and/or to perfect a general view-transformation algorithm that could be applied accurately to faces from any viewpoint. This pattern of results reveals the strong viewpoint-dependence of face recognition in both children and adults. Although children and adults demonstrated some improvement during training, this improvement did not transfer to a task requiring sensitivity to the spatial relations of facial features in upright faces. Examination of the pre-test accuracy indicates that 10-year-olds were above chance (66.7% correct, SD = 11.4%), and adults were below ceiling (80.7% correct, SD = 7.7%), a pattern suggesting that neither floor effects nor ceiling effects could account for the lack of improvement. Neither 10-year-olds nor adults showed a correlation between performance on the training task and sensitivity to second-order relations, and neither group showed a difference in the cost of inversion between the pre-test and post-test. Reaction times did decrease between the pre- and post-test with upright faces, but not more than in a control group that performed non-face tasks between the two measures. Thus, there was no evidence on any measure of a relationship between recognizing identity across viewpoints and sensitivity to second-order relations. We will return to the theoretical significance of the null findings in the General Discussion.

Experiment 2

The lack of transfer between learning to identify faces through changes in viewpoint and sensitivity to second-order relations in upright faces observed in Experiment 1 could be the result of insufficient training rather than the functional independence of these two skills. Indeed, four children and one adult were still performing at chance levels on the training task at the end of the two training sessions, a finding which suggests that the training task may have been too difficult. Besides task difficulty, a limitation with the stimuli used in Experiment 1 was that the same 15 identities were used throughout the 2-day training session. This design allows observers to learn simply to match different poses of the same individuals rather than improving a general skill of recognizing faces across changes in viewpoint (e.g., relying on second-order relations and predicting how they change with changes in viewpoint). Therefore, in Experiment 2 we modified the training paradigm so that new face stimuli were introduced as training progressed, to examine whether adults' improvements in the training task shown in Experiment 1 can be attributed to improvements in a general skill of viewpoint-invariant recognition, and/or improvements identifying the particular faces with which observers received training. We also reduced the amount of noise on the training stimuli to make the task slightly easier, but added a new noise field to the faces in every training block, so that the task could not be accomplished by learning to match the low-level properties of the training stimuli. We also modified the training task from a 2AFC match-to-sample task to a same/different sequential matching task, to match the structure of the pre- and post-test. We then assessed whether improvements on the training task were correlated with improvements in sensitivity to second-order relations. Only adults were tested in Experiment 2.

Methods

Participants

Observers were 12 Caucasian undergraduate students (9 female; age range 17 – 27 years, M = 19.2 years) from McMaster University, participating for course credit towards an undergraduate psychology course. All participants had normal or corrected-to-normal vision.

Training Stimuli

Training stimuli consisted of 147 photographs: 21 female Caucasian faces photographed from 7 viewpoints, 15 of which had been used in Experiment 1. A new Gaussian noise field was superimposed onto each photograph for every training block, so that the images were not identical across the 12 training blocks.

The 21 identities were separated into three sets of seven faces, so that sets of novel faces could be introduced as training progressed.

Test Stimuli

Pre- and post-test stimuli were identical to those used in Experiment 1.

Apparatus

The pre- and post-test stimuli were presented on a 22-inch Macintosh monitor (screen size = 47.0 cm x 30.0 cm; 25.2° x 16.7° of visual angle from a viewing distance of 100 cm), controlled by a Power Mac G4 Cube computer on Mac OS 9.1 software, using Cedrus Superlab software. The training stimuli were presented on a 19-inch Trinitron monitor, controlled by a Mac Mini running in OS X, using PsyScope software.

Procedure

The procedure and overall design were identical to Experiment 1 with a pre-test followed by 12 training blocks (6 per day) and a post-test, except for modifications in the structure of the training blocks and the use of a same/different procedure.

Training blocks were created so that each identity in a particular face set served as the first stimulus an equal number of times in every block. The second stimulus was chosen randomly with the restriction that it was a face from the same face set but from a different viewpoint than the first stimulus[7]. On Day 1,

[7] This design results in a bias to answer "different" because the viewpoint is always different across the two stimuli. Therefore, analyses were performed on accuracy

the first three blocks (56 trials/block) sampled faces from Face Set 1, and the next three blocks (56 trials/block) sampled faces from the Face Sets 1 and 2 (28 trials per face set). On Day 2, training began with two blocks (56 trials/block) using faces from Face Sets 1 and 2 (28 trials per face set), followed by four blocks (84 trials/block) using faces from Face Sets 1, 2, and 3 (28 trials per face set). The order in which the three face sets was shown was counterbalanced across participants.

On each training trial, the first face was shown for 1000 ms, followed by a blank interstimulus interval (ISI) of 390 ms, and then the second face for 200 ms. Auditory feedback was given for every correct response; no sound indicated an incorrect response. To match the structure of the training task, the checkerboard mask was removed from the ISI of the test trials of sensitivity to second-order relations.

Data Analysis

An initial analysis examining the effect of *order* (i.e., starting on Face Set 1, 2, or 3) revealed that there was no main effect of *order* $F(2, 9) = 1.51$, $p = 0.27$, and no *order* x *test* interaction, $F(4, 18) = 1.22$, $p = 0.34$. Therefore, the variable *order* was dropped from all subsequent analyses.

Accuracy could not be collapsed across training blocks as in Experiment 1 because the number of trials from each face set differed across training blocks (although presentation of face sets was equated *within* each training block).

(proportion correct) instead of d' which is designed to measure the smallest signal or "difference" that can be detected.

Additionally, because there was only one group of participants, and because we were interested specifically in differences in initial accuracy across face sets, analyses were performed on accuracy instead of improvement scores. We first examined whether we had replicated the findings from Experiment 1 that a 2-day training session was sufficient to allow adults to improve in making same/different judgements about facial identity across changes in viewpoint. A paired-samples t-test revealed that accuracy on the first 56 trials (block 1) was lower than on the last 56 trials (blocks 11 & 12 combined) from the 1st Face Set, $t(11) = 5.93$, $p < 0.001$, replicating the findings of Experiment 1. We also compared accuracy on the last training block from Day 1 and the first training block of Day 2, and found no evidence of the effect of sleep on memory consolidation for trials from the 1st face set, $t(11) = 1.10$, $p = 0.30$, or for trials from the 2nd face set, $t(11) = 0.70$, $p = 0.50$. These results also replicated the findings from Experiment 1, and allowed us to examine accuracy as a function of training block only, without the additional variable of *day*.

Given that observers were better at the end of training at making same/different identity judgments of faces from Face Set 1, we examined whether this learning generalized to novel face sets. To examine transfer of learning to the second face set, we conducted three paired-samples t-tests with a Bonferroni correction (alpha = 0.017). First, we compared accuracy on Blocks 1 and 3 to establish whether learning had occurred for Face Set 1 *before* novel faces were introduced. We then compared accuracy on Face Set 1 when Face Set 2 was introduced (blocks 4 & 5 combined to calculate accuracy from 56 trials per face set) versus the preceding Block 3, to examine whether performance on Face Set 1 was affected by the introduction of the novel face set. Finally, we compared accuracy on Face Sets 1 and 2 in Blocks 4 and 5 when Face Set 2 was first introduced, to test for transfer of learning. To examine transfer of learning to the third face set, we conducted a repeated-measures ANOVA to compare accuracy on Face Sets 1, 2, and 3 when the 3^{rd} face set was introduced (blocks 9 & 10 combined to calculate accuracy from 56 trials per face set), and planned pairwise comparisons to examine differences between specific face sets.

The relationship between performance on the training task and sensitivity to second-order relations was analyzed in a manner analogous to Experiment 1, for all three face sets, because we could not make clear *a priori* predictions about which face set would reveal the most transfer. Presumably improvement would be greatest for Face Set 1 because it was practiced the most, but improvements in Face Sets 2 and 3 may represent transfer of learning with Face Set 1, which may then be more easily transferred to the post-test.

Results

Training

The results from the training sessions are shown in Figure 10. A paired-samples t-test with a Bonferroni correction (alpha = 0.017) revealed that accuracy was higher in Block 3 than Block 1, $t(11) = 2.88$, $p < 0.017$, a result that shows improvement on Face Set 1 prior to the introduction of novel faces. A second paired samples t-test revealed that performance on Face Set 1 was not hurt by the introduction of Face Set 2, because accuracy on Face Set 1 did not differ between Block 3 and Blocks 4 & 5 combined, $t(11) = 0.25$, $p = 0.81$. Additionally, comparison of accuracy on Face Sets 1 and 2 when Face Set 2 was first introduced revealed similar performance with faces from Face Sets 1 and 2, $t(11) = 0.06$, $p = 0.56$. These findings indicate that improvement with the first face set generalized to the second face set. The repeated measures ANOVA on accuracy when Face Set 3 was first introduced revealed a main effect of face set $F(1, 11) = 7.60$, $p < 0.01$. Post-hoc planned comparisons revealed that observers were significantly less accurate with faces from Face Set 3 than Face Set 1, $t(11) = 4.45$, $p < 0.01$, or Face Set 2, $t(11) = 2.55$, $p < 0.05$. However, there was no difference in accuracy between Face Sets 1 and 2, $t(11) = 0.58$, $p = 0.57$. Additionally, the mean accuracy on the first 56 trials from Face Set 3 (M = 72.92%) was similar to the mean accuracy on the first 56 trials from Face Set 1 (M = 72.02%; see Figure 10). These results suggest that improvement on matching identities across changes in viewpoint did not generalize from the first two face sets to the third face set.

Sensitivity to second-order relations

Mean accuracy on upright trials was identical on the pre-test (M = 83.33%, SE = 3.1%) and the post-test, (M = 83.33%, SE = 2.9%; see Figure 11a). There was also no significant difference in the size of the inversion cost (i.e. drop in accuracy on inverted vs. upright trials) on pre-test and post-test, $t(11) = -1.09$, p

= 0.30[8]. A comparison of median reaction times on correct trials between pre-test and pos-test revealed no difference with upright faces, $t(11) = 1.32$, $p = 0.21$ (Figure 11b). As in Experiment 1, given the low accuracy on inverted trials (M = 60.0%, SD = 13.1%), the median reaction times from inverted trials were not analyzed statistically.

Accuracy at the beginning of training (i.e., Block 1) and pre-test sensitivity to second-order relations were not correlated significantly, $r(10) = 0.28$, $p = 0.38$, replicating the findings from Experiment 1. There was a significant *negative* correlation between final accuracy with Face Set 1 and improvement in sensitivity to second-order relations in upright faces, $r(10) = -0.60$, $p < 0.05$ (see Figure 12). Visual examination of the scatterplot reveals a clear outlier, and the correlation was no longer significant when the outlier was removed from the analysis, $r(9) = -0.42$, $p = 0.20$. Additionally, there was no significant correlation between improvement score in sensitivity to second-order relations in upright faces and improvement for Face Set 2, $r(10) = -0.36$, $p = 0.25$, or Face Set 3, $r(10) = -0.33$, $p = 0.30$, nor between improvement in accuracy for inverted faces and any face set: Face Set 1, $r(10) = -0.10$, $p = 0.76$, Face Set 2, $r(10) = -0.10$, $p = 0.75$, Face Set 3, $r(10) = -0.31$, $p = 0.32$. Alternatively, performance on all three face sets combined may better represent the general ability to recognize facial identity across changes in viewpoint, and for this

[8] Similarly, analysis of d' on pre- and post-test sensitivity to second-order relations revealed no main effect of test for upright faces, $t(11) = 0.85$, $p = 0.42$, or for inverted faces, $t(11) = -1.51$, $p = 0.16$.

reason, we also compared improvement in sensitivity to second-order relations to final accuracy averaged across all three face sets. The conclusions were the same, with the analyses showing that final accuracy on the training task did not correlate significantly with improvement in sensitivity to second-order relations in upright faces, $r(10) = -0.43$, $p = 0.17$, or inverted faces, $r(10) = -0.30$, $p = 0.35$[9]. In sum, there was no evidence that improvement on the training task improved sensitivity to second-order relations.

Discussion

The findings from Experiment 2 replicate the findings from Experiment 1 that given two days of training, adults improve in their ability to match identities across changes in viewpoint. Experiment 2 extends those findings by showing that training with a small set of seven faces improves in the first 168 trials of training, and that this improvement generalizes to performance with a novel set of seven faces. Furthermore, performance over the next 8 blocks did not differ between faces from the 1st face set and from the 2nd face set (see Figure 10). Therefore, some of the training appears to have induced improvement in a generalized skill. These findings are consistent with a model of face recognition that combines view-dependent and view-independent processes, by applying generalized algorithms to interpolate between view-dependent representations. The large improvement observed in the first two training blocks (Figure 10) may

[9] Similarly, no significant correlations were found between final accuracy on any face set and d' on post-test.

represent the initial process of learning the key viewpoints that are useful for the training task.

However, learning failed to transfer to a third face set introduced on the second day, as observers were more accurate with faces from the first two face sets than the third face set (see Figure 10). This pattern of results suggests that some of the learning from the training task is specific to the faces that were presented during training. This finding is consistent with the view-dependent model of facial recognition, in which the mental representation of faces contains view-specific information, and observers can learn to link previously seen views of familiar faces together. The failure of transfer to the third face set suggests that there is some capacity limit to training a general skill, beyond which learning becomes item-specific. This interpretation will be discussed further in the General Discussion.

Visual inspection of mean accuracy (see Figure 10) across training blocks also reveals that after novel face sets have been introduced, there appears to be little improvement even with Face Set 1. This pattern was confirmed by a post-hoc paired samples t-test that revealed no difference in accuracy on Face Set 1 between Block 3 and Blocks 11 and 12 (accuracy combined to equate number of trials), $t(11) = 1.77$, $p = 0.10$. This result suggests that although performance did not drop with the introduction of novel face sets, the processing demands of learning the specific views of the new items may have prevented further improvement with the first face set. A future study that trained adults in the same manner as the current study, but only with the faces from Face Set 1, would elucidate whether the lack of continuous improvement observed in the current study for face set 1 was caused by the processing demands of learning new faces as training progressed, or whether it represents the asymptotic improvement that can be achieved with this type of short-term training.

As in Experiment 1, there was no indication that the result of training was related to improved sensitivity to second-order relations, in either upright or inverted faces. Thus, short-term training on matching faces across changes in viewpoint appears to not lead to improved sensitivity to second-order relations in faces.

General Discussion

The present study examined whether view-invariant recognition of unfamiliar faces can be trained in a laboratory setting, and whether the efficacy of training is related to sensitivity to second-order relations. The results indicate that the ability improves with short-term training, but only to a limited extent that is unrelated to sensitivity to second-order relations. In both Experiments 1 and 2, adults began training at a low level of accuracy but at values above chance. This initial accuracy suggests that adults entered the experiment with a transformation process that can be applied to a few exemplars of novel faces in order to recognize them from different viewpoints. The results from Experiment 2 suggest that the improvement on the training task resulted both from learning more specific viewpoints of the faces-to-be-remembered and from an improvement of a general skill of recognizing faces across viewpoints that can be applied readily to a few novel faces. In Experiment 2, improved accuracy with the first seven faces transferred to initial accuracy on the second set of seven faces but not to the third set of faces. The successful transfer to the second set implies improvement in a general view-transformation process. The failure of transfer to the third set implies that the application of the general transform depends on the learning of specific exemplars, the learning of which is affected by a capacity limit, such as the number of novel viewpoints of unfamiliar faces than can be stored in memory quickly. Such a capacity limit may also account for adults' high level of errors even at the end of training (~20%) and the leveling off of improvements in Experiment 2 after additional faces were introduced (see Figure 10; see Foster & Gilson 2002 for even greater limits on improvements from training with a novel object set for which adults would not have had any pre-existing view-transformation algorithm).

Experiment 1 examined whether children, at an age when they are worse than adults at recognizing faces across changes in viewpoint, would show similar benefits of training. Ten-year-olds resembled adults in showing improvement that was significant in Block 3 but not Block 2. Additionally, they were less accurate overall than adults, and more variable during the last training block. An examination of individual performance indicates that more children than adults failed to show any improvement on the training task, and these children in particular appeared to show effects of fatigue. The age difference in overall accuracy replicates previous findings (e.g., Mondloch et al., 2002, 2003). Children's lower accuracy in this study may stem from the fact that adults had roughly twice as many years of experience processing faces than the 10-year-olds. The transfer results of Experiment 2 suggest that as important as additional experience differentiating faces—or perhaps more important—are the cognitive changes that allow adults to remember more exemplars than children (e.g., Sophian & Stigler, 1981) and to form complex spatial algorithms of the type underlying view-transformation (e.g., Halpern, 1992; Linn & Peterson, 1985; Mondloch, et al., 2003).

The present findings revealed no evidence of a functional relationship between view-invariant face recognition and sensitivity to second-order relations, either at the beginning or at the end of training. Because second-order relations represent one structural property of faces that is view-invariant, we reasoned that they might provide a useful cue for the transformations which underlies view-invariant recognition of faces. Our hypothesis about the functional relationship of these two abilities was based on two key assumptions: 1) view-invariant structural properties of faces, such as second-order relations, are important in supporting view-invariant face recognition, and 2) the two abilities have a similar developmental trajectory (e.g., Mondloch et al., 2002; Mondloch et al., 2003), perhaps because they are functionally related. One or both of these assumptions may be incorrect. For example, face recognition may be mainly view-dependent: adults and children may recognize faces from novel viewpoints mainly by interpolation between known exemplars, so that performance is limited mainly by the quantity and quality of the remembered exemplars. Better sensitivity to second-order relations may improve the fidelity of the memory representation, but more important limitations may be from limits on the storage of exemplars (e.g., general memory capacity; ability to link memory representations of the same person from different views; amount of exposure to the to-be-remembered face in different viewpoints). The second assumption may be incorrect in that the two abilities may require different amounts and/or types of visual experience. On the one hand, improvement in view-invariant face recognition may simply require more practice, which is suggested by the improvements observed in the current study. On the other hand, improvement in sensitivity to second-order relations after age 8 may result from general visual improvements, and not from more experience differentiating the identity of faces. That possibility is raised by a recent finding that both 8-year-olds and adults are better at detecting changes to second-order relations in human faces than monkey faces, and that the magnitude of this species effect is similar in children and adults (Mondloch, Maurer, & Ahola, 2006). Specifically, the amount of improvement between age 8 and adulthood was the same for human and monkey faces, even though the adults had not been exposed to monkey faces during development. Similarly, sensitivity to second-order relations in houses develops significantly from age 8 years to adulthood (Robbins, Shergill, Maurer, & Lewis, 2007). These findings suggest that improvements in general visual abilities contribute to improved sensitivity to second-order relations in general after 8 years of age. Examples of visual abilities that improve beyond 8 years of age that might be related include contour integration, vernier acuity, and mental rotation (e.g., Carkeet, Levi, & Manny, 1997; Heil & Jansen-Osmann, 2007; Jansen-Osmann & Heil, 2007; Kovacs, Kozma, Feher, & Benedek, 1999; Skoczenski & Norcia, 2002).

Alternatively, recognizing faces from different viewpoints and processing second-order relations may be functionally related, as predicted, but the current paradigm failed to reveal this relationship. One possibility is that the direction of the causal relationship between the two skills is opposite to that tested in the present study. We tested whether experience with recognizing faces from different viewpoints leads to improved sensitivity to second-order relations. However, it is equally likely that improved sensitivity to second-order relations (that likely represents maturation of a general perceptual skill beyond childhood, as described above) leads to an improved ability to recognize faces across changes in viewpoint. One finding that is consistent with this hypothesis comes from a patient with congenital prosopagnosia (a severe impairment in face recognition) who was trained to discriminate faces based on changes in second-order relations. After extensive training, the patient improved in a training task requiring classification of faces based on eyebrow and mouth height, and additionally, improved in her ability to recognize faces in her daily life (De Gutis, Bentin, Robertson, & D'Esposito, 2007). Another possibility is that two days of training with normal adults and children is insufficient to reveal the relationship.

However, both of these alternatives seem unlikely given that accuracy on the first training block and pre-test sensitivity to second-order relations were not correlated significantly in either experiment, even in adults who had had roughly 20 years of experience processing faces. The hypothesis could be tested directly, by training adults to discriminate faces based on differences in second-order relations, and testing their recognition of unfamiliar faces from different viewpoints before and after training. To simulate real-world learning of faces, the task should require recognition of facial identity based on second-order relations across changes in hairstyles, make-up, lighting conditions, and facial expressions, but from the frontal view only.

In the present study, both children and adults failed to show an effect of sleep on memory consolidation. Previous studies that found improvement in perceptual learning after sleep have typically used much simpler perceptual tasks, such as texture discrimination (e.g., Mednick et al., 2002, 2003), whereas the training task used in the present study used human faces, which are more complex stimuli. Additionally, recognizing faces is a task that children and adults perform every day, whereas texture discrimination is a relatively novel task for typical subjects. These differences in the stimuli and the nature of the training task may affect the amount of memory consolidation that occurs during sleep. It is also important to note that learning appeared to have transferred from the first face set to the second but not the third face set, and that these two face sets were introduced on separate days. Previous studies reporting benefits of sleep on memory consolidation have examined improvements within the same task (e.g., Mednick et al., 2002, 2003), whereas in Experiment 2 we introduced novel stimuli before and after sleep. Therefore, it is possible that learning transfers more easily between tasks that are performed in temporal proximity and/or without intervening sleep. This hypothesis could be tested by having participants perform the two training sessions on the same day, to examine whether similar transfer effects are observed without intervening sleep between the training sessions.

One limitation of the present study is that only seven points of view were tested. With such few exemplars of viewpoints, we cannot address whether training effects are similar for rotations about the horizontal and vertical axes, and whether more subtle differences between children and adults in training effects would be revealed if more viewpoints were tested. Foster and Gilson (2002) found that adults' accuracy decreased with greater angular difference up to 45° between object pairs, and that beyond an angular difference of 45°, discrimination accuracy asymptoted at a level above chance. The pattern of results suggests that the extent to which adults demonstrate view-dependent and view-independent effects depends on the angular difference between the two test faces. An interesting extension of the current paradigm would be to examine adults' and children's discrimination thresholds, measured as the amount of angular difference between pairs of faces that will allow correct identification of the face, and how these thresholds change with training both for the trained and novel faces.

In summary, the present study demonstrated that adults and children can improve their ability to recognize faces across changes in viewpoint through short-term laboratory training. Comparison of performance on the training task and sensitivity to second-order relations did not reveal a functional relationship between the two abilities. This finding suggests that second-order relations are not a useful cue that supports view-invariant face recognition, and/or that sensitivity to second-order relations does not improve as a consequence of increased experience recognizing faces across changes in viewpoint. The patterns of transfer suggest that general capacity limitations affect adults' ability to store enough viewpoints to apply accurate view-invariant transforms and, by implication, that children's slow development of accuracy in recognizing facial identity from different viewpoint may be explained, at least in part, by such cognitive limitations.

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Figure 1. An example of the training stimuli from Experiment 1. All faces were photographed from 7 viewpoints: frontal, left and right 45, and left and right 90 (profile views), up, and down.

Figure 2. Pre-test and post-test stimuli, originally developed by Mondloch et al (2002). Faces differ only in the spatial relations among features (second-order relations). Stimuli were presented upright and inverted, in separate blocks.

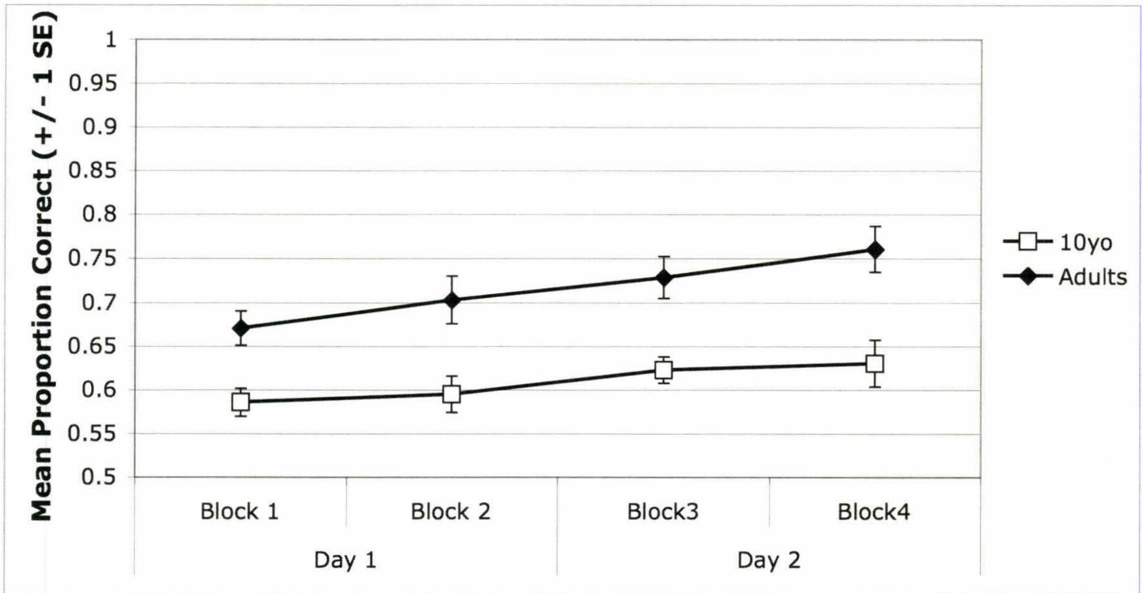


Figure 3. Mean proportion correct (+/- one standard error) on training task of matching identity across changes in viewpoint of 10-year-olds and adults across two days of training.

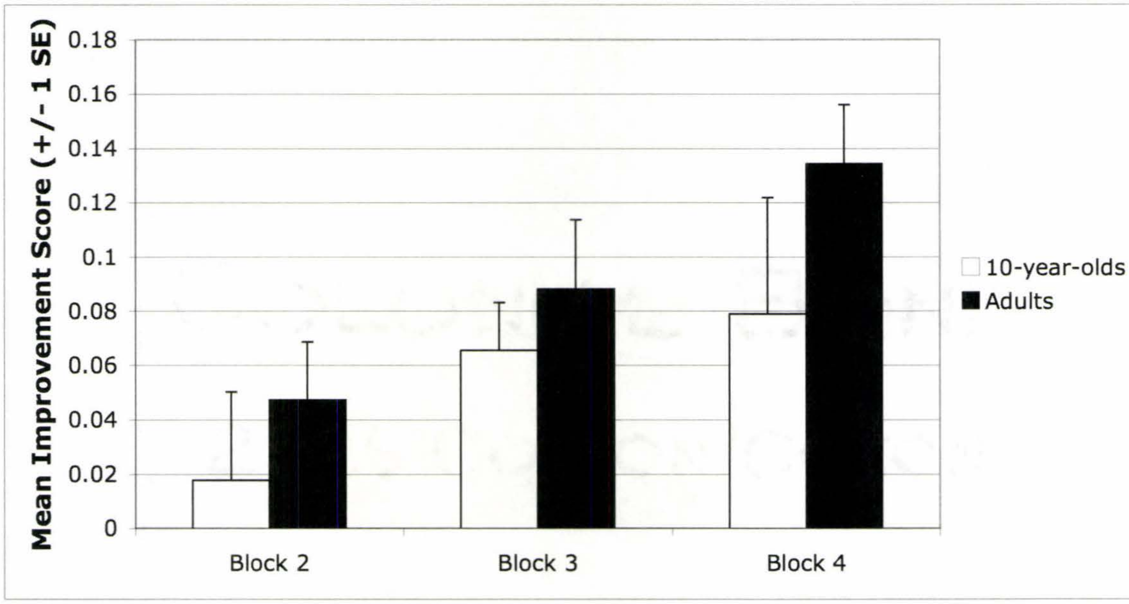


Figure 4. Mean proportionate improvement (+/- one standard error) across training blocks for 10-year-olds and adults. Proportionate improvement was calculated for every individual by subtracting accuracy on the first training block from accuracy on each subsequent block, and then dividing this difference by the accuracy on the first training block.

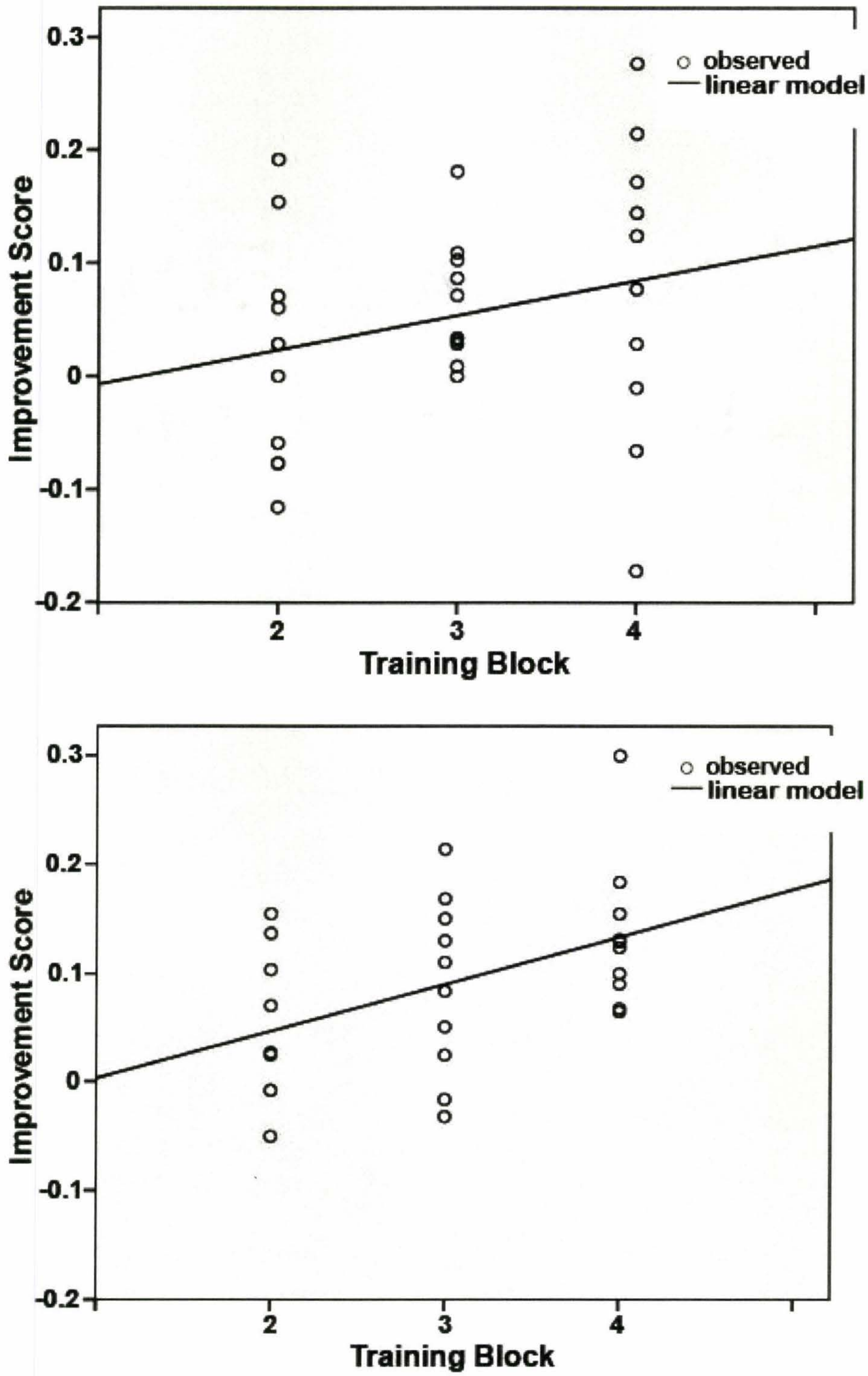


Figure 5. Linear curve fitting for improvement scores across training for a)10-year-olds and b) adults.

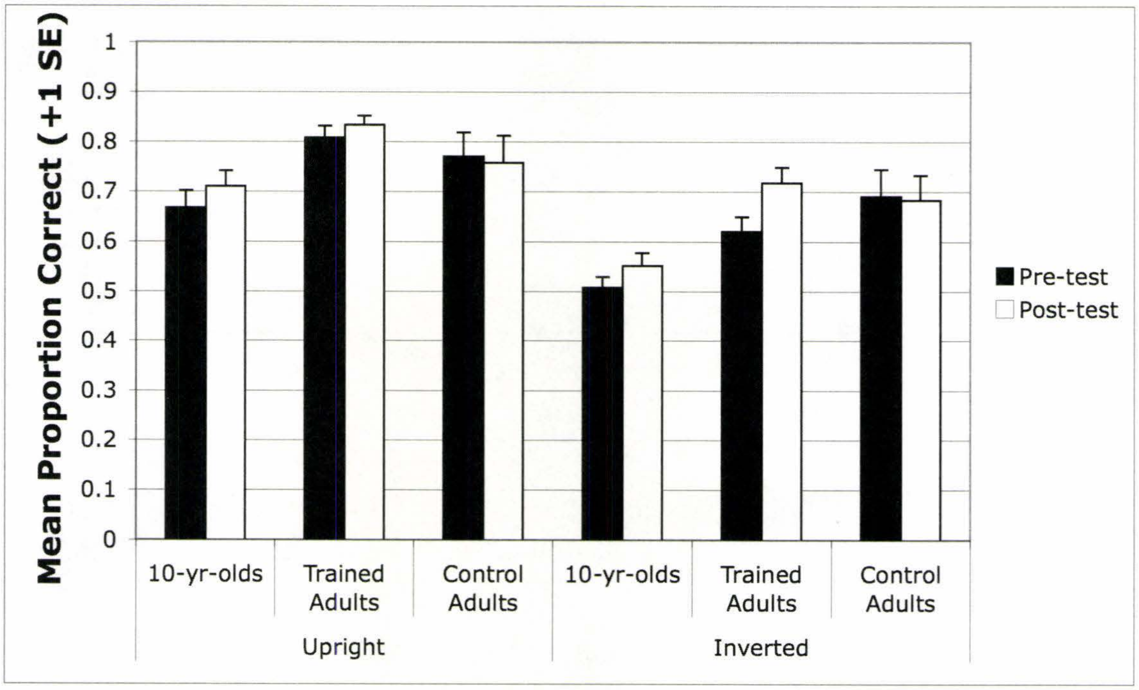


Figure 6. Mean proportion correct on pre- and post-tests of sensitivity to second-order relations in upright and inverted faces, before and after training to match identities across changes in viewpoint (Experiment 1).

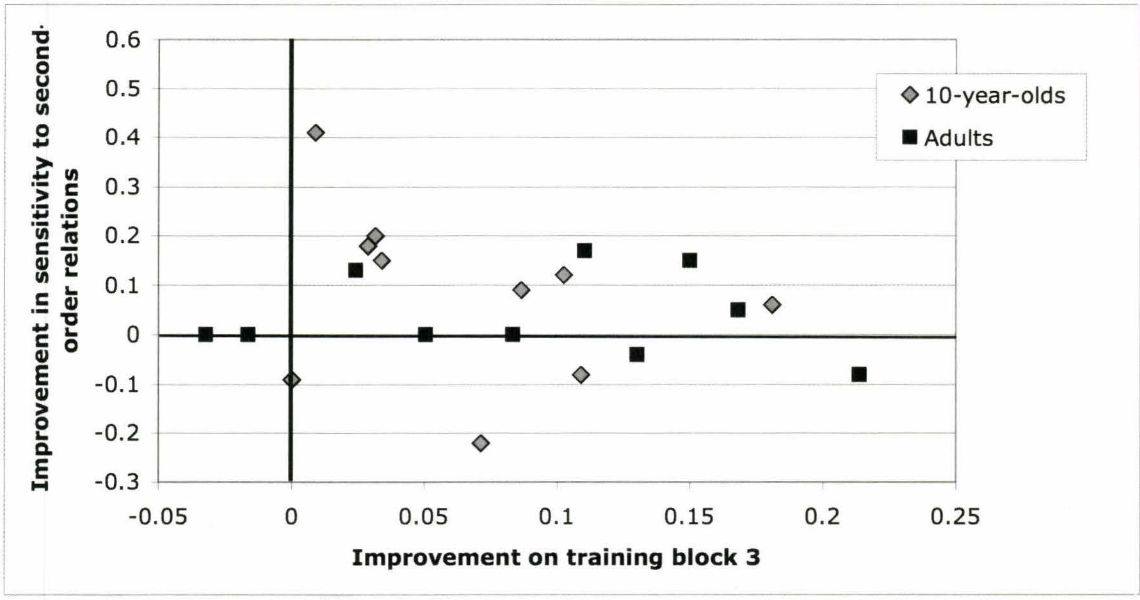


Figure 7. Plot of improvement score on training block 3 (block showing significant improvement in both 10-year-olds and adults) and on detecting changes to second-order relations in upright faces.

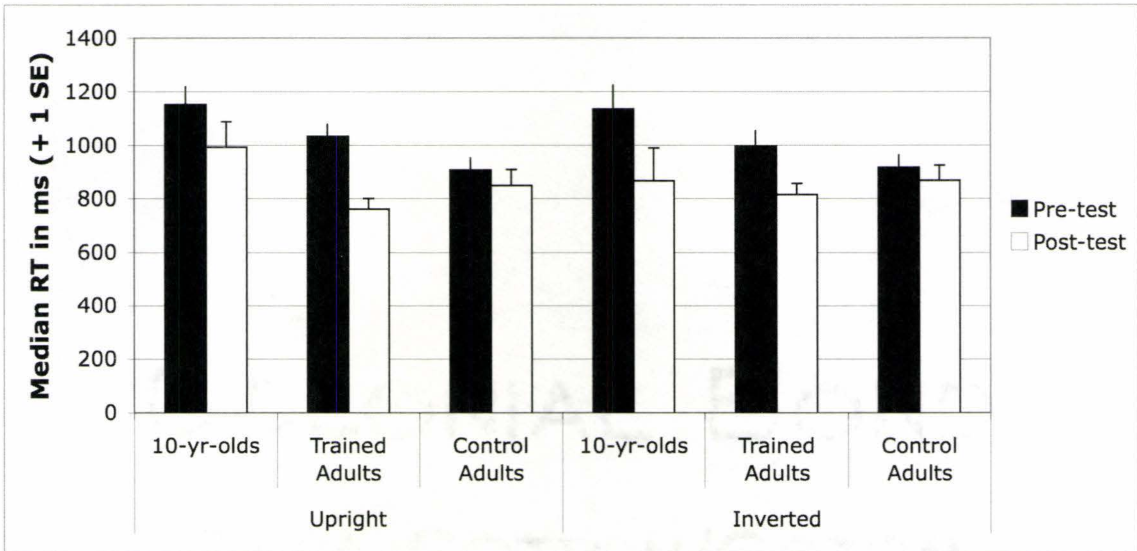
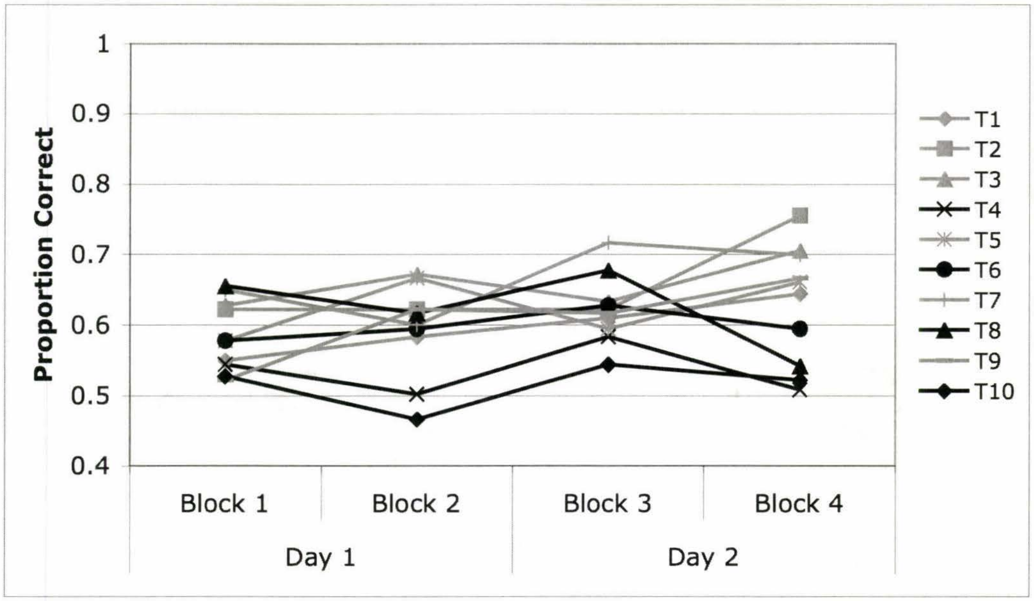


Figure 8. Sensitivity to second-order relations (median reaction times on correct trials) in upright and inverted faces, before and after training to match identities across changes in viewpoint (Experiment 1).



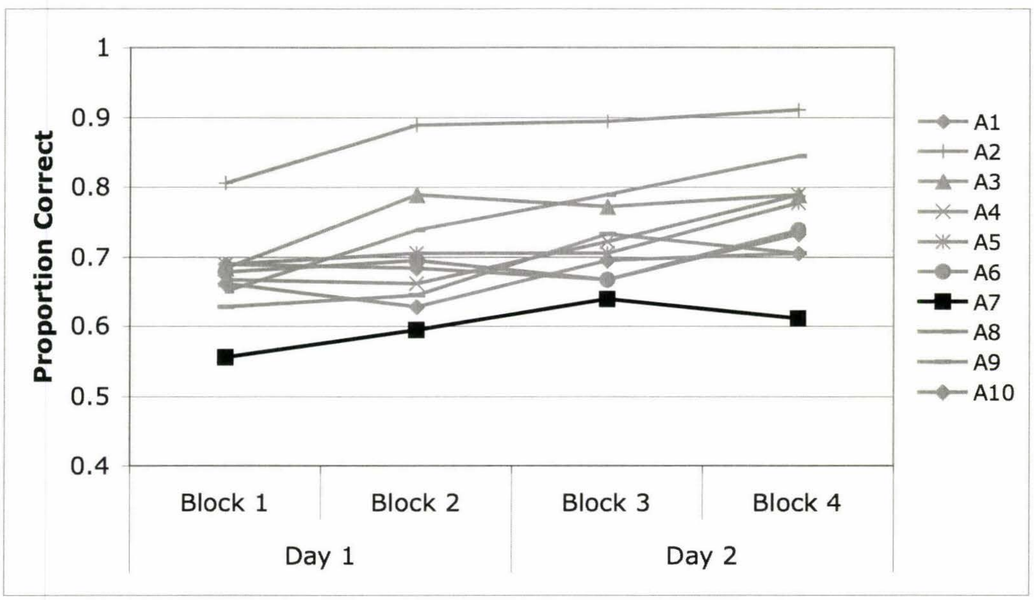


Figure 9. Individual performance on training task of a) ten 10-year-olds (T1-T10) and b) ten adults (A1-A10). Individuals whose accuracy on the final training block was not significantly above chance (> 0.625) are shown in black lines (four 10-year-olds and one adult).

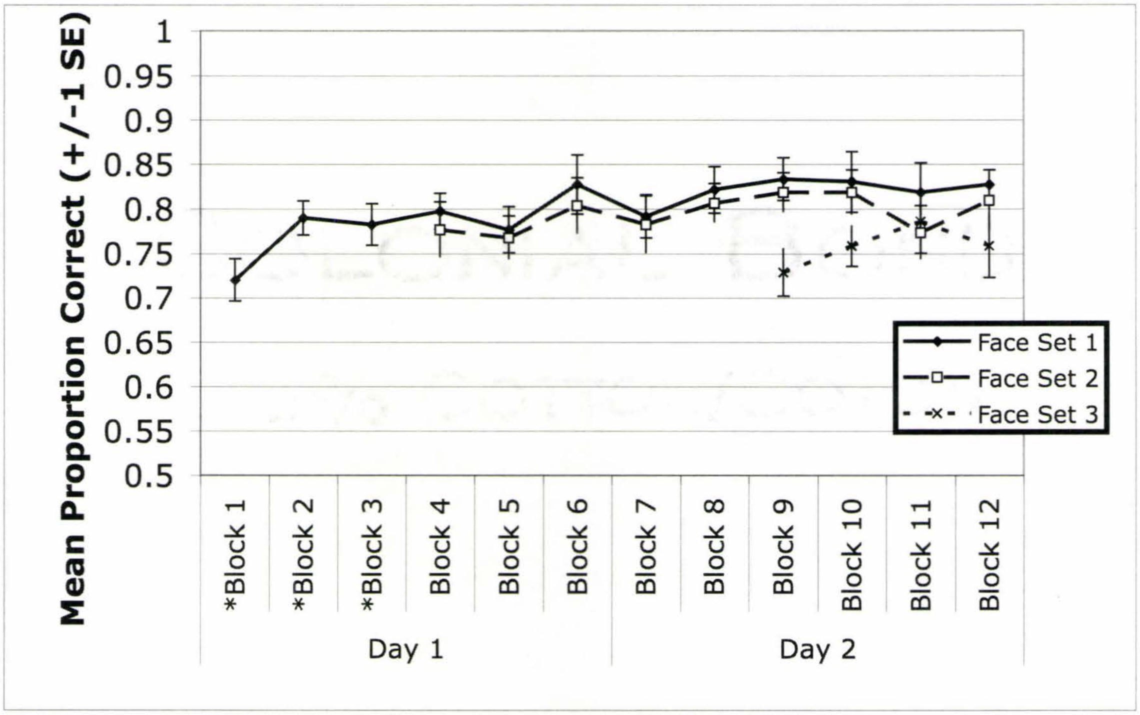


Figure 10. Mean accuracy on training task of making same/different judgments about facial identity across changes in viewpoint. *Blocks 1-3 consisted of 56 trials of Face Set 1; all subsequent blocks consisted of 28 trials per Face Set.

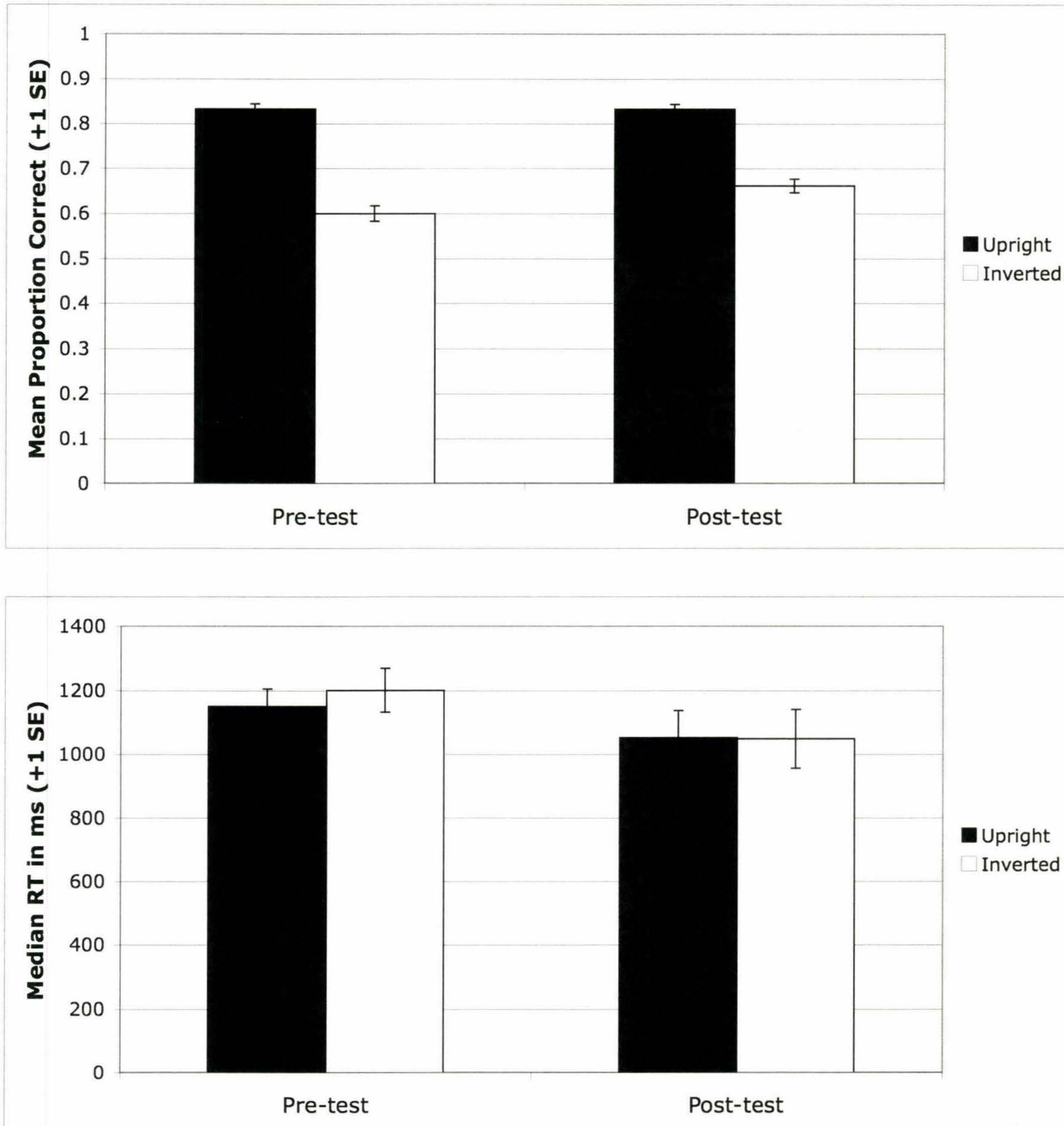


Figure 11. Sensitivity to second-order relations in upright and inverted faces (Experiment 2), before and after training to match identities across changes in viewpoint, shown in terms of a) mean accuracy and b) median reaction times on correct trials.

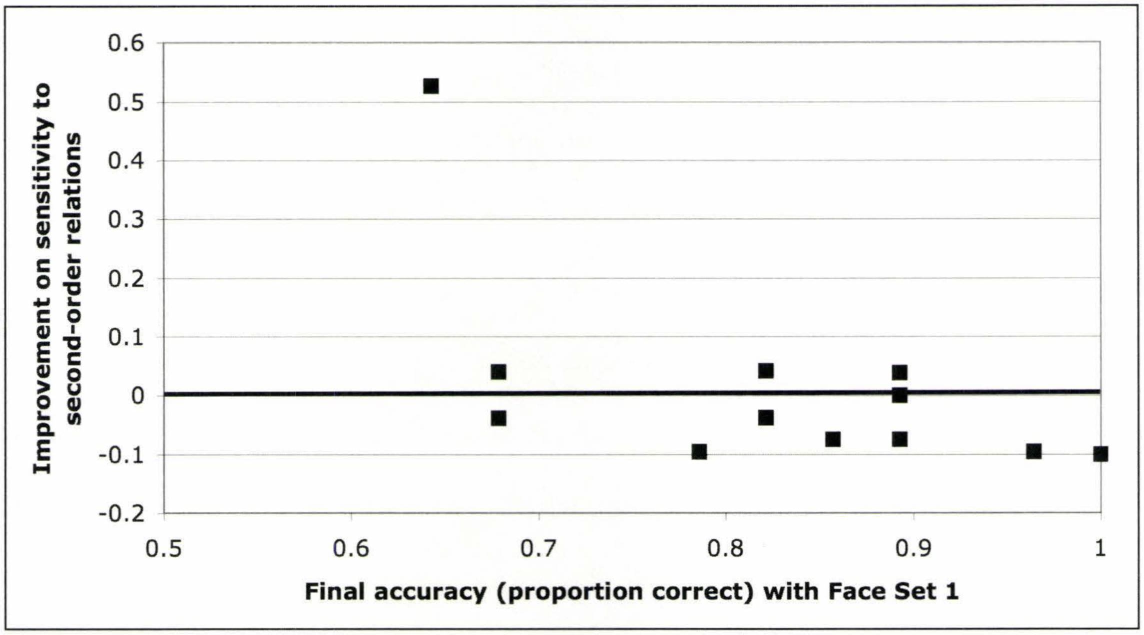


Figure 12. Correlation between final accuracy of making same/different identity judgements across changes in viewpoint for Face Set 1 and improvement in sensitivity to second-order relations in upright faces.

Chapter 5

Preface

The study described in this chapter is a manuscript accepted for publication in *Perception*, and has been reproduced in this thesis with permission granted by Lesley Sackett, Editorial Manager of *Perception*, and Jatinder Padda of Pion Ltd.

The present study examined the role of visual experience in face recognition using a complementary approach to the training study described in Chapter 4. The study in Chapter 4 trained children and adults to learn unfamiliar faces, to examine the extent to which information about second-order relations (spatial relations among internal features) supported recognition of faces, especially across changes in viewpoint. The present study examined the extent to which the type of visual experience shapes sensitivity to second-order relations. Specifically, adults were trained to identify novel objects that differed only in second-order relations, either at the level of individuals (as is the typical experience with face recognition) or at the level of categories (as is the typical experience with non-face object recognition). The results from two experiments revealed that observers showed improved sensitivity to second-order relations in untrained exemplars only after training to identify the objects at the individual level. The apparently paradoxical findings of such rapid improvement in sensitivity to second-order relations in adults and the slow development observed through childhood (e.g., Mondloch et al., 2002) suggest that acute sensitivity to second-order relations may require the development of general perceptual and cognitive processing capacities that underlie the ability to make fine perceptual discriminations, in addition to the specific task demands of recognizing faces at the individual level.

The effect of categorization on sensitivity to second-order relations in novel objects.

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ABSTRACT

Adults appear to be more sensitive to configural information, including second-order relations (the spacing of features), in faces than in other objects. Superior processing of second-order relations in faces may arise from our experience identifying faces at the individual level of categorization (e.g., Bob vs. John) but other objects at the basic level of categorization (e.g., table vs. chair; Gauthier & Tarr, 1997). We simulated this learning difference with novel stimuli (comprised of blobs) by having two groups view the same stimuli but learn to identify the objects only at the basic level (based on the number of constituent blobs) or at both the basic level and individual level (based on the spacing, or second-order relations, of the blobs) of categorization. Results from two experiments showed that, after training, observers in the individual-level training group were more sensitive to the second-order relations in novel exemplars of the learned category than observers in the basic-level training group. This is the first demonstration of specific improvement in sensitivity to second-order relations after training with non-face stimuli. The findings are consistent with the hypothesis that adults are more sensitive to second-order relations in faces than in other objects, at least in part, because they have more experience identifying faces at the individual level of categorization.

Adults are experts at face recognition. They can recognize thousands of individual faces easily and rapidly. Except with special training, adults do not demonstrate the same expertise with any other object category. Studies using functional magnetic resonance imaging (fMRI) and event-related potentials (ERPs) suggest the existence of specialized neural mechanisms that respond more to faces than to non-face objects (e.g., Downing, Chan, Peelen, Dobbs, & Kanwisher, 2006; Grill-Spector, Knouf, & Kanwisher, 2004; Golari, et al., 2007; Grill-Spector, Sayres, & Ress, 2006; Kanwisher, McDermott, & Chun, 1997; McCarthy Puce, Gore, & Allison, 1997; Scherf, Behrmann, Humphreys, & Luna, 2007; Tong, Nakayama, Moscovitch, Weinrib, & Kanwisher, 2000; Bentin, Allison, Puce, Perez, & McCarthy, 1996; Goffaux, Gauthier, & Rossion, 2003; Haxby et al., 1994). Based on behavioral evidence, Yin (1969) suggested that faces are processed differently from non-face objects by being the first to report that inversion disrupts the recognition of faces more than the recognition of other mono-oriented objects, such as houses. Later studies examining the source of the inversion effect revealed that although inversion impairs the use of all cues to identity, the use of configural information (relational information about facial features) appears to be particularly degraded by inversion, suggesting its importance in the processing of upright faces (e.g., Barton, Keenan, & Bass, 2001; Diamond & Carey, 1986; Farah, Wilson, Drain, & Tanaka, 1998; Goffaux & Rossion, in press; Rhodes, Brake, & Atkinson, 1993).

Configural processing can be divided into at least three types of processing: sensitivity to the first-order relations of a face (i.e. the common configuration shared by all faces, with two eyes being above the nose above the mouth), holistic processing (processing of all features of a face as a gestalt or single percept), and sensitivity to second-order relations – the metric differences in the spatial relations among features (e.g. spacing between two eyes) that can be used to distinguish individual facial identities (Maurer, Le Grand, & Mondloch, 2002). Recent evidence suggests that the identity of faces becomes harder to recognize when inverted, at least in part, because of a disruption to adults' unusually acute sensitivity to second-order relations in upright faces (e.g., Collishaw & Hole, 2000; Freire, Lee, & Symons, 2000; Leder & Bruce, 2000; Leder & Carbon, 2006; Malcolm, Leung, & Barton, 2005; Mondloch, Le Grand, & Maurer, 2002; Mondloch, Maurer, & Ahola, 2006b; Rhodes, Hayward, & Winkler, 2006; Tanaka & Sengco, 1997), although inversion can also disrupt the processing of feature shapes (Rhodes et al., 2006; Riesenhuber, Jarudi, Gilad, & Sinha, 2004; Sekuler, Gaspar, Gold, & Bennett, 2004; Yovel & Kanwisher, 2004, 2005). Haig (1984) examined adults' sensitivity to second-order relations in upright faces by slightly displacing the eyes, nose, or mouth in a set of face photographs. He found that observers were highly sensitive to such feature displacements: they noticed an upward movement of the mouth as small as 1 min of visual angle, very close to the visual acuity limit. Furthermore, the second-order relations of a familiar face appear to be recalled accurately, because adults are as sensitive to changes in second-order relations of a highly familiar face as in two unfamiliar faces presented simultaneously side-by-side (Ge, Luo, Nishimura, & Lee, 2003).

Adults' remarkable sensitivity to second-order relations takes many years to develop, such that only in adolescence do children demonstrate adult-like sensitivity to second-order relations (e.g., Freire et al. 2000; Mondloch, Le Grand, & Maurer, 2003b; Mondloch, Dobson, Parson, & Maurer, 2004; Mondloch, Leis, & Maurer, 2006a; but see Gilchrist & McKone, 2003, for evidence of earlier development for judgments of distinctiveness rather than identity). Experience appears to play an important role in this protracted development of sensitivity to second-order relations. Indeed, adults are more sensitive to second-order relations in upright human faces than upright monkey faces (Mondloch et al., 2006b), and in faces of their own race rather than another race (e.g., Caucasian vs. Chinese faces; Rhodes et al., 2006), although they are nevertheless above chance with monkey and other-race faces. The effects of species and race presumably arise from greater experience processing human faces and faces of their own race, respectively. These findings suggest that the particular type of experience influences the development of sensitivity to second-order relations, and that it does not generalize completely to a class of similar stimuli with which the observer has little experience.

Our typical experience processing faces versus non-face objects differs in the level of categorization involved in identification. Faces are usually identified at the individual (or subordinate) level of categorization (e.g., Bob vs. John) whereas other objects are usually identified at the basic level of categorization (e.g., chair vs. table; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). One exception to this difference in categorization between faces and non-face objects is in the case of experts, who tend to categorize their objects of expertise at the subordinate level (e.g., cardinal) rather than at the basic level of categorization (e.g., bird; Johnson & Mervis, 1997; Tanaka & Taylor, 1991). Interestingly, there is evidence to suggest that experts demonstrate what are traditionally considered "face-specific" effects. For example, when tested with their objects of expertise and compared to novices tested with the same objects, experts show a larger inversion effect (e.g., Diamond & Carey, 1986; but see Robbins & McKone, 2007, for failure to replicate this inversion effect), and greater activation of the right fusiform face area (FFA; Gauthier, Tarr, Moylan, Anderson, Skudlarski, & Gore, 2000). Like subjects tested with upright faces (e.g., Tanaka & Farah, 1993), laboratory-trained adults show holistic processing of nonsense objects (Greebles): superior recognition of parts when they are presented in the context of the whole relative to when they are presented in isolation (Gauthier & Tarr, 1997). Similarly, real-world experts demonstrate holistic processing of their objects of expertise. Accuracy of fingerprint experts on a match-to-sample task is degraded more than the performance of novices by removing partial information in the fingerprints (Busey & Vanderkolk, 2005), and it is more difficult for car experts to judge two bottom halves of cars to be the same if they are combined with the top halves of two different cars, than if they are combined with upside-down top halves, presumably because inversion disrupts holistic processing of cars (Gauthier & Curby, 2005; but see Tanaka et al., 1996, as cited in Tanaka & Gauthier, 1997 and Robbins & McKone, 2007, for failure to demonstrate increased holistic processing with greater expertise). Therefore, learning to identify any category of visually similar objects at the individual level of categorization may encourage holistic processing. However, to date, we are not aware of any study that specifically examined sensitivity to second-order relations as a cue to identity in a trained object category, other than faces.

Recently, Tanaka, Curran, and Sheinberg (2005) examined directly the effects of level of categorization on the ability to discriminate novel examples of a trained category in a laboratory setting. Specifically, they used real-world stimuli (owls and wading birds) to compare directly the role of subordinate-level learning to basic-level learning on the ability to discriminate novel examples of the learned birds. Adult observers learned 10 species (subordinate-level identification: e.g., barn owl, barrel owl, elf owl, etc.) of one family (owls) over seven consecutive days, while the other family was learned only at the basic level of categorization (wading birds). Subordinate-level training, but not basic-level training, led to better recognition of new examples of the learned species, and of new species of the learned family (see Scott, Tanaka, Sheinberg, & Curran, 2006, for a replication of this study and associated changes in ERP to the trained bird category). This finding suggests that subordinate-level training facilitates the development of perceptual expertise, and thus, subordinate-level training may improve sensitivity to second-order relations more than basic-level training.

Previous studies examining how training affects visual discriminability of objects have involved several days of training (e.g., Gauthier & Tarr, 1997; Robbins & McKone, 2003; Rainer & Miller, 2000; Tanaka et al., 2005; for a review see Fine & Jacobs, 2002), and/or stimuli that differed on a number of cues (e.g., Gauthier, James, Curby, & Tarr, 2003; Goldstone, 1994; Goldstone, Lippa, & Shiffrin, 2001; Livingston, Andrews, & Harnad, 1998). In the present study, we investigated how the level of categorization affects learning of novel objects in a single session, and limited the cues to identity to second-order relations. We predicted that training observers to identify objects at the individual level would lead to greater sensitivity to second-order relations than training at the basic level of categorization. Whether training observers to identify the stimuli only at the basic level would also lead to increased sensitivity to second-order relations was more difficult to predict, because some perceptual learning studies have demonstrated that observers can learn information about the stimuli that are not task-relevant (e.g., see Seitz & Dinse, 2007 for a review). For example, observers can demonstrate increased sensitivity to local motion through mere exposure, without task-relevance or even awareness (Watanabe et al., 2001). Observers can also learn objects from passive viewing of complex visual scenes (Fiser & Aslin, 2001), and their recognition can be altered by visual statistics that do not reach awareness (Cox et al., 2005). Interestingly, mere exposure can also induce neural changes even at the level of primary visual cortex (Frenkel et al., 2006). Therefore, observers learning to identify objects at the basic level of categorization, for which second-order relations is not a necessary cue, may still demonstrate increased sensitivity to second-order relations in those stimuli. However, the extent to which mere exposure can affect later processing is not consistent across tasks (Karni & Bertini, 1997). For example, vernier offset discrimination does not improve with mere exposure (Fahle, 2004). Furthermore, the current paradigm differs from many perceptual learning tasks (e.g., Fine & Jacobs, 2002; Gold, Sekuler, & Bennett, 1999) because observers are required to learn the names of specific stimuli, requiring some semantic memory. Therefore, the basic-level training group may not demonstrate improved sensitivity to second-order relations, analogous to our typical experience of being exposed to many individual exemplars of non-face objects (e.g. cars) without developing an acute sensitivity to second-order relations in those objects.

In order to relate the findings to face processing, the variation in second-order relations in the training and test stimuli was restricted to the variation that naturally exists in faces. Specifically, the pre- and post-test stimuli were created by replacing the eyes, nose, and mouth of the faces used by Mondloch et al. (2002) to test developmental changes in face processing, but the stimuli were inverted so as to not appear face-like. If these objects were recognized as faces, previous experience categorizing faces at the individual level may transfer differently to the two training tasks. Therefore, these 4-blob objects were face-like only in terms of their second-order relations, and referred to as "Bobos". It was also important to use novel stimuli, because tasks that use familiar stimuli generally demonstrate less learning than tasks using less familiar stimuli (Fine & Jacbos, 2002). Previous learning can interfere with attempts to learn novel distinctions in familiar stimuli (Werker & Tees, 2006), which may account for the small amount of learning observed after training to identify common objects relative to various other perceptual learning tasks (Furmanski & Engel 2000, as reviewed in Fine & Jacobs, 2002). Therefore, we chose to use stimuli that would not be easily perceived as a real-world object. If the level of categorization influences the development of sensitivity to second-order relations, observers who are trained to identify individual exemplars should show greater sensitivity to second-order relations in novel exemplars than those who are simply trained to recognize the objects at the basic level of categorization. Because the degree to which training stimuli differ from the test stimuli influences whether learning transfers to novel stimuli (Karni & Bertini, 1997), we ensured that the variation among the training Bobos was similar to the variation among the test Bobos, as is true of the faces one normally encounters.

Experiment 1

To test the effects of learning, we chose a discrimination task rather than a recognition task, because we were interested in how the level of categorization affects perceptual abilities, rather than memory or semantic strategies. Additionally, some studies have reported benefits of sleep in memory consolidation for perceptual learning (Mednick et al., 2002; Mednick, Nakayama, & Stickgold, 2003). Therefore, participants were also tested 24 hours later to determine whether sleep enhanced the training effect without any additional training on the second day.

Methods

Participants

Participants were 15 undergraduate students in the Individual Level Training Group (5 male, mean age = 19.4 years) and 15 undergraduate students in the Basic Level Training Group (6 male, mean age = 19.1 years) participating for credit in a first-year introductory psychology course or second-year cognitive psychology course at McMaster University. All had normal or corrected-to-normal vision.

Pre- and Post-test Stimuli

Each stimulus contained four dark blurred circles (blobs), roughly 13 mm in diameter (0.74° from a viewing distance of 100 cm). The "original" stimulus was created by placing four dark circles in the locations of the eyes, nose, and mouth of a female face with the features near an average position, that had been used previously by Mondloch et al. (2002) to study adults' sensitivity to second-order relations in faces. In order to simulate real facial features that do not have sharp edges, we then blurred the circles using the Gaussian blur tool (radius = 10.0) in the graphics software Adobe Photoshop to create blobs. Mondloch et al. created four more faces from the original female face by moving the eyes 4 mm

(0.23° from 100 cm) up, down, closer together, or farther apart relative to the original, while simultaneously moving the mouth 2 mm (0.12°) up or down. The blobs were moved in an analogous manner, such that the locations of the eyes, nose, and mouth in the five faces used by Mondloch et al. were represented using blobs for each feature. The five 4-blob stimuli were then inverted so that the stimuli did not appear face-like, and referred to as Bobos (Figure 1a). They were the stimuli used for both the pre- and post-test.

Training Stimuli

The training stimuli consisted of three additional Bobos, created by recombining the interocular spacing and mouth locations used in the pre- and post-test Bobos. As in the pre- and post-test stimuli, the bottom two blobs were moved 4mm (0.23° from 100 cm) in, out, and down relative to the original, while the top blob was moved 2 mm (0.12°) up or down. These Bobos were named "Bobo 1", "Bobo 2", and "Bobo 3" for the participants in the Individual Level Training Group, whereas all three stimuli were simply referred to as "Bobo" for the participants in the Basic Level Training Group. Two additional categories (a single exemplar per category) were created by adding more blobs to the original Bobo: Tika has 6 blobs and Peli has 7 blobs (Figure 1b).

Apparatus

The stimuli were presented on a 22-inch computer monitor (screen size = 47.0 cm x 30.0 cm; 25.2° x 16.7° of visual angle from a viewing distance of 100 cm), controlled by a Power Mac G4 Cube computer on Mac OS 9.1 software, using Cedrus Superlab Software.

Procedure

This study was approved by the research ethics board of McMaster University. The procedure was briefly explained and informed consent was obtained from all participants at the beginning of the experiment. Observers were seated 100 cm from the monitor in a dimly lit room.

<u>Pre-test</u>

Observers first performed the pre-test that measured their initial sensitivity to second-order relations in the 4-blob stimuli, and that was modeled on the procedure used by Mondloch and colleagues (2002). There were five 4-blob images. The task required observers to indicate whether two sequentially presented 4-blob images were the same or different using a Macally iShock controller. There were 30 trials (15 same and 15 different). The first image was shown for 200 msec, followed by a checkerboard mask for 390 msec, and then the second image remained on the screen until the observer made a response (Figure 2). No feedback was given. The trials were presented in a random order. Observers were asked to respond as quickly but as accurately as possible.

<u>Training</u>

Following the pre-test, participants were randomly assigned to the Individual Level Training Group or the Basic Level Training Group. Participants in both groups were informed that they would undergo a training procedure in which they were required to learn the names of blob-stimuli. The training paradigm was modeled after previous studies in which observers were trained to discriminate highly similar visual stimuli, such as sets of artificial objects called greebles (Gauthier & Tarr, 1997), or sets of female twins (Robbins & McKone, 2003). On each trial a label was presented, followed by an image, and the participants' task was to indicate whether the label matched the image. Importantly, all observers, regardless of the training group, saw the same images for an equal number of trials and duration. Only the level at which the three Bobos were learned (i.e. Bobos 1, 2, 3 versus the basic-level categorization of "Bobo") differed between the two groups. There were 32 trials in each training block, 24 trials of which involved a Bobo. Every observer completed 6 blocks of training, regardless of performance.

During each trial, a label on the screen appeared for 1000 msec, followed by a central fixation point for 300 msec, and then the target stimulus (a blob-image). For the first two training blocks, the target was shown for 1000 msec, but in order to increase task difficulty with increasing trials, the presentation time was decreased to 500 msec in the 3rd and 4th blocks, and 200 msec in the 5th and 6th blocks. The participant's task was to hit the button for "yes" if the label matched the target (matched trials), and "no" if it did not (mismatched trials). Half the trials were matched trials. Auditory feedback was given immediately after the response was made, with a different sound for correct versus incorrect responses, followed by a repeat presentation of the target with the correct label shown underneath for 3000 msec, regardless of whether the participant had answered correctly or not (see Figure 3). Participants were encouraged to study the label and the image while they were shown together at the end of each trial in order to learn the correct pairings. Participants then initiated a new trial by pressing the space bar.

Although the presentation of the target images was equated between the two groups, the labels given to the target images differed between groups when a Bobo stimulus was presented: participants in the Individual Level Training Group had to indicate whether the stimulus was (or was not) Bobo 1, Bobo 2, or Bobo 3 (see Figure 3), whereas participants in the Basic Level Training Group were only required to indicate whether the stimulus was (or was not) a Bobo. For trials with the Peli/Tika stimuli, both groups responded at the basic level. For example, the basic-level version of the mismatched trial shown in Figure 3 would have instead started with a label at the basic level of categorization, such as "Peli?", followed by the same Bobo image for the same duration, so that the correct answer for this trial would still be "no" (a mismatch). Similarly, the correct label shown after auditory feedback would have been at the basic level (i.e. "Bobo").

Post-tests

Following the training task, participants completed the post-test in which they were asked to indicate whether two sequentially presented 4-blob images (now referred to as Bobos) were the same or different. The task was identical to the pre-test. Accuracy and reaction times were recorded. Participants then returned 24 hours later to perform the same post-test again (5 Bobos, 30 trials).

Results

Training

A 2 x 6 repeated measures ANOVA on accuracy during the training blocks with *group* (Individual vs. Basic Level Training) as the between-subjects variable and *training block* (training blocks 1-6) as the within-subjects variable revealed a significant main effect of *training block*, $F(5, 140) = 38.05$, $p < .01$, indicating that participants improved over time. The main effect of *group* was also significant, with the participants in the Basic Level Group performing better (M = 97.3%, SD = 4.5%) than the participants in the Individual Level Group (M = 78.9%, SD = 13.2%), $F(1, 28) = 77.73$, $p < .01$. The better performance of the Basic Level Group is not surprising because learning only the category label of "Bobo" is expected to be much easier than learning the individual Bobos. There was also a significant interaction, $F(1, 28) = 10.76$, $p < .01$, indicating that the Individual Level Group improved more across the training blocks (M = 63.8% on Block 1 vs. M = 86.0% on Block 6) than did the Basic Level Group (M = 90.0% on Block 1 vs. M = 98.5% on Block 6).

An ANOVA on observers' median reaction times on correct trials also showed a main effect of *training block*, $F(5, 28) = 0.39$, $p < .01$, indicating that all observers responded faster with more training. There was also a main effect of *group*, $F(1, 28) = 414.56$, $p < .01$, with the Basic Level Group (M = 402 ms, SE =

37 ms) responding faster than the Individual Level Group (M = 653 ms, SE = 37ms). However, unlike the analyses on accuracy, there was no significant *training block* x *group* interaction, $F(5, 24) = .12, p = .99$.

Pre- and Post-tests – All Observers

A 2 x 3 repeated measures ANOVA was conducted using d' on the pre- and post-tests to compare the effect of *group* (Individual vs. Basic Level Training), a between-subjects variable, and *test* (pre-test vs. immediate post-test vs. post-test 24 hours later), a within-subjects variable. Only the main effect of *test* was significant, $F(2, 27) = 9.64, p < .01$, indicating that participants in both groups improved their ability to detect spacing changes in the Bobos following training (see Figure 4a). T-tests comparing the test means, with a Bonferroni correction, indicated that accuracy was higher on both the immediate and 24-hour post-tests than on the pre-test (both *ps* <.01), with no difference between the two posttests ($p = 1.0$). The main effect of *group* ($F(1, 28) = 2.21, p = .15$) and the *group* x *test* interaction ($F(2, 27) = .98, p = .39$) were not significant.

Similarly, a 2 x 3 repeated measures ANOVA conducted on median reaction times on correct trials revealed only a main effect of *test*, $F(1, 28) = 27.98, p < .01$, indicating that all observers responded faster on the post-tests than the pre-test. T-tests, with a Bonferroni correction, indicated that reaction times decreased monotonically across tests (all *ps*<.01). The main effect of *group* ($F(1, 28) = 1.0, p = .33$) and the *group* x *test* interaction ($F(1, 28) = .27, p = .76$) were not significant (see Figure 4b).

Matched Observers

Although the group difference in accuracy was not significant, a closer examination of the raw data revealed that some of the individuals in the Individual Level Training Group had not learned the Bobos well during training (performance on the last training block ranged from 62.5% to 93.75%). Therefore, we re-analyzed the results including only those individuals who obtained a score of more than 75% correct on the last training block (n = 11). There was also great variability in pre-test performance, with 4/15 participants in the Basic Level Training Group, but none in the Individual Level Training Group, performing significantly below chance (44% correct, $p < .05$). Therefore, we matched participants in the Individual Level Group to participants in the Basic Level Group with similar pre-test accuracy (within +/- one correct trial), such that the mean accuracy was 60.02% for the Individual Level Group and 58.51% for the Basic Level Group. Median reaction times on correct trials also did not differ between observers in the two groups, $t(16) = .96$, $p = .35$.

Training

A comparison of the training data from the matched observers (n = 9 matched pairs) again revealed that the accuracy on the last training block was higher for the Basic Level Group (M = 98.3%, SE = 1.1%) than the Individual Level Group (M = 90.3%, SE = 2.5%), $t(16) = 2.98$, $p < .01$. As would be expected, the task of learning to identify the stimuli only at the basic level of categorization was easier than the task of also learning to identify some stimuli at the individual level. This finding was also confirmed with a comparison of median reaction times on correct trials, with the Basic Level Group (M = 377 ms, SE = 28 ms) responding faster than the Individual Level Group (M = 662 ms, SE = 56 ms) on the last training block, $t(16) = 4.55$, $p < .01$.

Post-tests

When the immediate post-test scores of the two groups were compared using d' analysis, the Individual Level Group was significantly more accurate than the Basic Level Group, $t(16) = 2.38$, $p < .05$[10]. However, this group difference was not observed 24 hours later, $t(16) = 1.02$, $p = .32$ (see Figure 5a). Reaction times were also not significantly different between the two groups on the immediate post-test, $t(16) = .45$, $p = .66$, or the post-test 24 hours later, $t(16) = .43$, $p = .67$ (see Figure 5b).

Discussion

Within a single training session involving only 144 trials (24 Bobo discrimination trials x 6 blocks), observers in the Individual Level Training Group learned to identify 4-blob images (Bobos) that differed only in second-order relations. Furthermore, there was some evidence that this learning transferred to a different set of Bobos from the ones used during training. When groups were matched on accuracy during the pre-test, observers who had learned to identify Bobos at the individual level of categorization were better able to discriminate a different set of Bobos than observers who had learned to only identify these

[10] Because variance on the pre-test was constrained by matching the performance of the two training groups, we did not do an ANOVA including pre- and post-test as a within subject factor.

images at the basic level of categorization, as predicted. This finding suggests that the level of categorization at which learning takes place influences sensitivity to second-order relations of an object, and that this effect can be observed after only 144 trials of training lasting approximately 45 minutes. The absence of a group difference in reaction times rules out a speed-accuracy trade-off. However, this difference was not significant when the performance of observers was not matched based on pre-test sensitivity to second-order relations.

When the whole group is considered, the observers in the Individual Level Training Group appeared to learn the Bobos well (M = 86.0% on Block 6). However, 4/15 observers were less than 75% correct in identifying the Bobos, even after 6 blocks of training. Therefore, for some participants, 144 trials with feedback may not be sufficient for learning to discriminate very similar visual stimuli. Moreover, the group difference was not observed 24 hours later, a result suggesting that the learning benefit demonstrated by the Individual Level Training Group was temporary and indicating no evidence of the benefit of sleep in memory consolidation that has been reported with other perceptual tasks (e.g., Mednick et al., 2002; Mednick et al., 2003).

Although these results suggest that learning to identify objects at the individual level of categorization may lead to greater sensitivity to changes in second-order relations that are relevant to correct identification, this interpretation must be tempered because the variability in learning and in the pre-test performance made it necessary to exclude 12 participants from the final analysis

(6 participants from each of the Individual and Basic Level Training Groups). Therefore, we attempted to replicate the findings in Experiment 2 with a matched yoked design such that the pre-test performance of the observers in the basic- and individual-level training groups would be matched.

Experiment 2

In Experiment 2, we used a matched yoked training paradigm and re-examined the influence of the level of categorization on sensitivity to second-order relations. In order to decrease the amount of variability in the performance of the Individual Level Training Group, we trained participants to criterion. The procedure was the same as in Experiment 1 except that participants in the Individual Level Training Group were required to continue training until their accuracy during a block exceeded 80% correct. Each participant in the Basic Level Group was matched to a participant in the Individual Level Group based on his/her pre-test score, and was then given as many training blocks as his/her matched counterpart required, in order to reach 80% accuracy. Therefore, although amount of training and exposure to the stimuli varied across individuals, every matched pair across the two groups completed the same number of training trials. We also added a fourth Bobo stimulus to be learned by the Individual Level Training Group to further promote general learning. Additionally, we included a control group to aid interpretation of the small improvement in the Basic Level Training Group between the pre- and post-test that was revealed by the main effect of *test* in Experiment 1, in the analyses involving the unmatched groups. This effect may reflect a practice effect or some improvement in sensitivity to second-order relations even though this group was not required to differentiate among the Bobos during training, as has sometimes been found in the perceptual learning literature (e.g., Fiser & Aslin, 2001; Cox et al., 2005). To differentiate these possibilities, in Experiment 2 we included a control group that performed a visual discrimination task unrelated to face or object processing (motion discrimination of sinusoidal gratings) between the pre- and post-tests. Unlike Experiment 1, there was no post-test 24 hours later.

Methods

Participants

Participants were 75 undergraduate students (n = 25 per group) enrolled in either a first-year psychology course or a second-year cognitive psychology course (Mean age = 19.24 years; 23 males). Participants were randomly assigned to the control group or an experimental group (Individual vs. Basic Level Training Groups). The pre-test scores determined the placement of participants in the two experimental groups so that each participant in the Individual Level Group had a matched counterpart in the Basic Level Group with the same pre-test score (+/- 1 correct trial). Two additional participants in the Individual Level Group failed to reach the learning criterion of 80% correct within the allotted time (45 minutes), and therefore their data were excluded from the analyses. Two additional individuals were tested as part of the Control Group, but their data were not analyzed because there were no matches for their pre-test scores in the experimental groups.

Stimuli

The pre- and post-test stimuli were identical to those used in Experiment 1. The training stimuli were the same except for the addition of one Bobo stimulus (Bobo 4) and two basic-level stimuli (Kiki with 9 blobs and Lula with 10 blobs), which were added to promote greater learning by making the training task more challenging (Ahissar & Hochstein, 1993). Participants in both the Individual Level Training Group and the Basic Level Training Group were required to learn the 5 category names (Bobo, Jiji, Lula, Tika, and Kiki). In addition, the Individual Level Training Group was required to learn the 4 individual Bobos (Bobos 1, 2, 3, and 4; see Figure 6).

Procedure

Pre-test

The pre- and post-tests were the same as in Experiment 1.

Training

The training blocks were constructed in the same way as those used in Experiment 1. Observers in the Individual Level Training Group completed a minimum of 4 training blocks, and then continued training to the criterion of at least 80% correct on individual-level identification trials within a single block (24 trials). Performance was monitored on every block starting with the fourth block and additional blocks were presented until the participant reached criterion (see Figure 7a).

Later participants were assigned to one of the experimental groups depending on the pre-test score. If pre-test accuracy matched the score of an earlier participant in the Individual Level Training Group, that observer was placed in the Basic Level Training Group, and underwent as many training blocks as his/her matched counterpart (see Figure 7a). If there was no match, he/she was placed in the Individual Level Training Group (and trained to criterion). As in Experiment 1, observers in both the Individual and Basic Level Training Groups saw the same Bobos. The only difference was that all names presented to the Basic Level Group were at the basic level of categorization, whereas Bobos were labeled individually for the Individual Level Group. Those participants who were randomly assigned to the Control Group completed the pre-test, followed by a motion discrimination task using vertical gratings that lasted roughly 30 minutes (training with the blob-stimuli took 15 – 45 minutes; Figure 7b).

<u>Post-test</u>

Following the training or control blocks, all participants completed the post-test. Unlike in Experiment 1, observers did not return for a second post-test 24 hours later.

Results

Pre-test

The pre-test scores of observers in the Individual Level Training Group (M = 62.1%), Basic Level Training Group (M = 61.6%), and Control Group (M = 61.5%) were well matched.

Training

On average, participants in the Individual Level Training Group required 6.3 blocks of training (range: 4 – 13 blocks) in order to reach the criterion of 80% correct on a block of individual-level identification trials. Participants in the Basic Level Group completed the same number of training blocks (i.e. M = 6.3 blocks) because the training protocols of the participants in the Basic Level Training Group were yoked to the participants in the Individual Level Training Group, based on pre-test performance. The Basic Level Training Group (M = 98.0%, SD = 2.8%) performed better on their last training block than the Individual Level Training Group (M = 91.2%, SD = 3.5%), $t(48) = 7.52$, $p < .01$, indicating that it was easier to learn to identify these images at the basic level than at the individual level of categorization. Median reaction times on correct trials also revealed that observers in the Basic Level Group (M = 457 ms, SE = 26 ms) were faster to respond correctly than the Individual Level Group (M = 836 ms, SE = 59ms) on the last training block, $t(48) = 5.86$, $p < .01$.

Post-test

After training[11], a one-way ANOVA using d' analysis revealed a significant effect of *group* on the post-test, $F = 5.37$, $p < .01$ (Figure 8a). In order to determine whether training led to improvements in sensitivity to second-order relations, post-hoc comparisons using Dunnett's t-test were performed against the performance of the Control Group. The results revealed that the Individual Level Training Group (M = 73.9%) was significantly better than the Control Group (M = 63.9%, $p < .01$), whereas the Basic Level Training Group (M = 67.7%) did not differ significantly from the Control Group ($p = .13$)[12]. Thus, training at the individual level led to improved sensitivity above any effect of repeat testing, but training at the basic level did not.

Observers' median reaction times on correct trials were compared across the 3 groups by a repeated measures ANOVA with *group* as the between-subjects variable, and *test* (pre-test vs. post-test) as the within-subjects variable. The main effect of *group* was not significant, $F(2, 72) = .19$, $p = .83$. There was a main effect of *test*, $F(1, 72) = 8.56$, $p < .01$, indicating that observers in all three groups were faster to respond on the post-test than the pre-test (see Figure 8b). The *group* x *test* interaction approached significance, $F(2, 72) = 3.05$, $p = .05$. However, post-hoc Dunnett's t-test on the pre-test and post-test did not reveal any significant group differences.

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[11] Because variance on the pre-test was constrained by the yoked design, we did not do an ANOVA including pre- and post-test as a within subject factor.

[12] Unlike in Experiment 1, we did not re-test sensitivity to second-order relations 24 hours later, and therefore we cannot address the question of whether the Individual Level Training Group would have demonstrated an effect of sleep on memory consolidation in this experiment.

Discussion

Experiment 2, which required observers in the Individual Level Training Group to continue training until they were 80% correct on the last training block, replicated the results of Experiment 1. Adults who learned to identify 4-blob images at the individual level of categorization were more sensitive to the second-order relations of the blobs in novel exemplars than adults who had seen the images as often but had learned to identify them only at the basic level of categorization. The results demonstrate that learning to discriminate individual exemplars of an object category can increase sensitivity to second-order relations. Furthermore, the Basic Level Training Group was no more accurate on the post-test of sensitivity to second-order relations than a group of control subjects who did not receive any training with the 4-blob images. Therefore, exposure to the stimuli without the task demands of individual-level recognition was not sufficient for improving sensitivity to second-order relations. These results are consistent with the hypothesis that the level of categorization at which objects are identified directly influences how those objects are processed, and therefore acute sensitivity to second-order relations in upright faces may arise, in part, from our experience identifying faces at the individual level.

General Discussion

Experiments 1 and 2 demonstrate that after a single training session adults can learn to discriminate individual 4-blob objects that differ only in second-order relations, and that this learning transfers to a different set of 4-blob objects.

Furthermore, exposure to the same images without being required to recognize them at the individual level was not sufficient to improve sensitivity to second-order relations. This is the first demonstration that the level of categorization at which non-face objects are identified can directly influence sensitivity to the second-order relations in those objects. The results are consistent with previous findings showing that learning to identify exemplars at the individual level of categorization improves discrimination of novel exemplars from the learned category (e.g., Gauthier & Tarr, 1997; Gauthier, Williams, Tarr, & Tanaka, 1998; Scott et al., 2006; Tanaka et al., 2005).

Observers in this study demonstrated improvements in sensitivity to second-order relations after a single training session, whereas sensitivity to second-order relations in faces is still developing after 14 years of experience (Mondloch et al., 2003b). Likely as a result of the short training, the improvement in discriminating Bobos appears temporary (Experiment 1), but this temporary process may be the same process underlying the development of sensitivity to second-order relations in upright faces that becomes consolidated with more experience. Experience with faces differs from experience with non-face objects in three important ways: 1) faces are a visually homogenous category because all faces share the same first-order relations (i.e. the basic configuration of having the eyes above the nose above the mouth), 2) it is necessary to identify faces at the individual level (e.g., Bob vs. John), and 3) one reliable cue to discriminating individual faces is second-order relations. Although improvements in basic visual sensitivity are likely also to be involved (Mondloch et al., 2006b), our results suggest that learning to identify faces at the individual level of categorization may contribute to the development of adults' acute sensitivity to second-order relations in faces.

The results are consistent with the hypothesis that sensitivity to second-order relations in faces develops, at least in part, because of our experience individuating faces. However, Bobos differ from faces in an important way. Individual Bobos can be discriminated only in terms of second-order relations, whereas there are many cues that differentiate the faces we encounter in everyday life (e.g., hair colour, skin colour, glasses, beards, etc.). Sensitivity to second-order relations in faces may develop because other cues to facial identity (e.g., hair colour, skin colour, feature shapes) are less reliable than second-order relations, as they can change in different contexts (e.g., different lighting, point of view, make-up, facial expression, etc.). In future research it would be interesting to examine whether adult observers can learn to differentiate Bobos when other cues are available, but less reliable, than second-order relations, in order to extend the present findings to a real-world context. It would also be interesting to use this paradigm to study children, who change with age from relying more on salient, but less reliable, feature cues for face identification and being readily fooled by paraphernalia (e.g., Campbell & Tuck, 1995; Campbell, Walker, & Baron-Cohen, 1995; Carey & Diamond, 1977; Freire & Lee, 2001; Freire, et al., 2000; Mondloch, et al., 2002; Mondloch et al., 2006a) to becoming adept at recognizing the identity of faces based on second-order relations and through changes in point of view (Mondloch et al., 2002; Mondloch, Geldart, Maurer, & Le Grand, 2003a), and are not being fooled by paraphernalia (e.g., Freire & Lee, 2001).

The successful transfer of learning demonstrated by the Individual Level Training Group is most likely attributable to the similar amount and type of variability that existed in the training and test stimuli (Karni & Bertini, 1997). The Bobo stimuli used during training and test differed only in second-order relations, and the variations were limited to the variability that naturally exists among faces. Another contributing factor may have been the ease of the task, as shown by the relatively few trials (mean = 151 trials) needed to reach the criterion of 80% correct in Experiment 2 and the fact that 25/27 participants reached the criterion within a single training session lasting at most 45 minutes. This finding is consistent with previous findings that with greater task difficulty, the effects of perceptual learning become more specific (Ahissar & Hochstein, 1997). Thus, the relative ease with which the individual Bobos were learned may have also contributed to the successful transfer of learning to novel exemplars.

Identifying the neural basis of the improvement observed in the Individual Level Training Group is beyond the scope of the current study, however, previous findings suggest that the locus of the learning effect is in the higher visual areas. Ahissar and Hochstein (2004) postulate that in easy tasks with large signal-to-noise ratios, learning can occur at higher areas of the visual stream allowing more generalization, whereas more difficult tasks may require neural modifications at lower levels where the receptive fields are more specific to retinal position and orientation. This hypothesis is supported by evidence that monkeys trained to categorize a continuous set of digitally morphed stimuli as cats or dogs showed differential activation of the prefrontal cortex to the two trained categories (Freedman, Riesenhuber, Poggio, & Miller, 2003). Furthermore, monkeys trained to categorize faces based on second-order relations (eye height and eye separation) demonstrated increased neuronal fine-tuning in the inferotemporal cortex for those cues (Sigala & Logothetis, 2002). These findings suggest that the locus of the categorization effect observed in the current study is not likely to be in low-level areas such as the primary visual cortex, but rather in the higher visual areas.

One limitation of the current study is that task difficulty during training was not equated between the Individual Level and Basic Level Training Groups. We chose to equate the amount of visual exposure to the blob-stimuli in both groups, which necessarily resulted in the task requiring individual-level identifications being more difficult than the task requiring only basic-level identifications. Therefore, the current study cannot separate the effect of differences in the level of categorization per se from differences in the cognitive demand of the two procedures, such as differences in the amount of attention required. However, these effects are not necessarily mutually exclusive. For example, even newborns orient towards face-like stimuli more than non-face stimuli, suggesting that humans are naturally biased to attend to faces (e.g., Johnson, Dziurawiec, Ellis, & Morton, 1991; Maurer & Young, 1983). Therefore, attention may also play a role in the real-world experience of categorizing faces at the individual level but categorizing non-face objects at the basic level of categorization. Nevertheless, future studies should attempt to equate task difficulty by introducing more basic level categories to be learned only by the Basic Level Group, or by using a divided attention paradigm to increase attentional load.

The paradigm developed in the current study could be extended in a number of ways to explore the conditions under which increased sensitivity to second-order relations in blob-images transfers to sensitivity to second-order relations in other stimuli. In order to expand our understanding of perceptual learning in general, one could test whether observers in the Individual Level Training Group would demonstrate improved sensitivity to second-order relations in one of the basic-level trained categories, such as the "Tikas" composed of 5 blobs. One could also present individual Tikas simultaneously with the individual Bobos, but only train observers to learn individual Bobos, to determine whether learning generalizes to similar objects learned concurrently without an individual-level categorization task. To better understand the development of face processing, one could continue training with the individual Bobos for thousands of trials over several days. Although "fast learning" effects (as in the current single-session paradigm) are very task-specific (Karni & Bertini, 1997), a recent study using an interference paradigm suggests that the recognition of faces and non-face objects of expertise are functionally related (Gauthier & Curby, 2005; but see also Rhodes, Byatt, Michie, & Puce, 2004 for lack of FFA activation in response to non-face objects of expertise). It is possible that with "slow learning" (involving modifications in the neural representation of Bobos, Karni & Bertini, 1997), the learning would transfer to improved sensitivity to second-order relations in faces, especially other-race faces. Such a finding would suggest that the greater sensitivity to second-order relations shown for upright faces than inverted faces (e.g., Mondloch et al., 2006b) is not specific to faces per se, but rather to experience discriminating individual exemplars of an object category. Conversely, if extensive training with Bobos does not transfer to the processing of second-order relations in faces, the results would lend support to the hypothesis that faces are processed differently than other objects of expertise.

In summary, in a single training session, adults trained to identify individual objects improved their sensitivity to the second-order relations of those objects, whereas adults trained to identify the same objects at the basic level of categorization did not. Thus, adults' acute sensitivity to second-order relations in upright faces may develop, at least in part, through our experience identifying faces at the individual level of categorization.

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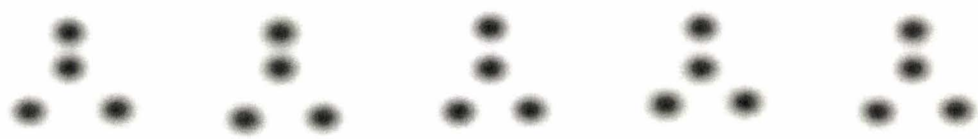


Figure 1a. Pre- and post-test stimuli for measuring sensitivity to second-order relations. The actual stimuli were much larger (see text).

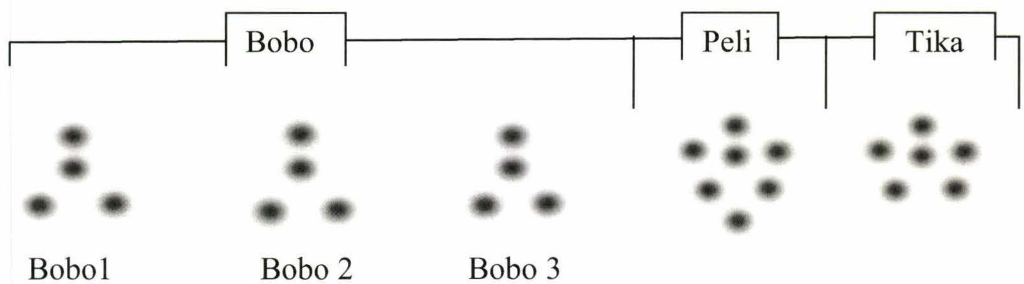


Figure 1b. Training stimuli. Basic level category labels are shown along the top. The Individual Discrimination Group was also required to learn the individual names of the Bobos, shown along the bottom. The actual stimuli were much larger (see text).

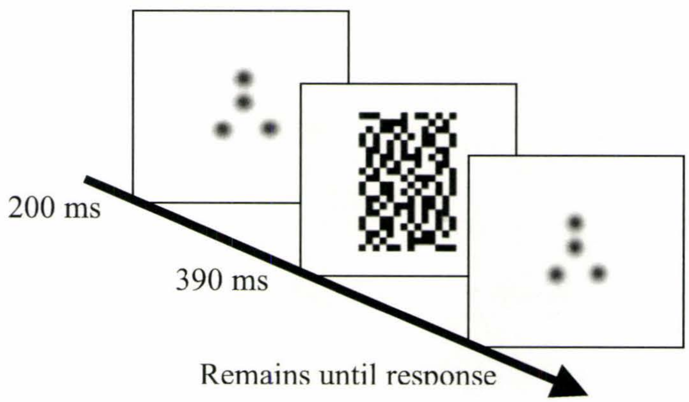


Figure 2. An example of a pre- and post-test trial.

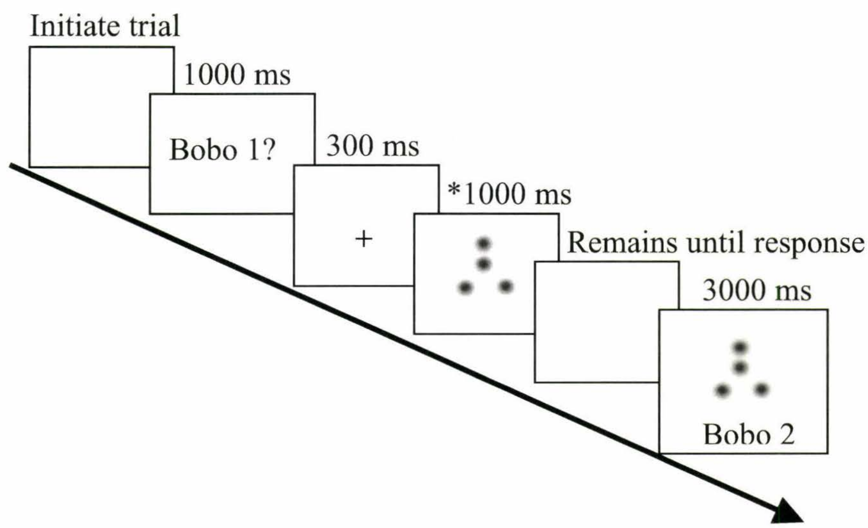


Figure 3. An example of a mismatched training trial for the Individual Level Training Group. *Presentation times of the stimulus was decreased over the 3rd and 4th blocks to 500ms, and again over the 5th and 6th blocks to 200ms.

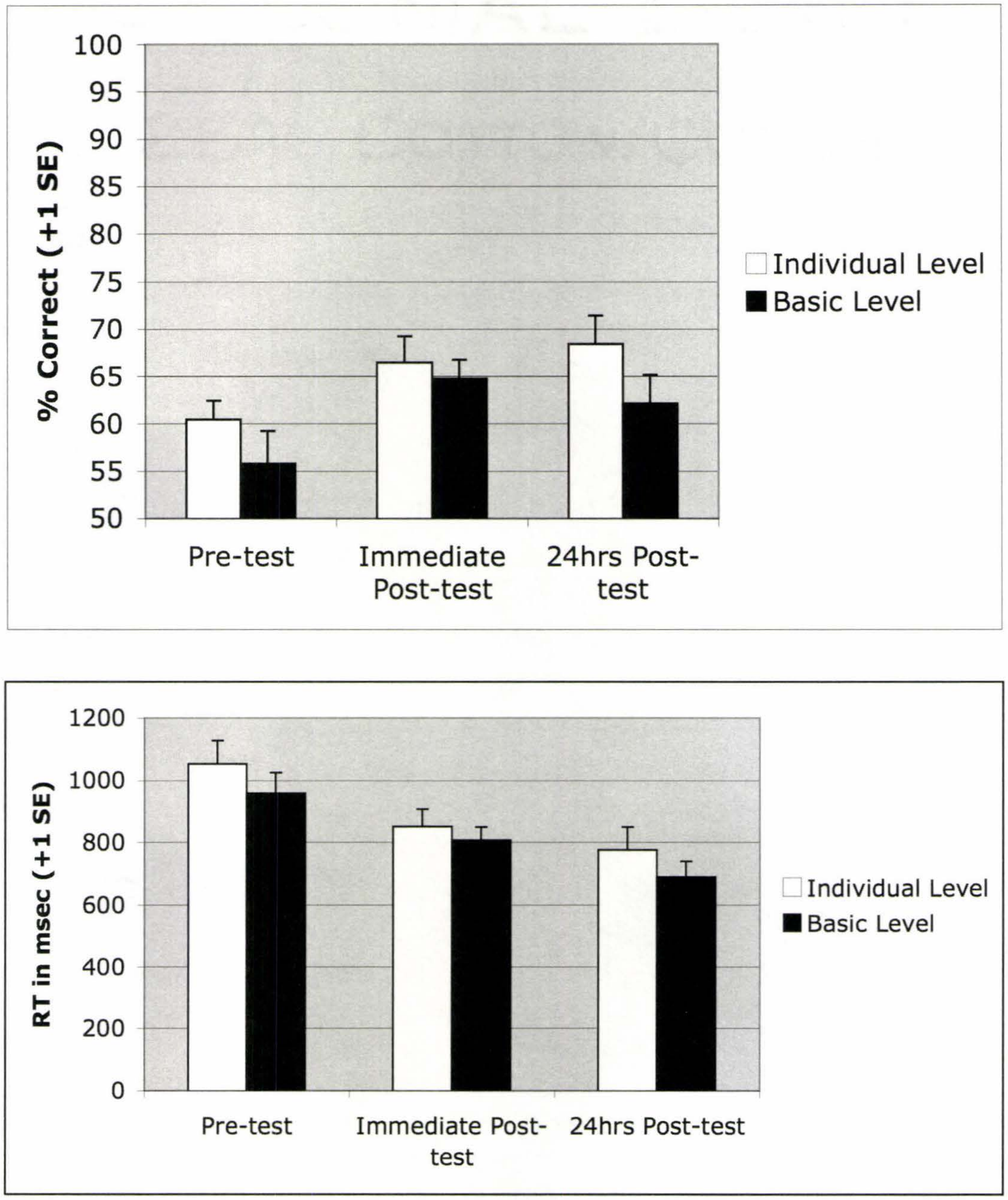
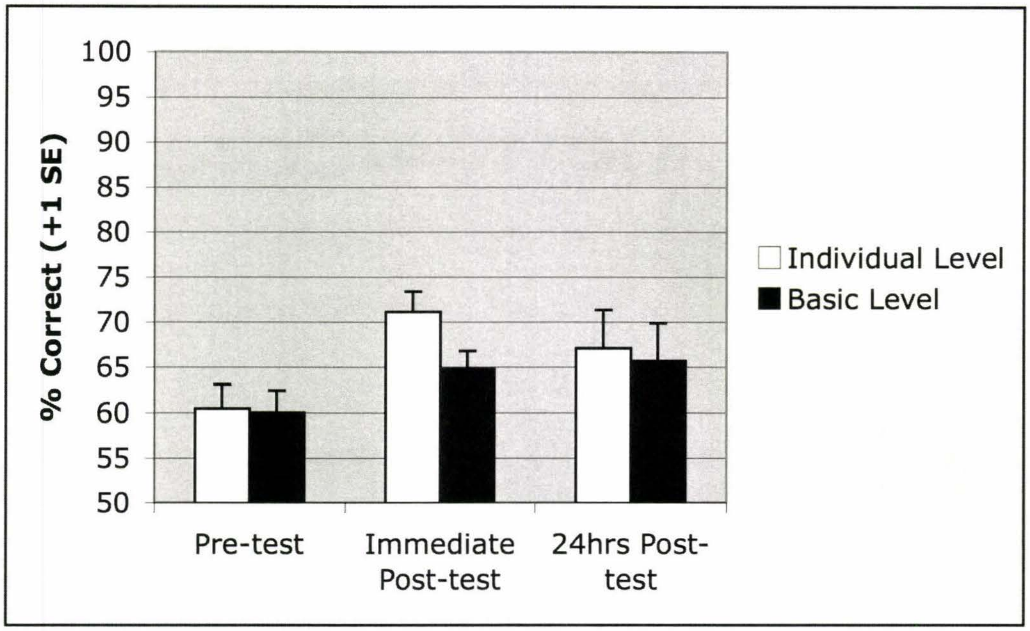


Figure 4. Experiment 1. a) mean accuracy (+ one standard error; 50% correct = at chance) and b) mean reaction times (+ one standard error) on correct trials, on pre-test, immediate post-test, and post-test 24 hours later by the Individual Level Training Group and Basic Level Training Group.



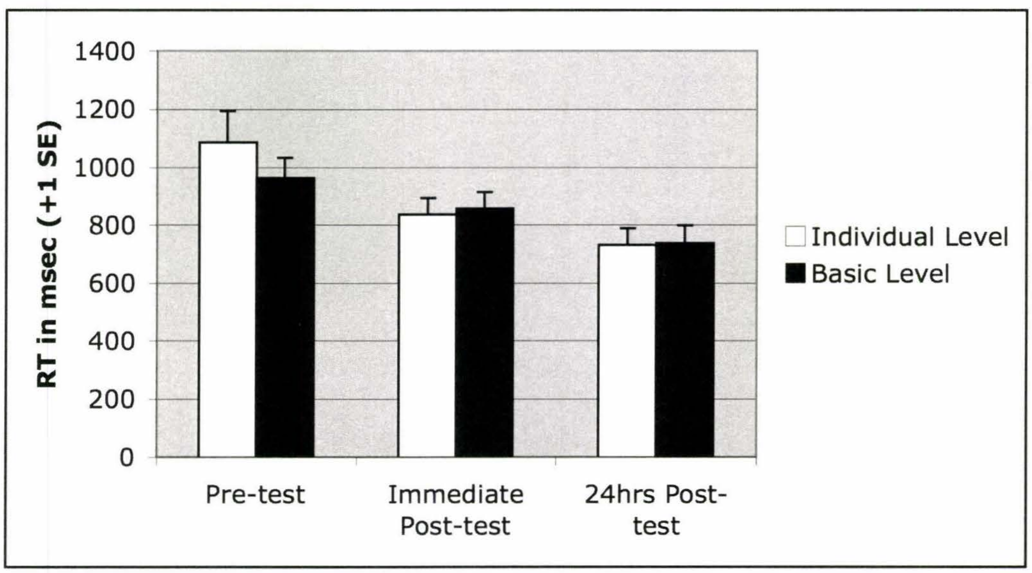


Figure 5. Experiment 1. a) mean accuracy (+ one standard error; 50% correct = at chance) and b) mean reaction times (+ one standard error) on correct trials, in pre-test, immediate post-test, and post-test 24 hours later by paired observers in the Individual Level Training Group and Basic Level Training Group matched on pre-test sensitivity to second-order relations (on an individual basis).

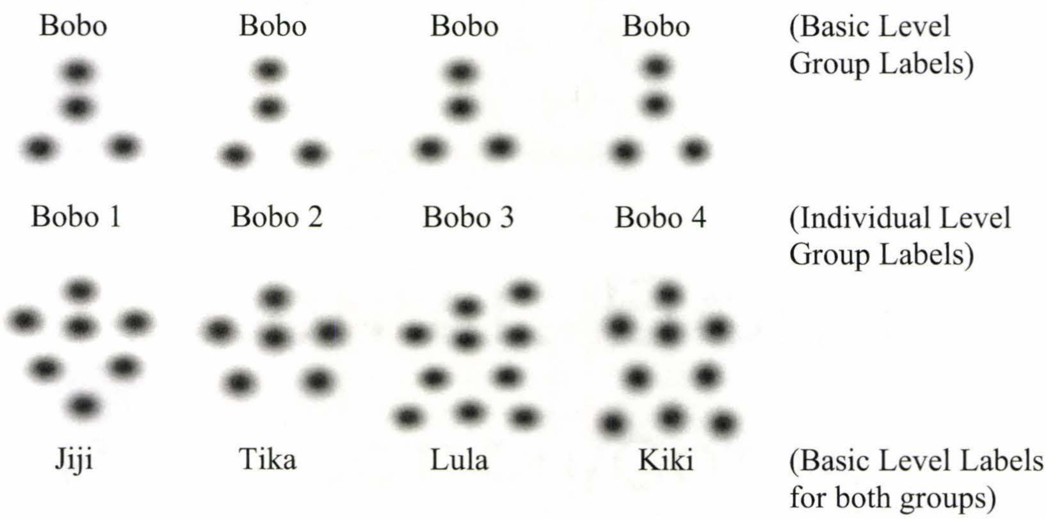


Figure 6. Training stimuli for Experiment 2.

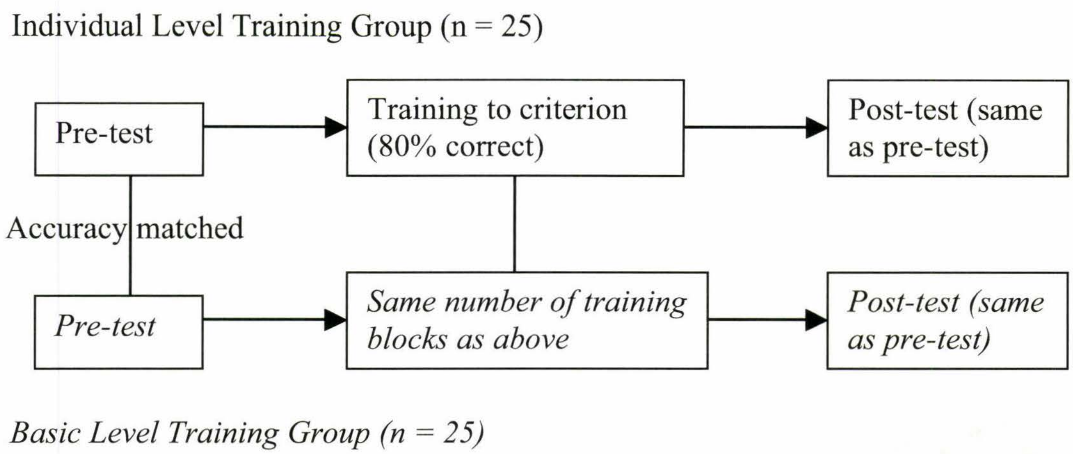


Figure 7a. Flow-chart of the procedure for participants in the Individual Level Training Group and the Basic Level Training Group. Pairs of individual participants were matched on pre-test accuracy and underwent the same number of training blocks.

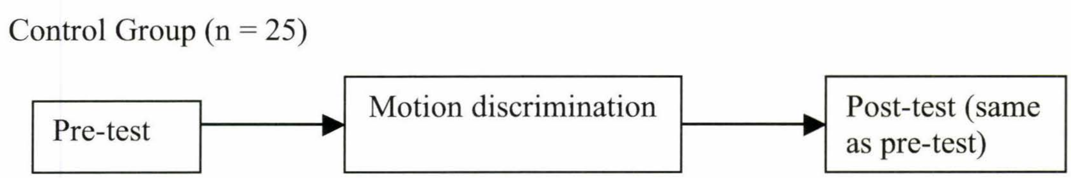


Figure 7b. Flow-chart of the procedure for participants randomly assigned to the Control Group.

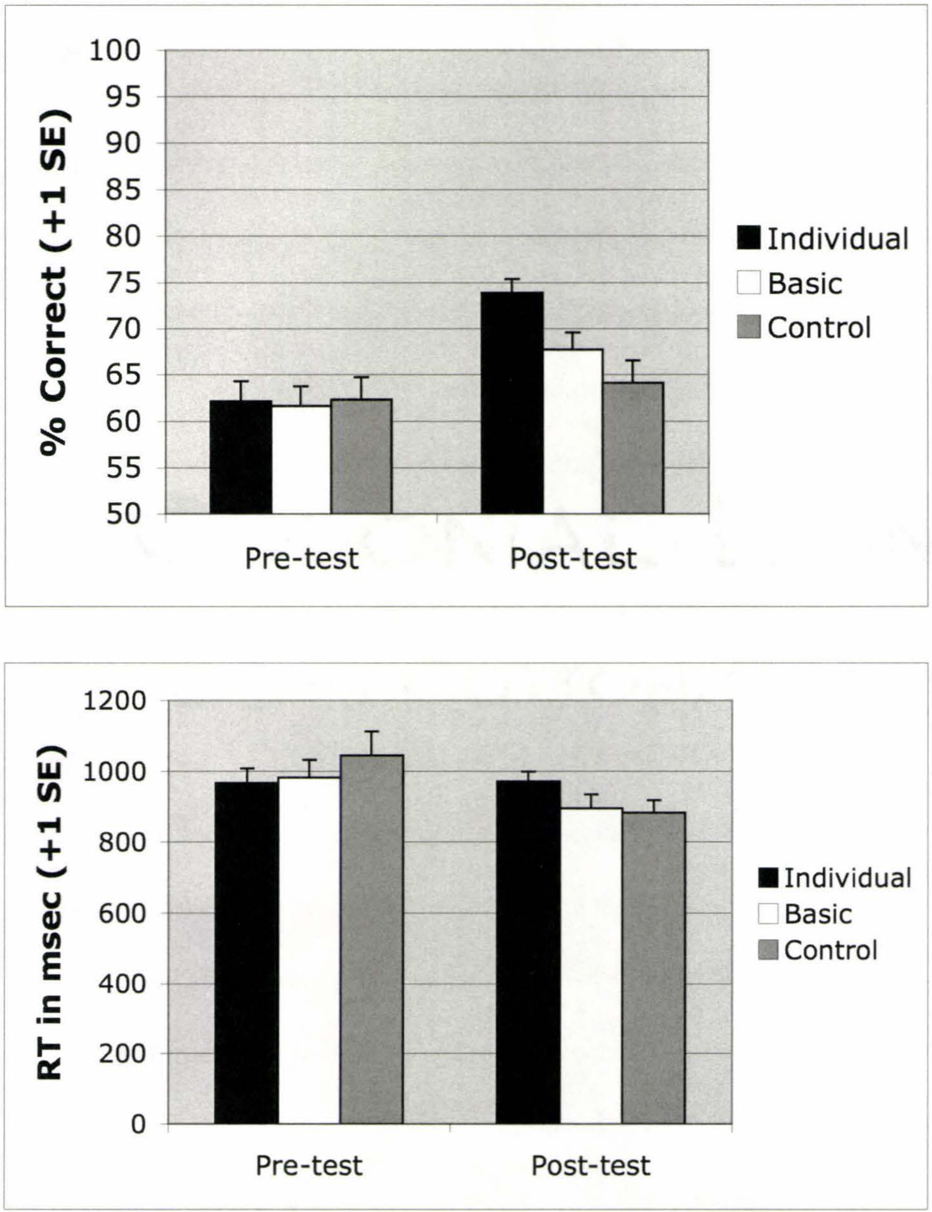


Figure 8. Experiment 2. a) ean accuracy (+ one standard error; 50% = at chance) and *median* reaction times (+ one standard error) on correct trials, on the pre-test and post-test sensitivity to second-order relations for the Individual Level Training Group, Basic Level Training Group, and the No Training Group (matched on pre-test accuracy on an individual basis).

Chapter 6

General Discussion

Children and adults recognize many faces throughout each and every day. However, this task is computationally complicated, as the visual image of faces can vary for many reasons, only one of which is a difference in identity. Therefore, for successful identification of a face, the brain must solve the computational problem of differentiating between the differences among facial images that represent different identities, and the differences that represent cues unrelated to identity, although they may be useful for other percepts (e.g., emotional expression). This computational problem is further complicated by different viewing conditions (e.g., lighting, viewing angle) that can change the appearance of faces. Although many studies have examined face processing over the past two decades, it is not yet clear how the brain learns to solve this problem of recognizing the same identity under different viewing conditions. In this thesis I used two complementary approaches to examine role of visual experience in face recognition. The first approach examined developmental differences in visual experience by comparing the mental representation of facial identity in adults and children at an age when there are known behavioral and neural immaturities in face processing. The second approach examined the effects of short-term visual experience on aspects of face processing that normally take many years to develop. Collectively, the studies reveal aspects of face processing that are already adult-like by 8 years of age, and also provide clues as to what develops beyond 8 years of age.

A useful framework for understanding how adults represent faces is face-space: a multidimensional space in which faces are coded as deviations from the average or norm (Valentine, 1991). However, little is known about how well the face-space framework accounts for children's mental representation of facial identities. The studies described in Chapters 2 and 3 tested the predictions of the face-space model against children's face processing abilities. The study described in Chapter 2 utilized an adaptation paradigm to test whether 8-year-olds encode faces relative to an average or norm, which is a key assumption in the face-space framework. Norm-based coding in adults is inferred through the demonstration of an identity aftereffect: a shift in the perception of facial identity in the direction opposite to the adapting face relative to an average face (e.g., Leopold ,O'Toole, Vetter, & Blanz, 2001; Rhodes & Jeffery, 2006). Eight-year-olds demonstrated adult-like identity aftereffects (Chapter 2), a result suggesting that 8-year-olds encode faces relative to a norm. Furthermore, the magnitude of this aftereffect was similar to that of adults, a finding that suggests that 8-year-olds utilize norm-based coding of faces in a manner similar to adults.

To examine the dimensions of children's and adults' face-space, one previous study used multi-dimensional scaling (MDS) to show that three dimensions, likely representing hair colour, hairstyle, and face width, accounted for perceived facial similarity in 7-, 9-, 12-year-olds and adults (Pedelty, Levine, and Shevell, 1985). This result suggests that children and adults have similar dimensions of face-space. However, the finding that two of the three dimensions used by children and adults represented hair cues makes it difficult to interpret the developmental implications, because even patients with severe deficits in face recognition can use hair cues to correctly match faces (e.g., Duchaine & Weidenfeld, 2003). Therefore, the availability of hair cues may have led to an overestimation of the similarity between children's and adults' face-space. The study described in Chapter 3 provided a more rigorous comparison of children's and adults' face-space by using 25 faces (twice as many as used by Pedelty et al., 1985), all with the same hair so that observers could not use hair cues to make similarity judgments. The results revealed that 8-year-olds' judgments of facial similarity were highly correlated with those of adults. The results of the MDS analysis revealed that independently rated typical faces were located closer to the origin than distinctive faces in the MDS solutions of both 8-year-olds and adults, as predicted by the face-space model. Additionally, the pattern of local clustering of faces was similar in the 8-year-olds' and adults' MDS solutions. These findings suggest that the face-space of 8-year-olds and adults have a similar spatial layout.

The results from the study described in Chapter 3 also revealed some differences between children's and adults' MDS solutions. The average weightings of each dimension in the best-fit 5-dimensional MDS solutions of children and adults suggested that many 8-year-olds relied heavily on a single dimension that likely represented eye colour, whereas adults tended to utilize all 5 dimensions roughly equally. The most striking difference between the MDS solutions of children and adults was the poor fit of the MDS solutions to 8-year-olds similarity judgments, presumably because there was more variability in judgments made by 8-year-olds than in those of adults, both within and across individuals. Greater variability was also observed in the individual weightings of the MDS dimensions in 8-year-olds than adults. Such variability may, in part, underlie children's lower recognition accuracy compared to adults when making identity judgments of newly learned faces (e.g., Mondloch et al., 2002; Chapter 2) and when recognizing facial identity across changes in viewpoints (e.g., Mondloch et al., 2003; Chapter 4).

Because the ability to recognize faces across changes in viewpoint and to discriminate faces based on changes in second-order relations (the spatial relations among internal features) takes many years to develop to adult levels (e.g., Mondloch et al., 2002, 2003), the studies described in Chapters 4 and 5 utilized a training paradigm to examine the effect of short-term training on these two skills. The pattern of results from the study described in Chapter 5 suggests that the experience of recognizing faces at the individual level of categorization is important in developing initial sensitivity to second-order relations. Short-term training to identify novel objects that differed in second-order relations led to improved sensitivity to second-order relations in novel exemplars, but only in adults who were trained to identify the objects at the individual level (e.g., Bobo 1 vs. Bobo 2), and not in adults who were trained to identify them at the basic level of categorization (Bobos vs. Tikas). The results support the hypothesis that sensitivity to second-order relations of faces develops as a consequence of identifying individual faces. One reason may be that second-order relations are useful when recognizing faces from different viewpoints. However, the results from the study described in Chapter 4 suggest that the real-world demands of having to recognize faces across changes in viewpoint are not directly related to sensitivity to second-order relations. In both 10-year-olds and adults, there was no evidence of a correlation between the two skills prior to training (even though observers had at least 10 years of experience processing faces), and training effects failed to transfer from the ability to recognize identity across changes in viewpoint to sensitivity to second-order relations. Recent evidence that 8-year-olds are worse than adults in detecting changes to second-order relations of monkey faces suggests that improvement in sensitivity to second-order relations beyond 8 years of age may be related to improved general cognitive and/or perceptual abilities, rather than specific improvement in processing of faces (e.g., Mondloch, Maurer, & Ahola, 2006). Other visual abilities, such as contour integration and vernier acuity, and spatial abilities such as mental rotation, also develop beyond 8 years of age (e.g., Carkeet, Levi, & Manny, 1997; Heil & Jansen-Osmann, 2007; Jansen-Osmann & Heil, 2007; Kovacs, Kozma, Feher, & Benedek, 1999; Skoczenski & Norcia, 2002), and those improvements may contribute to the observed improvements in face processing from 8 years to adulthood (Chapters 2, 3, and 4).

The results from the study described in Chapter 4 also indicate that short-term training leads to an improvement in the ability to recognize unfamiliar faces from different viewpoints, both in 10-year-olds and adults. The improvement demonstrated by 10-year-olds after just two one-hour training sessions suggests that the fundamental architecture supporting view-invariant recognition is present by 10 years of age and that it can be applied to newly encountered faces. However, the rate of improvement was more variable in children, which is consistent with the findings from Chapter 3. When greater memory demands were imposed on adults by introducing more faces as training continued, improvements did not transfer to faces introduced later in training. This result suggests some memory capacity limit in how quickly adults can learn enough examples of unfamiliar faces to apply view-transformation algorithms for successful recognition of identity across viewpoints. A similar capacity limit may underlie the lower accuracy observed in children.

Limitations

There are remaining issues that the studies described in this thesis did not address. A major concern is the generalizability of the current findings to face processing under more naturalistic conditions. For example, hair cues to identity were purposely removed in all of the present studies in order to examine how children and adults recognize identity based on internal facial structures and features, rather than recognizing identity based on hairstyles. Nonetheless, it is the case that when hair cues are available, both children and adults make use of them in making similarity judgments (e.g., Johnston, Milne, & Williams, 1997; Pedelty et al., 1985). Similarly, faces and novel objects that differ only in second-order relations (stimuli used in the studies described in Chapters 4 & 5) do not typically exist in the real world. Although manipulating a single aspect of facial identity is a good test of whether the perceptual system is sensitive to that cue, it does not reveal how such processing interacts with processing of other cues, as is the case in everyday face processing. The paradigms described in this thesis compared children and adults' face processing abilities under conditions that tested the limits of the perceptual system under constrained conditions; however, the possibility that different mechanisms underlie face processing in more naturalistic conditions must be acknowledged.

Another limitation is that the present paradigms used static images of faces, whereas faces in the real world are dynamic, providing rich 3-dimensional information that may play an important role in face recognition, especially when observers must recognize the identity of faces from different viewpoints. The temporal and spatial continuity across different views and emotional expressions of faces as we interact with people in the real world may provide important information about the structural properties of a face that cannot be computed from static images. If this hypothesis is correct, then training observers to recognize faces from different viewpoints using dynamic movies may lead to improved sensitivity to second-order relations.

Although limitations exist in any statistical procedure, one specific limitation of multi-dimensional scaling is that interpreting what the MDS solutions represent psychologically is inevitably subjective. Interpretation of the dimensions was especially problematic in inferring the dimensions of children's and adults' face-space (Chapter 3), because faces do not appear to be coded along dimensions that represent easily identifiable features. Rather, each MDS dimension appeared to represent multiple characteristics. The difficulty in interpreting the dimensions of the solutions reveals that multi-dimensional scaling by itself is not an optimal method for examining what the psychological dimensions of face-space represent. One approach to obtaining a more objective interpretation would be to ask independent observers to judge what the dimensions represent psychologically by presenting samples of faces that lie on opposite ends of each dimension. Another approach would be to calculate, for each face, which pixels are correlated with the dimensional values. The pixels that are highly correlated across all 25 faces can be used to create a pixel map of the most informative pixels for that dimension. Although the psychological interpretation of what those pixels represent will inevitably be subjective, this method would provide an objective spatial map of the face regions that drive the dimensional values.

A final limitation is in the design of the training paradigms. The effects of short-term training can provide useful insights for understanding the development of face processing, but it is important to acknowledge the difference between the training effects demonstrated by adults, who have already acquired expertise at face processing, and the developmental changes observed in children as they gain experience with processing faces. For example, one interpretation of the rapid improvement in adults' sensitivity to second-order relations of novel objects after individual-level training (Chapter 5) is that the improvement represents generalization of sensitivity to second-order relations that developed through face processing to a novel object category, rather than acquisition of a new skill per se. Adults' face expertise may allow bootstrapping of tasks that have similar processing demands, which is not the case for children when they are still developing sensitivity to second-order relations in faces. Although the complementary approach of examining both childhood development and short-term training effects expands our understanding of how the visual system changes with experience, these behavioral effects may be guided by different underlying mechanisms. This difference cannot be addressed in the current collection of studies. Further insights to the development of face processing, and the underlying mechanisms, may be gained if training is continued over several weeks or months, and in combination with neuroimaging techniques.

Proposals for future research

The present collection of studies provides a starting point for further examination of the development of face-space. For example, although 8-year-olds demonstrated a face identity aftereffect that was of a similar magnitude to that of adults (Chapter 2), it is unclear whether the adaptation aftereffect would be similar under different adapting conditions. Recent studies reveal that the magnitude of the identity aftereffect demonstrated by adults increases logarithmically with longer adaptation durations, and decreases exponentially with longer test durations (Leopold, Rhodes, Muller, & Jeffery, 2005; Rhodes, Jeffery, Clifford, & Leopold, 2007). At an age when not all face-processing abilities are adult-like, children's face-space may be more malleable and hence identity aftereffects in children may have different temporal dynamics from those of adults. For example, children may show stronger identity aftereffects with shorter adaptation durations than adults, and/or they may demonstrate longer lasting identity aftereffects when longer test durations are used. The flexibility in children's face-space is suggested by the finding that Korean adults, who were adopted into French Caucasian families before the age of 9 years, demonstrate an other-race effect that is similar to Caucasian adults, not Korean adults (Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005).

The greater variability in 8-year-olds' similarity judgments of facial identity (Chapter 3) may be a manifestation of the fact that children's face-space is more malleable, because their judgments would be more easily influenced by faces seen earlier in the task, as well as the faces being compared in each trial

(Yotsumoto, Kahana, Wilson, & Sekuler, 2007). The source of this variability can be examined in future research by presenting the same triads repeatedly to children. Repeat trials would allow an assessment of whether children's inconsistent similarity judgments reflect variability in the face stimuli or in children's responses in general. If the same face is chosen to be most different on each repeat trial, it would suggest that children are generally consistent, but that their judgments are being influenced by the most salient cue on which to base their decision, which can differ depending on the faces in each trial. If different faces are chosen to be most different on repeat trials, it would suggest that children are variable in their responses in general.

Another interesting avenue for future research is to examine whether norm-based coding applies only to faces, or whether this is a computational mechanism that applies to all object categories. This is a question that has not been addressed adequately even in adult object perception. Norm-based coding provides an efficient way to represent important stimulus attributes because averaging across various viewing conditions cancels out information that does not provide diagnostic cues (e.g., Burton, Jenkins, Hancock, & White, 2005). Indeed, the idea of norm-based coding as a way of discriminating between specific objects in a category has been suggested in the cognition literature (e.g., Huttenlocher, Hedges, & Duncan, 1991). Such coding relative to an average could be effective for non-face object categories, like faces, which have homogeneous first-order relational properties. Adaptation paradigms will be useful in examining this hypothesis in the future, but limited to object categories that are homogeneous enough that a digitally morphed average looks prototypical and not like an unidentifiable pattern.

The stimuli created in the viewpoint training study (Chapter 4) may be useful in extending our knowledge of children's and adults' face-space. Currently, it is unclear how different viewpoints of a face are encoded in face-space (e.g., Newell, Chiroro, & Valentine, 1999; O'Toole, Edelman, & Bulthoff, 1998). For example, is a profile face encoded relative to the average profile face, or is it first normalized to frontal view and then encoded relative to the frontal-view norm? Results from studies using adaptation with faces in different viewpoints suggest that some neurons are tuned to different viewpoints, but it is not yet clear how encoding of facial identity interacts with the coding of viewpoint (Fang & He, 2005; Fang, Ijichi, & He, 2007; Jeffery, Rhodes, & Busey, 2007).

Another approach to examine how viewpoint is represented in face-space is to test how the typicality or distinctiveness of faces interacts with changes in viewpoint. If the correct face-space model is the one in which all faces are encoded relative to a single average, then view transformation should occur before the face is compared to the average, because the observer will have the most experience with frontal views. The prediction would be, then, that a view-normalization process would be applied more successfully to typical faces (because typical faces would have average structural properties that can be predicted more accurately by a general view-transformation algorithm), and hence the advantage for distinctive faces in individual identification would be diminished with greater rotation from frontal view. Alternatively, if norm-based coding occurs at multiple levels, such that each face is encoded relative to the "grand average" as well as the "prototypical view" of individual identities, then distinctive faces may be identified more easily than typical faces from each viewpoint, because typicality per se should not interact with the effect of viewpoint.

Although the present collection of studies did not address the importance of different spatial frequencies in processing faces, recent studies have examined the differential use of spatial frequencies when processing faces versus non-face objects (e.g., Ruiz-Soler & Beltran, 2006). An interesting approach for future research is to determine how spatial frequencies map onto the dimensions of face-space. Additionally, comparing the useful spatial frequencies for children and adults may provide further insight to how face processing develops. Studies examining the critical bandwidth for face recognition reveal the importance of mid-range spatial frequencies, between 8-16 cycles per facewidth (e.g., Costen, Parker, & Craw, 1994, 1996; Parker & Costen, 1999), although the critical bandwidth also depends on task demands and available information in the image (e.g., Oliva & Schyns, 1997; Ruiz-Soler & Beltran, 2006; Schyns 1998). A recent finding that the neural representations of faces retain the spatial frequency information of the original image from V1 to V4 and into the fusiform face area

(Yue, Tjan, & Biederman, 2006) suggests that spatial frequency provides information that is important for face recognition.

Conclusion

The present collection of studies examined how processing of facial identity develops with experience, by comparing face perception in children and adults, and by utilizing training paradigms to reveal short-term learning effects. The findings contribute to the existing literature on face perception by demonstrating that by 8 years of age, children's face-space appears similar to that of adults (Chapter 2), although their responses are more variable (Chapter 3). This greater variability, both within and across individuals, may partially explain the overall lower recognition accuracy of children than adults. By 10 years of age, children show improvements in recognizing unfamiliar faces across changes in viewpoint after short-term training, although the training effects are more robust in adults (Chapter 4). The experience of recognizing faces across changes in viewpoint does not appear to be directly related to sensitivity to second-order relations (Chapter 4); however, recognition at the individual level of categorization, as is usually performed with faces, may be important in developing this skill (Chapter 5). The general pattern of findings suggests that the fundamental architecture for representing facial identity is in place by 8 years of age. Future studies suggested in this thesis will aid in understanding to what extent improvements beyond 8 years of age are specific to face processing rather than reflecting general cognitive and perceptual improvements.

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