The development of face recognition in infants and children

Kate Crookes

A thesis submitted for the degree of Doctor of Philosophy of The Australian National University (Department of Psychology).

September, 2009

Declaration

I certify that the work presented in this thesis is an accurate account of research performed during the academic program towards the degree of Doctor of Philosophy. Chapters 2-6 of this thesis are published (or submitted) articles on which I am a co-author. I made a major contribution to each of these papers. The contribution of each author is detailed in the context statement preceding each chapter. Chapters 1, 7 and 8, aside from the usual contribution of my supervisor Elinor McKone, are my own work.

Examiners should note that: (1) in Chapter 4 Experiment 2 data for the "performance matched adult" group were taken from Robbins and McKone (2007) and were not collected by me; and (2) in Chapter 4 Experiment 3B 48 of the 64 child participants were previously included and examined in my Honours thesis (2004).

Kate Crookes ______________________

Previously published (or in press) material appearing in this thesis

McKone, E., & **Crookes, K.** (2007). Understanding the developmental origins of primate face recognition: Theoretical commentary on Martin-Malivel and Okada (2007). *Behavioral Neuroscience, 121*(6), 1437-1441.

McKone, E., **Crookes, K.,** & Kanwisher, N. (in press). The cognitive and neural development of face recognition in humans. In M. S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (IV ed.). Cambridge, Massachusetts, USA: Bradford Books.

Crookes, K., & McKone, E. (2009). Early maturity of face recognition: No childhood development of holistic processing, novel face encoding, or face-space. *Cognition, 111*(2), 219-247.

Susilo, T., **Crookes, K.,** McKone, E., & Turner, H. (2009). The composite task reveals stronger holistic processing in children than adults for child faces. *PLoS One, 4*(7), e6460.

Acknowledgements

Firstly, thank you to my supervisor Elinor McKone for her support throughout my PhD and her endless enthusiasm for faces and research. Thank you to my supervisory panel: Rachel Robbins who went above and beyond the description of panel member – conference roomie, programming guru, and most importantly wise advisor who had been through it all before; Michael Cook who provided invaluable insights into baby research; and Barbara David. Thanks also to Cobie Brinkman for her knowledge of all things monkey (and horse), for alerting me to papers I really should be reading and for willingly proof reading my thesis.

Thank you to my co-authors for allowing me to include our papers in this thesis and for your insights and helpful discussions on the development of face processing. I also appreciate the useful feedback from the reviewers of the papers presented in this thesis and the various academics in talks and poster sessions where I have presented this work.

Thanks to Jacqui and Stefan, who taught me everything I know (well at least about psyscope, photoshop, cricket graph, excel and how to spot a quality problem) and are two of the loveliest people I have had the privilege of knowing.

To all members of the Cognition and Perception Labs in the Department of Psychology, ANU I have encountered along the way, your encouragement, generosity with time and ideas, and sense of community provide a shining example of how academia should be. Thank you to the administrative and technical staff for all your support (especially Allan and Shane for making my incomplete plan for a baby lab a very professional looking reality).

Thank you to all the participants, the parents who let me test their children and babies, and the schools, principals, teachers, school holiday programmes, nurses, and doctors who went out of their way to help me run my studies.

Finally, thank you to my friends and family who got me through this process, with special mentions to Mukesh, Ben, Alison, Hilary, Graham and, of course, Mum.

Abstract

Despite substantial research, the developmental origins of adult face recognition skill remain unclear. At the most general level this thesis is about the contributions of innate representations, experience, and the timing of experience, to the development of adult face recognition ability. Within this, the specific aims are to contribute to open questions concerning: (a) the role of extended experience continuing into adolescence in establishing quantitative maturity of core face perception mechanisms (specifically, "special" processing for faces compared to objects, face-space, and ability to encode novel faces); (b) the retention of flexibility in older children and adults, whereby recent experience with certain face subtypes might influence face processing, and; (c) the nature and role of an experience-expectant component present at birth, tuned by experience with certain stimulus classes and face subtypes in infancy.

Empirical chapters are separated into three independent papers addressing the above aims. The first empirical chapter investigated the age of quantitative maturity of face-specific perceptual mechanisms in childhood. Historically, the conventional understanding has been that, driven by experience, face processing undergoes protracted development across childhood and does not reach full maturity until mid-adolescence. Here, however, it is argued that the basis of determining the age of maturity of face effects – quantitative comparison across age groups – is a task made difficult by the need to disentangle development in face perception from development in all the other cognitive factors that affect task performance. I argue that, in fact, all putative face-specific perceptual mechanisms reach both qualitative and *quantitative* functional maturity relatively early in development, by 5-7 years at the latest and possibly earlier. This conclusion is based on a comprehensive literature review, plus three new experiments testing development of holistic processing (faces versus objects, disproportionate inversion effect), ability to encode novel faces (assessed via implicit memory) and face-space (own-age bias) in the 5 years to adult age range.

The second empirical chapter investigated whether recent exposure to a certain subtype of faces can strengthen holistic processing in children. Here, children (8-13 years) showed a larger composite effect than adults for child faces, suggesting an own-age bias on holistic processing. This finding supports previous findings in adults that recent experience with one face subtype can affect holistic processing. Theoretically, the origins of own-age biases are discussed in terms of whether experience has a direct role in tuning perceptual mechanisms, or an indirect role though social categorisation and attention mechanisms.

The final empirical chapter investigates infancy. Previous research has shown that face individuation undergoes perceptual narrowing across infancy, arguing that infants are born with an innate face representation which is initially broadly tuned to include non-human primate as well as human faces. However, it has implicitly been assumed that this is a *face* representation. Here I consider the possibility that it is even broader. Individual level discrimination of whole animals (bay thoroughbred horses, shown in side view) was tested in 4-month-olds (an age before any narrowing for faces has been observed). Results showed 4-month-olds could discriminate upright horses at least as well as upright faces, despite adults showing the expected pattern of poor discrimination of upright horses compared to upright faces. Infants could not individuate inverted horses. Our findings imply innate individuation is broader than a primate face, including at least other mammal heads, and possibly whole bodies of all animals.

Taken together, the results of this thesis argue that the developmental origin of "special" processing of faces is not experience that extends into adolescence. Instead, I argue that adult face recognition ability derives from the combined contributions of: (a) an innate representation that starts out very broadly tuned (broad enough to include non-primate animals, either as heads or whole bodies) and becomes face, species and race specific with experience in infancy; and (b) face-specific perceptual mechanisms that require at most 5-7 years of face experience to become fully mature (and possibly much less). I also conclude that, once the face system is mature, there is ongoing flexibility in children and adults in the engagement of this system, based on concentrated recent exposure to a subtype of faces.

Table of Contents

CHAPTER 1 – INTRODUCTION TO THESIS

1.1 Overview of the thesis

Recognising individuals, and discriminating them from each other on the basis of facial appearance, is an essential skill for successful human social interaction. It is also a skill at which most adults excel. There has long been interest in how this important ability develops and the age at which it reaches maturity. Yet, many questions remain.

The general intent of this thesis is to contribute to an active debate in the literature, which centres on the relative roles of an inborn capacity present at birth, experience with faces, and the timing of that experience, in producing adult face recognition ability. At the heart of this debate is an apparent conflict in the literature. On the one hand, newborns display remarkable adult-like abilities with faces – including the ability to individuate upright faces, cross-view recognition, and inversion effects – and there is further evidence of an experience-expectant innate mechanism from the existence in infancy of both perceptual narrowing and a sensitive period. This argues for strong abilities in face recognition present *very early* in development. On the other hand, performance on all laboratory face tasks – including tasks assessing both face perception and face memory – undergoes substantial and protracted improvement across childhood, not reaching adult levels until well into adolescence. These latter results have commonly been interpreted as demonstrating *very late* maturity of face recognition abilities, and have been used to argue that, theoretically, very extended lifetime experience (e.g., at least 10 years) is necessary to develop adult levels of face recognition ability.

The aim of this thesis is to clarify the developmental origins of face processing by a combination of behavioural experiments, literature review, and theoretical critique addressing three specific questions. These were: (a) What is the age of quantitative maturity of face-specific perceptual mechanisms, and does extended experience continuing into adolescence in fact play any role in establishing maturity of these mechanisms?; (b) Do the mature face perception mechanisms of children (and adults) retain flexibility such that concentrated recent experience with a certain face subtype can influence the operation of these mechanisms?; and (c) How broadly tuned is the experience-expectant innate component present at birth?

The present chapter provides a broad overview of the themes and structure of this thesis. It assumes the reader has at least moderate expertise in the area of the development of face perception. Full definitions of terms, explanations of theories, and references are provided in later chapters.

The thesis begins with a theoretical discussion of the types of empirical evidence relevant to debate about the relative roles of an experience-expectant innate component versus extended experience, and how these types of evidence can logically be used to inform this debate (Chapter 2). Chapter 3 then goes on to critically review much of the relevant empirical evidence from previous studies.

Regarding an innate component, these chapters argue that three findings strongly support the classic claim that there exists some form of innate representation ((although this does not take the exact form originally suggested by Morton & Johnson, 1991), but also strongly support more recent findings regarding the importance of early experience in infancy. These findings are: evidence of remarkable face discrimination abilities in newborn human infants and face-experience deprived monkeys; evidence of perceptual narrowing for faces during infancy; and the existence of a sensitive period in infancy for at least one aspect of face perception. Theoretically, it should be noted that by "innate" I mean some basic skill *present at birth*, presumably of *evolutionary* origin; but I do *not* mean that face perception is fully mature at birth or unaffected by experience. As with all other perceptual or cognitive capacities argued to have an innate component (e.g., perception of line orientation, phoneme discrimination, language processing) post-birth experience plays an important role in the normal development of that capacity. Therefore any use of the term "innate" in this thesis should always be read merely as shorthand for an "*experience-expectant* innate" component.

Regarding the effects of extended experience, Chapters 2 and 3 introduce the traditional Carey and Diamond (1977, 1994) theory, which proposed that core face perception mechanisms are not present at all, and/or do not fully mature, until very late in childhood development (e.g., in adolescence). These chapters then raise a number of important theoretical critiques of this idea, including whether the observation of late maturity on a task indicates that *experience with faces* rather than *maturation* is responsible; and whether the fact that face recognition can be affected by recent experience with certain face types (even in *adulthood*; see Chapter 5) necessarily shows that basic adult levels of ability are dependent on extended childhood experience and/or rule out innate contributions. The chapters also raise key methodological critiques which question whether, in fact, face perception per se does show late maturity at all (a discussion continued in Chapter 4). Chapter 3 concludes by highlighting a number of critical open questions.

The first of these questions then addressed empirically by the present thesis concerns the age of maturity of core face recognition mechanisms. The specific mechanisms addressed are: holistic/configural processing for faces, including differences between perception of faces and non-face objects (i.e., dogs); face-space; and the ability to encode a perceptual representation of a novel face. In this context, the thesis first reviews evidence that (in contrast to the very early ideas from the 1970s and 1980s) all behavioural face recognition effects shown by adults are *qualitatively* present in children and/or infants, in all cases at the youngest ages tested; this review material appears primarily in Chapter 3. The thesis then moves on to the more difficult question of addressing the general presumption in the field that the capability of the "special" mechanisms underlying face processing does not reach full adult levels *quantitatively* until mid-adolescence. Here, I argue that the question of when quantitative maturity is reached is a much more difficult question to answer, partly because almost all prior experimental techniques confound development in face perception with the effects of general cognitive development, and partly because almost all previous studies suffer methodological difficulties in making comparisons of the size of effects across age groups (e.g., ceiling effects, floor effects, change in baseline performance across age). The theoretical ideas and literature review making this point appear in Chapter 4.

I then present three new experiments, also to be found in Chapter 4, which empirically separate development of face-specific perceptual mechanisms from development in generic cognitive factors. These factors are known to develop across childhood, and affect task performance for all stimulus types; they include, for example, concentration ability and explicit memory ability. My experiments test the 5 years to adult age range. They contrast rates of memory development for face versus non-face objects, compare the size of face and object inversion effects across ages, and test the development of explicit versus implicit memory for faces. Results demonstrate quantitative maturity of face perception mechanisms at the youngest ages tested (5 years or 7 years). This conclusion is further supported in Chapter 5, where early maturity of holistic/configural processing is demonstrated using the composite effect as an additional technique; indeed, results show that, at least under some circumstances, children can show *stronger* holistic processing than adults (in a finding which cannot be attributed to methodological problems such as baseline changes across age groups).

Thus, with respect to the first major question, the thesis concludes that all components of face-specific perceptual mechanisms are mature, both qualitatively and quantitatively, by 5-7 years. I also argue that there is currently no reason to believe that full maturity could not be reached rather earlier in childhood (or even infancy). Theoretically, I argue (see Chapter 4) that that these results demonstrate that extended lifetime experience is not necessary to produce behaviourally mature face perception mechanisms (although of course this does not rule out a crucial role for experience earlier in life, for example during a sensitive/critical period in infancy). I also discuss the apparent conflict between my behavioural findings, showing early functional maturity, and recent ERP and fMRI evidence suggesting much later maturity of supporting neural mechanisms (Chapters 3 and 4).

The second question addressed by this thesis concerns the effects of recent face-type experience, particularly in older children. Here, I ask: Does the mature face processing system of children (and adults) retain flexibility such that concentrated experience with a certain face subtype post-infancy can influence the tuning or engagement of face-specific perception mechanisms? This was investigated in Chapters 4 and 5 through the "own-age bias", where better recognition or stronger face-processing effects are demonstrated for own-age versus other-age faces, presumably due to greater recent experience with the faces of peers. Findings were that children (aged 5-13 years) demonstrated an own-age bias on explicit recognition memory (Chapter 4) and holistic processing (Chapter 5) but not implicit memory (Chapter 4). Theoretically, the origins of own-age biases are discussed in terms of whether experience has a direct role in tuning perceptual mechanisms, or an indirect role in switching the mechanisms on or off via social categorisation and attention mechanisms.

The final empirical question turns to the role of experience in infancy and investigates the nature of the experience-expectant component present at birth. The literature review in Chapters 2 and 3 presents recent evidence that argues for an innate component to face individuation but also demonstrates the importance of early experience in tuning the initial representation. Evidence is presented, based on previous studies, that (a) infants are born with an innate representation which supports individual level discrimination of faces, (b) this representation is rather broadly tuned, representing not only all types of human faces but also other non-human primate faces, and (c) this innate representation narrows with experience to become specific to the experienced species (e.g., human rather than monkey) and to experienced races within humans (e.g., Caucasians rather than Asians). In these previous studies, it has implicitly been presumed that the innate representation, while broad, is specifically of a *face*. However, it remains possible that the representation is in fact even broader, and the literature gives some reason to suspect it may be an innate representation of *whole animal bodies*. I then test this issue experimentally in Chapter 6 by assessing individual level discrimination of bay thoroughbred horses in 4-month-olds (an age before any narrowing has previously been observed). Results show that infants can individuate whole horses at least as well as human faces, in contrast to adults, who perform much more poorly with horses than faces. These findings demonstrate that infants are born with a representation which supports individual level discrimination of non-primate animals which narrows with lack of individuation experience. Findings are discussed in terms of whether this innate representation is (1) of whole bodies or animal heads; (2) even broader including all objects; and (3) the same representation that eventually narrows to only support own-species own-race face.

Following presentation of the core empirical work (Chapters 4-6), the thesis contains a short chapter (Chapter 7) describing the method and results of the extensive pilot studies required for many of the experiments.

Finally, Chapter 8 provides a General Discussion. The aim of this chapter is primarily to highlight what is now – following the results of the present thesis – known about the developmental course of face recognition, and what still remains unknown. It contains suggestions for future research both at the local level (e.g., individual experiments arising from the results of the present thesis) and at the more global level of the most interesting directions in the field.

1.2 Notes on the structure of the thesis

This thesis consists of two theoretical, literature review chapters (Chapter 2 & 3) and three experimental chapters (Chapter 4-6). Each of these chapters has been prepared as a standalone paper for publication. Three are published, one is in press and one is to be submitted.

The chapters are presented in an order that is both logical and chronological (the order in which they were written). Therefore some of the more recent literature is missing from the earlier papers but is covered in the later papers. Where necessary, a note on, or review of, subsequent literature is included either before (Chapter 2) or after (Chapters 3 & 4) the accepted manuscript. A short discussion follows Chapter 5 drawing together the findings of the two papers (Chapters 4 & 5) investigating the age of maturity of standard face effects and the own-age bias in children. Each chapter is preceded by: 1) an introductory context statement, which places it within the broader theoretical structure of the thesis; 2) its publication status and full reference; and 3) a statement of author contributions, as each paper is co-authored.

CHAPTER 2 – UNDERSTANDING THE DEVELOPMENTAL ORIGINS OF PRIMATE FACE RECOGNITION: THEORETICAL COMMENTARY ON MARTIN-MALIVEL AND OKADA (2007)

2.1 Context statement

The present chapter provides a general theoretical background to the empirical work in this thesis. It was written as an invited commentary on Martin-Malivel and Okada (2007) "Human and chimpanzee face recognition in chimpanzees: Role of exposure and impact on categorical perception". Martin-Malivel and Okada (2007) compared the performance of chimpanzees with differing levels of exposure to humans in recognising human and chimpanzee faces. Their results showed that chimpanzees with high exposure to both chimpanzee and human faces discriminated both these face types equally well, whereas chimpanzees with greater exposure to human than chimpanzee faces showed better discrimination of human faces than chimpanzee faces. Martin-Malivel and Okada (2007) discussed their findings in terms of the importance of experience over any innate component in the development of face processing.

Our commentary talks broadly about the type of evidence (from both human and non-human primates) required to draw such conclusions about the developmental origins of face processing, and briefly evaluates the relevant literature available at the time. A more detailed literature review follows in Chapters 3 and 4.

2.1.1 Notes on relevant literature published after this paper was accepted

This paper was accepted in September 2007 (and published in December 2007). Shortly after this date, two studies appeared which very much strengthened the arguments for the presence of an innate component to face perception. These papers provided evidence of sophisticated face processing in human neonates (Turati, Bulf, & Simion, 2008), sophisticated face processing in face-deprived monkeys (Sugita, 2008), and perceptual narrowing for faces in monkeys (Sugita, 2008). These studies are reviewed in Chapter 3. Also note that recent evidence of heritable component to face recognition is also discussed in that chapter (specifically, a twin study of neural activation patterns for faces in humans, Polk, Park, Smith, & Park, 2007; and findings that congenital prosopagnosia (that is, an inability to recognise faces) can run in families, e.g., Duchaine, Germine, & Nakayama, 2007; Schmalzl, Palermo, & Coltheart, 2008).

On a different topic, the following article (p 1440) asks whether the specific face-processing component of *holistic processing* can be sensitive to ongoing experience post-infancy. Note that more recent publications providing the first tests of this question are covered in Chapter 5.

2.2 Publication Status

This chapter is published as:

McKone, E. & **Crookes, K.** (2007). Understanding the developmental origins of primate face recognition: Theoretical commentary on Martin-Malivel and Okada (2007). *Behavioral Neuroscience, 121*(6), 1437-1441.

2.3 Author contributions

2.3.1 Content of Literature review

- Regarding the literature review on *human* development, **Crookes** had primary responsibility for the content.
- **Crookes** and McKone jointly researched and read the non-human primate literature.

2.3.2 Theory development

- McKone and **Crookes** worked together to develop the theories presented.

2.3.3 Writing

- McKone wrote the paper.
- **Crookes** commented on drafts, provided some rewording and proof read the final submission.

Behavioral Neuroscience
2007, Vol. 121, No. 6, 1437–1441

0735-7044/07/$12.00 DOI: 10.1037/0735-7044.121.6.1437

COMMENTARIES

Understanding the Developmental Origins of Primate Face Recognition: Theoretical Commentary on Martin-Malivel and Okada (2007)

Elinor McKone and Kate Crookes
Australian National University

J. Martin-Malivel and K. Okada (2007, this issue) reported that chimpanzees raised with extensive social contact with humans show face discrimination abilities for human faces that exceed those for conspecific faces. Martin-Malivel and Okada have placed this finding in the theoretical context of the relative role of experience and innate face representations. The present article discusses the logic of the various styles of studies relevant to this question—considering primates without prior visual experience, sensitive periods, perceptual narrowing, childhood development, other-species effects, other-race effects, social quality of experience with nonconspecifics, and perceived social group membership—and also reviews the key current data. A case is made that there is still a long way to go in understanding whether there is an innate representation of conspecific faces, how tightly tuned any such representation is to conspecific morphology, and how experience obtained during different age brackets (e.g., infancy versus adulthood) affects discrimination and interacts with any innate representation.

Keywords: face recognition, conspecifics, other-species, innate, experience

Face recognition provides an important means of conspecific individuation in primate societies. The developmental origin of conspecific face recognition is thus an important topic, with longstanding interest in the relative roles of experience-expectant innate components, experience during critical periods in infancy, and ongoing lifetime experience into adulthood. Several different styles of study, and types of evidence, are relevant to this debate. These include adult performance and development trends, in humans and nonhuman primates, for own-species and other-species faces, on tasks assessing discrimination ability and other potentially related aspects of performance, such as looking preference and holistic processing. In some cases, the logical relationship between experimental outcomes and theory is relatively straightforward; in other cases, however, it is not. We believe it is useful to lay out this logic explicitly.

The Logic of Evaluating Innate and Experience-Based Contributions

First, any finding of an ability to do something with faces without experience must provide strong evidence for an innate representation. For example, if animals with no prior visual experience of any conspecific faces showed preference for looking at conspecific faces over nonconspecific faces, better discrimination for conspecifics, or holistic processing for conspecifics but not nonconspecifics, then good evidence would be obtained for an innate representation of conspecific face morphology. Unfortunately, it seems that no very direct tests of this hypothesis have been conducted. We could find no studies that, for example, took newborn monkeys without prior experience (social or pictorial) of any face types and tested discrimination or preference for conspecifics versus faces of other species.

In humans, the closest relevant findings are that newborns (1–6 days old) can discriminate a once-seen novel face from another similar face (Pascalis & de Schonen, 1994; Turati, Macchi Cassia, Simion, & Leo, 2006) and also show inversion effects on this discrimination ability (Turati et al., 2006). These results are suggestive of an innate representation of upright face structure, although an entirely experience-based contribution cannot be ruled out, given that faces are likely to have formed the great majority of the infant's in-focus visual experience during the first few days of life (Sinha, Balas, & Ostrovsky, 2007). In nonhuman primates, Fujita (1990, 1993) argued that rhesus and Japanese monkeys have an innate representation of rhesus morphology but can also learn Japanese morphology on the basis of evidence that, for monkeys removed from their mother within the 1st week of life, both rhesus and Japanese monkeys preferred rhesus monkey stimuli, and that, for infants cross-fostered from 1 day old, rhesus monkeys did not show a clear species preference, while a Japanese monkey preferred rhesus monkey pictures. Also, Sackett (1966) found that monkeys reared in social isolation with visual exposure to humans for the 1st week of life showed an onset of disturbance responses to conspecific threat pictures in comparison with conspecific nonthreat pictures at 2–3 months of age; given that threat and nonthreat pictures had been experienced equally often prior to this age, this argues for the maturation of an innate representation able to

---

Elinor McKone and Kate Crookes, School of Psychology, Australian National University, Canberra, Australia.

This work was supported by Australian Research Council Grant DP0450636 to Elinor McKone.

Correspondence concerning this article should be addressed to Elinor McKone, School of Psychology, Australian National University, ACT 0200, Australia. E-mail: elinor.mckone@anu.edu.au

recognize conspecific emotion. An important caveat to the studies of Fujita (1990, 1993) and Sackett (1966), however, is that stimuli were whole-body images. Thus, the results could suggest an innate representation of conspecific body shape and posture rather than of faces; note that the adult human brain develops regions selective for coding bodies (Taylor, Wiggett, & Downing, 2007) as much as it develops regions selective for coding faces.

Second, evidence of either *critical/sensitive periods* or *perceptual narrowing* in early infancy is strongly suggestive of an innate component. In other domains, such as low-level vision (see Sengpiel, 2007, for a review), sensitive periods are normally obtained when an inborn neural system decays away or is taken over for other purposes if the expected appropriate input beginning soon after birth is not obtained. In humans, there is evidence of a sensitive period for holistic processing of faces: Holistic processing does not occur in humans born with dense bilateral cataracts, despite many years of exposure to faces after the removal of the cataracts at the age of 2–6 months (Le Grand, Mondloch, Maurer, & Brent, 2004). Perceptual narrowing occurs when a broad ability present at birth narrows with a lack of experience with certain subtypes of a stimulus class. The classic example is that newborns can discriminate phonemes present in all languages, but by 6–12 months of age, children can discriminate phonemes only in the language or languages to which they have been exposed (Kuhl, Tsao, & Liu, 2003). Humans demonstrate perceptual narrowing for faces: Children at the ages of 3 and 6 months can discriminate faces of nonexperienced races (Kelly et al., in press) and nonexperienced monkey species (Pascalis, de Haan, & Nelson, 2002), while 9-month-old children and adults have lost these abilities (Kelly et al., in press; Pascalis et al., 2002). These results are consistent with an innate representation of face structure, which in the case of humans is quite broadly tuned (i.e., covering monkey faces as well as conspecifics). Note, however, that the evidence for an innate representation would be strengthened if it could also be shown that broad perceptual tuning to primate faces was present earlier than 3–6 months of age (e.g., by testing the discrimination of monkey faces in newborns) and that the early ability to individuate members of a stimulus class is limited to faces rather than being present for all objects (e.g., dogs); neither of these types of studies has been conducted.

Third, studies of development of face recognition in older human children and adults are of some relevance in that late onset, a gradually increasing ability, or both can indicate a strong role for ongoing experience. In other domains (e.g., with dogs [Robbins & McKone, 2007] and with greebles [Gauthier & Tarr, 1997]), it is clear that extensive training without an innate representation is sufficient to support excellent discrimination (albeit not based on the same holistic processing mechanism as that used for faces; McKone, Kanwisher, & Duchaine, 2007). Is extensive training necessary (or sufficient) to produce adult-like processing of faces? We believe this is a situation in which current evidence is commonly misrepresented. Very early studies suggested that children did not show even qualitatively adult-like patterns of face processing until approximately 10 years of age (e.g., no inversion effect in Carey, Diamond, & Woods, 1980; strong distraction by paraphernalia in Diamond & Carey, 1977), and these studies are often cited without attention to many subsequent studies showing opposite results (e.g., Carey, 1981; Flin, 1985; Lundy, Jackson, & Haaf, 2001) or to newer evidence of remarkably good face discrimination, even in newborns (Pascalis & de Schonen, 1994; Turati et al., 2006), and of holistic processing on all standard tests at 4 years of age, the youngest age tested (Carey, 1981; de Heering, Houthuys, & Rossion, 2007; McKone & Boyer, 2006; Pellicano, Rhodes, & Peters, 2006). There is thus no evidence of late onset of core face processing abilities. There is more active debate about whether there might be a gradually increasing ability. Again, however, there is a tendency to cite studies claiming to show that face perception ability increases into adolescence (e.g., Mondloch, Le Grand, & Maurer, 2002) without reference to theoretical argument (Want, Pascalis, Coleman, & Blades, 2003) and empirical evidence (Carey, 1981; Gilchrist & McKone, 2003; Lundy et al., 2001; McKone & Boyer, 2006; Mondloch, Maurer, & Ahola, 2006), suggesting the overall developments are at least as likely to be due to age-related changes in factors such as attention, concentration, and general memory as to changes in face perception per se. This is not to say, of course, that face discrimination does not receive some degree of experience-based tuning even late in life—as is evident in the finding that Koreans adopted to European countries in mid-childhood demonstrate a reverse other-race effect when tested as adults (Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005)—neither is it to ignore evidence of age-related changes until adolescence in the specific neural regions most responsive to faces (see Cohen Kadosh & Johnson, 2007, for a review). It is merely to say that there has commonly been an overstatement of the effects of postinfancy experience on perception of conspecific faces in humans.

Finally, we come to the case of other-species effects in mature adults. The standard experiment here is of the general type conducted by Martin-Malivel and Okada (2007, this issue), in which face discrimination in one species of subjects (e.g., chimpanzees) is compared for conspecific faces (chimpanzees) and other-species faces (e.g., humans, monkeys, other mammals).

Of such studies, many have a confound between whether the species is own or other with the lifetime history of experience of that species. For example, Dufour, Pascalis, and Petit (2006) showed that adult brown capuchin monkeys (*Cebus apella*) could discriminate brown capuchin faces but not white-faced capuchin faces (*Cebus capucinus*) when they had substantial lifetime exposure to brown capuchins and none to white-faced capuchins. Results of this type cannot help in determining the relative contributions of innate representations and experience: The own-species advantage could arise entirely from an innate representation of conspecifics, entirely from the greater lifetime experience with conspecifics, or from some combination of both, and there is no way of distinguishing among these possibilities.

The potentially more interesting case is testing own- versus other-species effects when strong experience is present with the other species. Several studies have taken this approach of manipulating conspecific status independently of lifetime experience by testing nonhuman primates with human faces. Chimpanzee and monkey subjects are available that have substantial exposure to humans, in a few cases equaling or even exceeding that to their own species. How relevant are the results of such experiments to understanding the relative roles of innate face representations and experience? In fact, we argue that even for such studies, the interpretation is far from straightforward.

Pascalis and Bachevalier (1998) tested rhesus monkeys (*Macaca mulatta*) described as raised with humans including caretakers, veterinarians, and researchers, and as having daily periods of social interactions with peers. Despite the substantial exposure to both humans and conspecifics, the monkeys showed spontaneous discrimination in a novelty-preference-following-habituation task for conspecific faces but not for human faces. Plentiful experience with humans failed to lead to discrimination.

Does this imply that the recognition ability evidenced with conspecifics must be derived from an innate representation? Well, it might. Alternatively, however, it could have something to do with quality of exposure. Infants were raised in family groups, presumably fed and cared for by a conspecific mother, and still lived in conspecific groups as adults. Thus, conspecifics were likely to count as more socially meaningful for individuation than were humans. Quality of exposure is suspected to play a role in cross-race effects in human subjects and so could potentially contribute to other-species effects.

Two studies of similar structure to that of Pascalis and Bachevalier (1998) have obtained opposite results. Neiworth, Hassett, and Sylvester (2007) found cotton-top tamarins showed novelty preference nearly as strong for human faces as for tamarin faces; the tamarin subjects were described as having been brought up and housed in family groups but exposed to human caretakers throughout their lives. Martin-Malivel and Okada (2007) obtained a similar result in chimpanzees (*Pan troglodytes*) but have pushed it even further. Chimpanzees with fairly plentiful exposure to both chimpanzees and humans (Yerkes subjects) were as good at discriminating human faces as they were at discriminating chimpanzee faces. Chimpanzees with very extensive, lifelong exposure to humans but also with exposure limited to a handful of own-species individuals (Language Research Center [LRC] subjects) showed a reverse other-species effect in which discrimination was better for human (nonconspecific) faces than for chimpanzee (conspecific) faces. The LRC subjects also demonstrated categorical perception of morphed images between individuals within a species only for human faces.

What can we conclude from these latter two studies? Given the apparent conflict in results with those of Pascalis and Bachevalier (1998), we first need to consider the possibility of methodological differences having contributed to one set of results or the other.

We can rule out differential similarity within the conspecific versus the human stimulus sets. Martin-Malivel and Okada (2007) took the nice approach of using a computational model to ensure matched similarity. Other studies have not done this, but Pascalis and Bachevalier (1998) showed a full cross-over interaction in which monkey subjects discriminated the monkey but not the human faces, and human subjects discriminated the human but not the monkey faces; this is sufficient to show that the own-species advantage in one group cannot be due to the stimuli of that species being simply less similar to each other.

Possibly more problematic is the question of prior training in discrimination tasks using human faces. Pascalis and Bachevalier (1998) criticized early studies showing that monkeys could discriminate human faces on the grounds that the monkey subjects had received extensive training with human faces in the match-to-sample test task. Their point was that training of this nature could potentially encourage subjects to use unusual strategies that would not be used in more naturalistic tasks (e.g., possibly focusing on a single local region of the image). Martin-Malivel and Okada (2007) used match-to-sample, and subjects had had previous training in this task using human faces. The tamarins of Neiworth et al. (2007), however, had had no experience of match-to-sample; half their subjects had had prior experimental exposure to human faces, but only in a novelty preference task, which is unlikely to provide motivation for developing unusual strategies.

Turning to more interesting theoretical possibilities, Martin-Malivel and Okada's (2007) results may indicate that quality of exposure to humans does indeed matter. Within captivity-bred animals, chimpanzees are commonly raised with higher levels of social interaction with humans than are rhesus monkeys. This is particularly true of the LRC subjects, who were raised as part of a research project on language training in chimpanzees and who were described as having been involved in numerous training sessions involving direct interactions with humans as social partners since they were babies. This idea does not obviously explain Neiworth et al.'s (2007) finding that tamarins showed good individuation of humans, but it is possible the tamarins had some subtle difference from Pascalis and Bachevalier's (1998) rhesus monkeys in style of human interaction.

Another idea is that social categorization at time of testing could influence patterns of discriminability. In human subjects, manipulated outgroup categorization has been shown to reduce discrimination ability in comparison with ingroup categorization, even when perceptual expertise is held constant (i.e., all faces are own-race members; Bernstein, Young, & Hugenberg, 2007). Moreover, there is evidence suggesting a chimpanzee raised in a human household can categorize itself as human (Hayes & Nissen, 1971). Thus, it is possible that nonhuman primates discriminate humans poorly when they have categorized humans socially as outgroup members and discriminate humans well when either their prior lifetime history or some subtlety of the experimental testing situation leads them to consider humans to be "ingroup" members at the time of testing.

Yet another possibility is that there may be an innate representation of conspecifics, and this representation can generalize to morphological structures that are broader than just conspecifics (i.e., it could cover similar species), but it does not completely generalize, or it can be expanded slightly through experience but not very far. Specifically, it could be that chimpanzees show good recognition of human faces because human faces are quite structurally similar to chimpanzee faces, while rhesus monkeys are poor at recognizing humans because human faces are not sufficiently similar to conspecific faces. Again, this idea does not obviously explain the tamarin data, given that tamarin faces are quite different from human faces in structure, but we suggest it might be worthwhile exploring the idea in future studies.

A final theoretical issue is that, in all other-species studies to date, the subjects are adults, and their experience with humans includes a mix of exposure during infancy and exposure later in life. The findings of Pascalis et al. (2002) and Kelly et al. (in press) regarding perceptual narrowing in human infancy strongly suggest the need for controlled studies varying the time during development that primates receive human experience.

To wrap up this section, we note that other-species articles, such as that of Martin-Malivel and Okada (2007), commonly frame their theoretical questions in terms of evaluating the relative contributions of innate representations and experience. We have argued that current evidence from these studies does not give a clear answer to this question.

Other Potentially Relevant Theoretical Factors

Two other important theoretical issues affect the current literature on face processing in nonhuman primates. First, there appears to be a general assumption that any experience-attributable discrimination ability for nonconspecific faces must be arising from the same system that drives recognition of conspecifics. This assumption might not be warranted. In humans, excellent within-class discrimination of nonface objects can be achieved without the use of face recognition mechanisms; not only does this expertise not rely on holistic processing (McKone et al., 2007), but functional magnetic resonance imaging reveals that it reflects greater neural changes in cortical regions associated with object processing than in regions associated with face processing (Moore, Cohen, & Ranganath, 2006; Op de Beeck, Baker, DiCarlo, & Kanwisher, 2006; Yue, Tjan, & Biederman, 2006). It is thus logically possible that, for example, monkeys learn to discriminate human faces using general object recognition mechanisms, but a different own-species-face system is responsible for discriminating conspecific faces. Currently, we do not have data on when an other-species face becomes sufficiently dissimilar from a conspecific to be treated as an object rather than as a face. These issues could potentially be addressed by functional magnetic resonance imaging in monkeys or by recording from face-selective cells, the primary question being whether the same regions or cells that support conspecific recognition are involved in human face discrimination.

A second general presumption is that all aspects of face performance—discrimination, preference, and holistic processing—must show the same balance of effects of experience versus innate factors. Again, this presumption might not be true. It could be, for example, that one aspect is driven more by innate contributions and another is driven more by experience. In humans, it seems possible that there might be a dissociation between discrimination and holistic processing. Discrimination is strongly sensitive to experience, as evidenced by perceptual narrowing in infancy, other-race effects in adults, and reversal of race effects following country shifts between childhood and adulthood. Holistic processing for faces, in contrast, seems to be insensitive to ongoing experience in many ways. In children, holistic processing is strong in the youngest children tested to date (4-year-olds); it is also as strong for the relatively rare profile view of faces as for the more common frontal view (McKone, in press). Holistic processing appears to be sensitive to experience only during a critical period in infancy (Le Grand et al., 2004). Thus, a theoretical possibility suggested by human findings is that an innate (but infancy-experience-expectant) representation of conspecifics drives holistic processing and also drives good face individuation of all races of face in early infancy, but that experience narrows the use of this system for discrimination to experienced subtypes of faces. These observations suggest that it would be valuable for other-species studies to independently assess both holistic processing and discrimination. We note that doing so will also require better measures of holistic processing than have been used to date: Inversion effects are not guaranteed to arise from holistic processing (Valentine, 1991), and an attempted implementation of the composite effect (Parr, Heintz, & Akamagwuna, 2006) bears little similarity to the procedure used in humans.

Conclusion

In summary, little is currently known about the relative roles of innate representations and experience in conspecific face recognition, despite more than 20 years of research relevant to the topic. There is evidence indicating some form of innate representation of conspecifics in monkeys, but it is not known specifically whether this is of faces, nor how tightly tuned it is to conspecifics. Evidence in humans is consistent with an innate face representation, although entirely experience-based explanations are also conceivable. Regarding the effects of experience, it is clear that experience can tune face discrimination performance both during infancy and later in life, but the interaction between experience at different stages of life and possible innate mechanisms is not understood. There is also little data relevant to experience obtained at different developmental periods and to the issue of the relevance or otherwise of the social quality of that experience.

Given the obvious limitations on testing human subjects, we suggest that nonhuman primate studies can contribute crucially to resolving these questions. Several types of future studies would be of particular value. Innate representation of faces could be tested directly by taking newborn monkeys with no prior visual experience of faces and assessing preference and discrimination for conspecific faces in comparison with preference and discrimination for the faces of other species; single-unit recording could also be used to test whether such monkeys have face-selective cells. If these studies show processing biases toward conspecifics, the tuning of the innate representation could be investigated by assessing faces at various distances from the morphology of conspecifics (e.g., own species of monkey, other species of monkey, human, nonprimate mammal). Tuning could also be explored in multiple species of subject, following Fujita's (1987) suggestion that different species could have different selection pressures for breadth of tuning. Regarding experience effects, these could usefully be explored by systematically varying the age at which experience (with conspecific faces or other groups such as human faces) is obtained and by systematically varying the extent of social involvement with nonconspecifics. Finally, there may be some mileage in trying social priming experiments, which attempt to induce nonhuman primates to categorize humans more as ingroup members or more as outgroup members.

References

Bernstein, M. J., Young, S. G., & Hugenberg, K. (2007). The cross-category effect: Mere social categorization is sufficient to elicit an own-group bias in face recognition. *Psychological Science, 8,* 706–712.

Carey, S. (1981). The development of face perception. In G. Davies, H. D. Ellis, & J. Shepherd (Eds.), *Perceiving and remembering faces* (pp. 9–38). New York: Academic Press.

Carey, S., Diamond, R., & Woods, B. (1980). Development of face recognition—A maturational component? *Developmental Psychology, 16*(4), 257–269.

Cohen Kadosh, K., & Johnson, M. H. (2007). Developing a cortex specialized for face perception. *Trends in Cognitive Sciences, 11*(9), 367–369.

de Heering, A., Houthuys, S., & Rossion, B. (2007). Holistic face processing is mature at 4 years of age: Evidence from the composite face effect. *Journal of Experimental Child Psychology, 96,* 57–70.

Diamond, R., & Carey, S. (1977). Developmental changes in the representation of faces. *Journal of Experimental Child Psychology, 23,* 1–22.

Dufour, V., Pascalis, O., & Petit, O. (2006). Face processing limitation to own species in primates: A comparative study in brown capuchins, Tonkean macaques and humans. *Behavioural Processes, 73,* 107–113.

Flin, R. H. (1985). Development of face recognition: An encoding switch? *British Journal of Psychology, 76,* 123–134.

Fujita, K. (1987). Species recognition by five macaque monkeys. *Primates, 28*(3), 353–366.

Fujita, K. (1990). Species preference by infant macaques with controlled social experience. *International Journal of Primatology, 11*(6), 553–573.

Fujita, K. (1993). Development of visual preference for closely related species by infant and juvenile macaques with restricted social experience. *Primates, 34*(2), 141–150.

Gauthier, I., & Tarr, M. J. (1997). Becoming a "Greeble" expert: Exploring mechanisms for face recognition. *Vision Research, 37*(12), 1673–1682.

Gilchrist, A., & McKone, E. (2003). Early maturity of face processing in children: Local and relational distinctiveness effects in 7-year-olds. *Visual Cognition, 10*(7), 769–793.

Hayes, K. J., & Nissen, C. H. (1971). Higher mental functions of a home-based chimpanzee. In A. M. Schrier & F. Stollnitz (Eds.), *Behavior of nonhuman primates: Modern research trends* (Vol. 4, pp. 60–116). New York: Academic Press.

Kelly, D. J., Quinn, P. C., Slater, A., Lee, K., Ge, L., & Pascalis, O. (in press). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science.*

Kuhl, P. K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences, USA, 100,* 9096–9101.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science, 15*(11), 762–768.

Lundy, B. L., Jackson, J. W., & Haaf, R. A. (2001). Stimulus properties, attentional limitations, and young children's face recognition. *Perceptual and Motor Skills, 92,* 919–929.

Martin-Malivel, J., & Okada, K. (2007). Human and chimpanzee face recognition in chimpanzees: Role of exposure and impact on categorical perception. *Behavioral Neuroscience, 121,* 1145–1155.

McKone, E. (in press). Configural processing and face viewpoint. *Journal of Experimental Psychology: Human Perception and Performance.*

McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology, 94*(2), 134–162.

McKone, E., Kanwisher, N., & Duchaine, B. C. (2007). Can generic expertise explain special processing for faces? *Trends in Cognitive Sciences, 11*(1), 8–15.

Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception, 31,* 553–566.

Mondloch, C. J., Maurer, D., & Ahola, S. (2006). Becoming a face expert. *Psychological Science, 17*(11), 930–934.

Moore, C. D., Cohen, M. X., & Ranganath, C. (2006). Neural mechanisms of expert skills in visual working memory. *Journal of Neuroscience, 26,* 11187–11196.

Neiworth, J. J., Hassett, J. M., & Sylvester, C. J. (2007). Face processing in humans and new world monkeys: The influence of experiential and ecological factors. *Animal Cognition, 10,* 125–134.

Op de Beeck, H., Baker, C., DiCarlo, J., & Kanwisher, N. (2006). Discrimination training alters object representations in human extrastriate cortex. *Journal of Neuroscience, 26,* 13025–13036.

Parr, L. A., Heintz, M., & Akamagwuna, U. (2006). Three studies on configural face processing by chimpanzees. *Brain and Cognition, 62,* 30–42.

Pascalis, O., & Bachevalier, J. (1998). Face recognition in primates: A cross-species study. *Behavioural Processes, 43,* 87–96.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296,* 1321–1323.

Pascalis, O., & de Schonen, S. (1994). Recognition memory in 3- to 4-day-old human neonates. *NeuroReport, 5,* 1721–1724.

Pellicano, E., Rhodes, G., & Peters, M. (2006). Are preschoolers sensitive to configural information in faces? *Developmental Science, 9*(3), 270–277.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition, 103*(1), 34–79.

Sackett, G. P. (1966). Monkeys reared in isolation with pictures as visual input: Evidence for an innate releasing mechanism. *Science, 154,* 1468–1473.

Sangrigoli, S., Pallier, C., Argenti, A.-M., Ventureyra, V. A. G., & de Schonen, S. (2005). Reversibility of the other-race effect in face recognition during childhood. *Psychological Science, 16*(6), 440–444.

Sengpiel, F. (2007). The critical period. *Current Biology, 17*(17), R742–R743.

Sinha, P., Balas, B., & Ostrovsky, Y. (2007, May). *Discovering faces in infancy.* Paper presented at the annual meeting of the Vision Sciences Society, Sarasota, FL.

Taylor, J. C., Wiggett, A. J., & Downing, P. E. (2007). Functional MRI analysis of body and body part representations in the extrastriate and fusiform body areas. *Journal of Neurophysiology, 98,* 1626–1633.

Turati, C., Macchi Cassia, V., Simion, F., & Leo, I. (2006). Newborns' face recognition: Role of inner and outer facial features. *Child Development, 77*(2), 297–311.

Valentine, T. (1991). A unified account of the effects of distinctiveness, inversion, and race in face recognition. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 43*(A), 161–204.

Want, S. C., Pascalis, O., Coleman, M., & Blades, M. (2003). Face facts: Is the development of face recognition in early and middle childhood really so special? In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood* (pp. 207–221). New York: Nova Science.

Yue, X., Tjan, B. S., & Biederman, I. (2006). What makes faces special? *Vision Research, 46,* 3802–3811.

Received September 14, 2007
Revision received September 14, 2007
Accepted September 17, 2007 ■

CHAPTER 3 – THE COGNITIVE AND NEURAL DEVELOPMENT OF FACE RECOGNITION IN HUMANS

3.1 Context statement

The previous chapter identified a number of open research questions regarding the developmental origins of face perception in both human and non-human primates. The empirical work in this thesis (Chapters 4-6) focuses on those questions that could be answered by behavioural studies of typical human development. Chapter 3 provides a detailed literature review of previous findings relevant to this empirical work – specifically, the literature on behavioural development of face recognition in humans, covering both infancy and childhood – and also reviews what is known about the neural development of face recognition. Importantly, the focus in the present chapter is on the age at which the *qualitative* presence of standard face recognition and perception effects have been demonstrated in children or infants. The review at the beginning of the next chapter will deal in more detail with the literature relevant to *quantitative* development in the size of effects.

3.2 Publication Status

This chapter is in press as the following book chapter (to be published October, 2009):

McKone, E., **Crookes, K.** & Kanwisher, N. (in press). The cognitive and neural development of face recognition in humans. In M. S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (IV ed.). Cambridge, Massachusetts, USA: Bradford Books.

The accepted version of the book chapter was finished in June 2008. Discussion of four relevant papers published after this date is provided following the accepted manuscript.

3.3 Author contributions

This manuscript covered two main areas: *cognitive* development, discussing behavioural studies (approximately 70% of the chapter;) and *neural* development (30% of the chapter).

3.3.1 Content of literature review

- The content of the literature review for the *cognitive* development section was due 90% to **Crookes** (and 10% to McKone). **Crookes** was responsible for: ensuring all relevant literature had been identified; reading the papers; understanding the methods and results; and summarising the findings and any methodological issues in the papers.
- Kanwisher was responsible for the literature review in the *neural* development section

3.3.2 Theory development

- McKone and **Crookes** worked together to develop the arguments and theories presented in the *cognitive* development section
- Kanwisher was responsible for the theory development in the *neural* development section

3.3.3 Writing

- McKone wrote the *cognitive* development sections
- Kanwisher wrote the *neural* development sections
- **Crookes** commented on drafts, corrected content errors, provided some rewording and proof read the final submission

3.4 Abstract

Conventional wisdom has long held that face recognition develops very slowly throughout infancy, childhood, and adolescence, with perceptual experience as the primary engine of this development. However, striking new findings from just the last few years have overturned much of this traditional view by demonstrating genetic influences on the face recognition system as well as impressive face discrimination abilities present in newborns and in monkeys who were reared without ever seeing a face. Nevertheless, experience does play a role, for example in narrowing the range of

facial subtypes for which discrimination is possible and perhaps also increasing discrimination abilities within that range. Here we first describe the cognitive and neural characteristics of the adult system for face recognition, and then we chart the development of this system over infancy and childhood. This review identifies a fascinating new puzzle to be targeted in future research: all qualitative aspects of adult face recognition measured behaviorally are present very early in development (by 4 years of age; all that have been tested are also present in infancy) – yet fMRI and ERP evidence shows very late maturity of face-selective neural responses (with the fusiform face area increasing substantially in volume between age 7 and adulthood).

3.5 Introduction

One of the most impressive skills of the human visual system is our ability to identify a specific individual from a brief glance at their face, thus distinguishing that individual from hundreds of other people we know, despite the wide variations in the appearance of each face as it changes in viewpoint, lighting, emotional expression, and hairstyle. Though many mysteries remain, important insights have been gleaned over the last two decades about the cognitive and neural mechanisms that enable us to recognize faces. Here we address an even more difficult and fundamental question: how does the machinery of face recognition get wired up during development in the first place?

Our review of the available evidence supports a view of the development of face recognition dramatically different from that suggested by the first studies in the field. Twenty years ago, the standard theory was that core aspects of the ability to discriminate faces were not present until 10 years of age, and their emergence and eventual maturity were determined primarily by experience (Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980). This position has been overturned by recent findings demonstrating striking abilities even in neonates, and by mounting evidence of genetic contributions.

We organize our review by age group. Throughout, we ask how the available data address the following fundamental theoretical questions: (a) what are the inherited genetic contributions to the specification of the adult system for processing facial identity information; (b) what is derived from experience; and (c) how exactly do genes and/or experience work separately or together across the course of development to produce the adult system?

3.6 The Perception of Face Identity in Adulthood

We begin with a characterization of the end state of development: the cognitive and neural basis of the perception of facial identity in adults. Note that this is a major topic in its own right, with much internal theoretical debate. However, to facilitate our present interest in the *developmental* course of face recognition, we focus on empirical phenomena, especially those that (a) are well-established in adults, and (b) have subsequently been tested in development.

3.6.1 Core Behavioral Properties of Face Identity Perception in Adult Humans

Basic properties of face identification in adults are as follows. Identification is more accurate when faces are upright than when they are inverted (i.e., upside down) on both memory and perceptual tasks, and the inversion decrement is substantially larger for faces than nonface objects (the *disproportionate inversion effect*; Yin, 1969; also Robbins & McKone, 2007). Generalization from a single image of a novel face in one viewpoint to an image in another is relatively poor, albeit better from the three-quarter view to front or profile views than between the more distinct profile and front views (the *three-quarter view advantage*; Logie, Baddeley, & Woodhead, 1987). For familiar faces, performance in memory tasks relies more strongly on inner face regions than on external regions that include hair; for unfamiliar faces, the pattern is reversed (*inner vs. outer features effects*; Ellis, Sheperd, & Davies 1979). Finally, identification of own-race faces is better than identification of other-race faces (the *other-race effect*; Meissner & Brigham, 2001). Note that the first two properties (i.e., the disproportionate inversion effect and the three-quarter view advantage) derive directly from perceptual processing, but the last two are known to derive at least partly from deliberate task strategies (e.g., reliance on hair for novel faces if distinctive hair is present, Duchaine & Weidenfeld, 2003) or social and attentional factors (other-race effect, Bernstein, Young, & Hugenberg, 2007).

Additional experimental findings can be grouped under the heading of phenomena that have motivated the concept of *holistic/configural* processing. Holistic/configural processing is defined (e.g., Tanaka & Farah, 1993; Maurer, LeGrand, & Mondloch, 2002) as (a) a strong integration at the perceptual level of information from all regions of the face (so that altering one region leads to changes in the percept of other regions), which (b) codes the exact spacing between face features (and more controversially exact feature shape as well; Yovel & Duchaine, 2006) and, (c) is strongly sensitive to face inversion. Relevant phenomena are as follows. Subjects find it harder to identify one half of a combination face (e.g., top half of George Bush with bottom half of Tony Blair) if the inconsistent other half-face is aligned with the target half rather than misaligned (the *composite effect*; Young, Hellawell, & Hay, 1987). Subjects are also better able to distinguish which of two face parts (e.g., two noses) appeared in a previously-shown face when these are presented in the context of the whole face than when presented in isolation (the *part-whole effect*; Tanaka & Farah, 1993); part-choice is also better in the original whole than in a version of the whole face with an alteration in spacing between non-target features (the *part-in-spacing-altered-whole effect*; Tanaka & Sengco, 1997), a finding consistent with other evidence of strong *sensitivity to spacing changes* (e.g., distance between eyes) in upright faces (e.g., Rhodes, Brake, & Atkinson, 1993; McKone, Aitkin, & Edwards, 2005). When an upright and inverted version of a face are superimposed in transparency, the upright face is perceived more strongly (*perceptual bias to upright*; Martini, McKone, & Nakayama, 2006). All these holistic effects are specific to upright faces: they are not found for inverted or scrambled faces (Young et al., 1987; Tanaka & Sengco, 1997; Robbins & McKone, 2003; Martini et al., 2006), and are weak or absent for objects, including objects-of-expertise (for review see McKone, Kanwisher, & Duchaine, 2007; Robbins & McKone, 2007).

Finally, other behavioral phenomena have been taken to indicate coding within a perceptual 'face-space', defined as a multidimensional space in which each individual face is coded as a point by its value on underlying dimensions describing different aspects of facial structure, and for which the 'average' face lies at the centre of the space (Valentine, 1991). These phenomena include: *distinctiveness effects*, in which performance is better for distinctive faces than typical faces on old-new recognition tasks, but the pattern is reversed on face-nonface classification tasks (Valentine & Bruce, 1986) and *adaptation aftereffects*, in which, for example, adaptation to expanded faces make a physically normal face appear contracted (Webster & Maclin, 1999) and adaptation to 'anti-Bill' (the physical opposite of Bill in face-space) makes the average face appear like Bill (Leopold, O' Toole, Vetter, & Blanz, 2001).

3.6.2 Neurophysiology and fMRI in Adult Monkeys

Adult monkeys show cortical mechanisms specialized for face perception. Strongly face-selective responses from single neurons ("face cells") are well established in the temporal lobes of macaques (Desimone, Albright, Gross, & Bruce, 1984; Foldiak, Xiao, Keysers, Edwards, & Perrett, 2004), and face-selective cortical regions have been reported in macaques using fMRI (Tsao, Freiwald, Knutsen, Mandeville, & Tootell, 2003; Pinsk, DeSimone, Moore, Gross, & Kastner, 2005). Tsao, Freiwald, Tootell, and Livingstone (2006) demonstrated direct correspondence between face-selective fMRI patches and face selectivity of single cells within those patches. Note that the role of "face cells" in supporting the behavioural phenomena described in the previous section is mostly unexplored, with the exceptions that a preponderance of face-selective cells are tuned to upright (Perrett et al., 1988) and that their tuning to facial distortions from the 'average face' is consistent with a face-space coding of facial identity (Leopold, Bondar, & Giese, 2006). In development, only basic face-selectivity has been studied.

3.6.3 fMRI: Cortical Loci of Face Identity Processing in Adult Humans

Brain imaging in humans reveals three face-selective cortical regions (Figure 1), of which the "fusiform face area" or FFA (Kanwisher, McDermott, & Chun, 1997) is the main one investigated in children. This region, which can be found in essentially every normal adult in a short "localizer" scan (Saxe, Brett, & Kanwisher, 2006), responds more strongly to faces than to letterstrings and textures (Puce, Allison, Asgari, Gore, & McCarthy, 1996), flowers (McCarthy, Luby, Gore, & Goldman-Rakic, 1997), and indeed all other nonface stimuli that have been tested to date, including mixed everyday objects, houses, hands (Kanwisher et al., 1997), and objects of expertise (Kanwisher & Yovel, in press).

fMR-adaptation studies show that neural populations in the FFA can discriminate face identity (Rotshtein, Henson, Treves, Driver, & Dolan, 2005), but not facial expression (Winston, Vuilleumier, & Dolan, 2003). The FFA is involved in individual discrimination of upright but not inverted faces (Yovel & Kanwisher, 2005; Mazard, Schiltz, & Rossion, 2006), and its inversion effect (i.e., higher response to upright than inverted faces) correlates with the behavioral inversion effect (Yovel & Kanwisher, 2005). The FFA also demonstrates holistic processing, specifically a composite effect (Schiltz & Rossion, 2006).

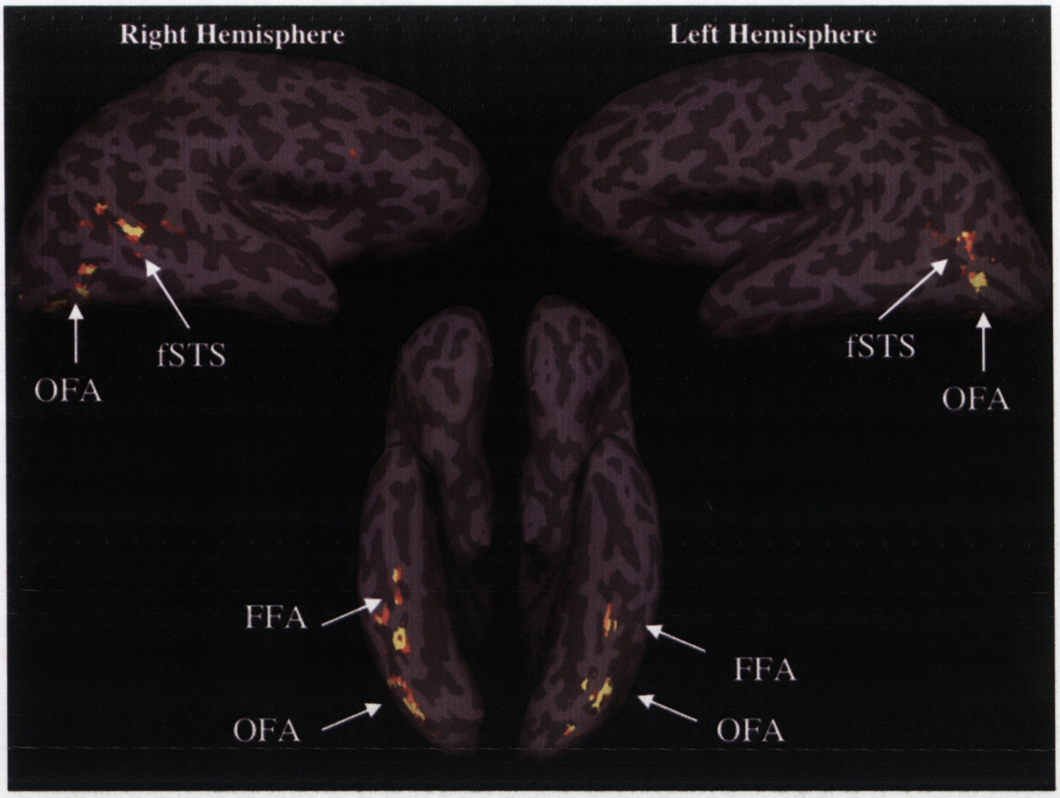


Figure 1. Cortical regions selectively engaged in face perception and the development of one of these regions (the FFA) from childhood to adulthood. A. Adults: Face selective activation (faces > objects, $p < .0001$) on an inflated brain of one adult subject, shown from lateral and ventral views of the right and left hemispheres. Three face-selective regions are shown: the FFA in the fusiform gyrus along the ventral part of the brain, the OFA in the lateral occipital area and the fSTS in the posterior region of the superior temporal sulcus. For studies of face *identification* (rather than expression, etc), the FFA and OFA are of greatest interest.

3.6.4 Electrophysiological Signatures in Human Adults

A negative-going ERP response peaking about 170 ms after stimulus onset over posterior temporal sites (N170) has been widely replicated to be face-selective (Halgren, Raij, Marinkovic, Jousmaki, & Hari, 2000; Liu, Harris, & Kanwisher, 2002). This peak is delayed by 10 ms, and is larger in amplitude, for inverted faces relative to upright faces (Bentin, Allison, Puce, Perez, & McCarthy, 1996). The N170 also shows identity discrimination (lower response for repeated compared to unrepeated faces), when the faces are upright but not inverted (Jacques & Rossion, 2006; Jacques, d'Arripe, & Rossion, 2007). An important point relevant to the interpretation of developmental studies is that the neural source of the N170 is unknown even in adults, and the sources of suggested equivalent components in children and infants could possibly be different again.

3.7 Data from adult subjects relevant to the roles of experience and genetics

Before considering what developmental studies tell us about the roles of experience and genetics in face recognition, we describe several findings from adults that also bear directly upon these issues.

Clearly, *experience in isolation* can influence face perception. Adults continue to learn new faces throughout life, and this improves perceptual discrimination of these faces: matching the correct face photograph to a degraded security-camera video image is more accurate if the face is familiar than if it is unfamiliar (Burton, Wilson, Cowan, & Bruce 1999; *also see* Bruce, Henderson, Newman & Burton, 2001). Temporary aftereffects from adaptation to distorted faces (e.g., Webster & Maclin, 1999) also indicate purely experience-based changes in the tuning of perceptual representations of faces. Training effects on ability to discriminate trained and novel faces have also been demonstrated in an adult prosopagnosic (DeGutis, Bentin, Robertson, & D'Esposito, 2007). Interestingly, however, there is no evidence that experience alone produces any fundamental *qualitative* change in face processing either neurally or cognitively: for example, holistic processing, 'face-space' effects, and FFA activation all occur strongly for both familiar faces and unfamiliar faces (Young et al., 1987; Kanwisher et al., 1997; Webster & Maclin, 1999; Le Grand, Mondloch, Maurer, & Brent, 2004; Carbon et al., 2007).

Studies of human adults provide two sources of evidence for genetic contributions. Inability to recognize faces in the absence of any known brain injury ('developmental prosopagnosia') often runs in families (Duchaine, Germine, & Nakayama, 2007; Grueter et al., 2007; Kennerknecht, Pluempe, & Welling, 2008). And, in normal adults, fMRI shows greater similarity in the pattern of activation across the ventral visual stream for monozygotic compared to dizygotic twins, but only for stimulus classes for which an evolutionary origin of the observed selective cortical regions could reasonably be proposed: faces, and places, but not written words or chairs (Polk, Park, Smith, & Park, 2007).

In summary, results from adults tell us that experience can fine-tune face recognition without changing its qualitative properties, and that genes explain some of the variation behaviorally and neurally. Importantly adult studies do not tell us at what developmental stage genes have their influence. In particular, they do not necessarily demonstrate that a face system is *present at birth*. Some genetically pre-determined processes are present at birth (e.g., sucking reflex), but others affect maturational processes later in childhood or adolescence (e.g., puberty).

3.8 Development: Infancy

In exploring genetic and experience-based contributions to face recognition via infancy studies, several interrelated questions are relevant. First, which abilities, if any, are present *at birth*? Visual abilities present in neonates (or in monkeys deprived of all face input) cannot be derived from experience and so provide the only method of revealing *genetic influences in isolation* from any visual learning. Second, if babies are born with a face representation, is its purpose merely to draw attention to faces (cf. CONSPEC in Morton & Johnson, 1991) or to support individuation? Third, how broadly tuned is any such representation: broad enough to cover any primate face, specific to own-species faces, or perhaps even to own-race faces? Finally, which, if any, of the types of effects of experience in early infancy that are found in other perceptual and cognitive domains occur for faces: Improvements with increasing experience? Perceptual narrowing (i.e., destruction of earlier ability)? Critical periods? Studies of these topics published within the last few years have dramatically altered our understanding of infant face recognition.

In a classic result, newborns (median age *9 minutes*) track an upright ‘paddle face’ (Figure 2a) further than versions in which the position of the internal blobs is scrambled or inverted (Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). Although it has been suggested this preference could arise from general visual biases (e.g., for stimuli with more elements in the upper visual field; Simion, Macchi Cassia, Turati, & Valenza, 2003), preference only for the normal contrast polarity of a (Caucasian) face (Farroni et al., 2005) argues for a level of specificity to face-like structure. Thus, humans are born with some type of innate preference that, at the very least, attracts infants’ attention to faces. Note the innate representation supporting face preference may be different from that supporting face individuation in adults (Johnson, 2005); indeed, a finding that neonates track faces in the temporal but not nasal visual field (Simion, Valenza, Umlità, & Dalla Barba, 1998) suggests a subcortical rather than cortical origin.

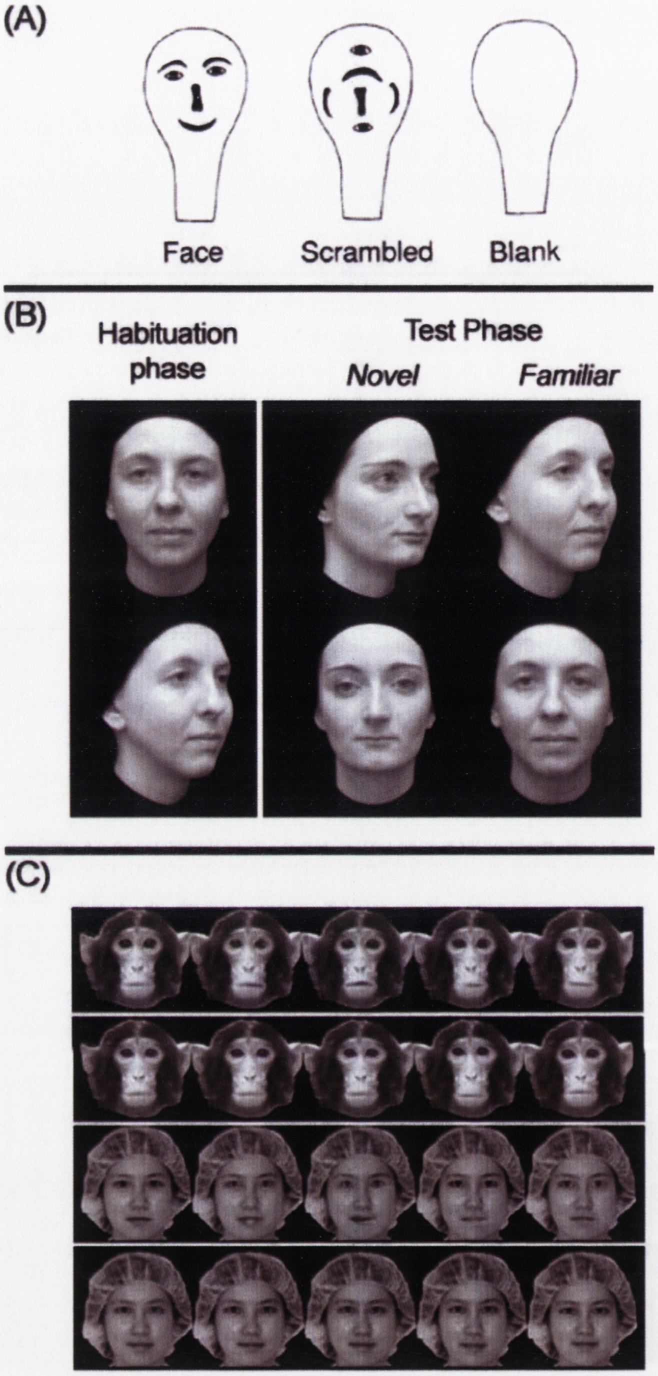


Figure 2. Face perception without experience. (A) Newborn humans (< 1 hour old) track the 'paddle face' on the left further than the scrambled version (Morton & Johnson, 1991); (B) Newborn humans (< 3 days) look longer at the novel than habituated face, indicating recognition of face identity even across view change (Turati et al., 2008); (C) Japanese macaques raised with no exposure to faces can, on first testing, discriminate very subtle differences between individual monkey faces (including differences both in shape and in spacing of internal features), and can also do this for human faces (Sugita, 2008).

Our concern in the present chapter is primarily with the development of face *individuation* ability. This can be measured in infants by looking time measures that assess preference and dishabituation-to-perceived-novelty. A classic finding is that neonates can discriminate their mother from other similar-looking women when less than 4 days old (Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995; Bushnell, 2001) although mother recognition in the first 24 hours may be partially dependent on prenatal familiarity with her voice, (Sai, 2005). More recent data demonstrate even more striking abilities. Three-month-olds can recognize the identity of *novel* individuals, with *similar-looking* faces (same sex, age, race), *without hair*, and *across view changes* (Pascalis, de Haan, Nelson, & de Schonen, 1998; Kelly et al., 2007). Indeed, it has very recently been discovered that *newborns* (< 3 days) can perform this task (Turati, Bulf, & Simion, 2008; see Figure 2b). The newborns moreover discriminated only front to 3/4 view changes and not 3/4 to profile, in a pattern somewhat (although not precisely) similar to the 3/4 view advantage seen in adults. Finally, newborns demonstrate an inversion effect on discrimination, with babies 1-3 days old discriminating same-view faces without hair upright but not inverted (Turati, Macchi Cassia, Simion, & Leo, 2006).

The newborn discrimination findings strongly suggest that a face representation, tuned to upright and able to support individual-level representation, is *present at birth.* It seems unlikely that 3 'days' of experience with faces – in fact, a maximum of perhaps 12 hours of visual experience of any kind (newborns sleep 16 hours per day plus have their eyes shut during breastfeeding and crying) – would be sufficient for a purely learning-based system to support the level of fine discrimination ability observed.

Even more compelling, however, is a recent behavioral study in monkeys (Sugita, 2008). Japanese macaques were raised by human caregivers wearing masks, giving them no exposure to faces, but otherwise normal visual experience in a complex environment. On their *very first* experience with faces (aged 6-24 months), the monkeys showed a preference to look at static photographs of faces over photographs of objects equally novel in their visual environment (e.g., cars, houses), and discriminated very subtle differences between individual faces (Figure 2c) in a habituation paradigm.

A variety of other infant findings also either directly argue that a representational capacity for differentiating individual face structures is present at birth, or at least do not reject this conclusion. Newborns (< 1 week) prefer faces rated by adults as attractive over unattractive faces, when they are upright but not inverted (Slater, Quinn, Hayes, & Brown, 2000). Regarding holistic processing, Sugita's (2008) monkeys discriminated spacing changes (Figure 2c) with almost no prior experience of faces (they had been exposed to faces only during the short face-preference task), and five-month-old humans discriminate spacing changes small enough to fall within the normal physical range, upright but not inverted (Hayden, Bhatt, Reed, Corbly, & Joseph, 2007); also babies 6-8 months old show a composite-like effect where the combination of the inner features of one old face with the outer features of another old face is treated as a new individual, upright but not inverted (Cohen & Cashon, 2001). At 3 months (although not 1 month), human infants falsely recognise the average of four studied faces as 'old', a phenomenon also shown by adults (de Haan, Johnson, Maurer, & Perrett, 2001). Importantly, there are no major behavioral properties of face recognition present in adults that are known *not* to be present in infants; where we have not mentioned properties (e.g., adaptation aftereffects), this is because no relevant data exist, not because infants have been tested and failed to show effects.

Findings of *perceptual narrowing* indicate that a representational capacity for faces that is present at birth (a) can initially be applied to a wide range of faces but that (b) this range gets restricted during the first several months of life to include only the kinds of faces (i.e., species or race) that have been seen in this period. Perceptual narrowing is best known from the domain of language (e.g., Kuhl, Tsao, & Liu, 2003). Infants are born with the ability to discriminate phoneme boundaries from all possible languages in the world (e.g., English and Japanese), but over the first 6-12 months of life lose the ability to discriminate phonemes from non-experienced languages (Japanese for a child from a monolingual English-speaking family), and even extensive exposure as an adult is usually insufficient to regain native-speaker levels of discrimination and reproduction. For faces, five studies have reported and explored properties of perceptual narrowing. In humans, Pascalis, de Haan and Nelson (2002) showed that 6-month-old infants could discriminate both human and monkey faces, while 9-month-olds and adults could discriminate only human faces. Kelly et al. (2007) reported that Caucasian babies from the north of England, with high exposure to Caucasians but essentially no exposure to African or Asian faces, could recognize individuals (across view change) from all three races at 3 months of age. At 6 months, Caucasian babies could no longer individuate African faces; at 9 months they had additionally lost the ability to individuate Asians. The Sugita (2008) study described earlier reported that, on first exposure to faces, the monkeys could not only discriminate individual monkey faces (other macaques), but could also make extremely fine discriminations amongst human faces (Figure 2c). Following 1 month of exposure to a single face type (either human or monkey, involving live interaction for least 2 hours per day), Sugita's monkeys lost the ability to discriminate individuals of the non-experienced species. Re-learning was also difficult: monkeys initially exposed only to humans failed to discriminate monkey faces even after subsequently sharing a cage with 10 other monkeys for 11 months. (Note, however, that there is some evidence of flexibility in humans into middle childhood: Korean children adopted to Caucasian Francophone countries at age 3-9 years showed, as adults, better recognition memory for Caucasian faces than Korean faces; Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005). During human infancy, perceptual narrowing can be avoided by deliberate exposure to face types that the infant would not naturally see, with regular exposure to monkey faces beginning at 6 months leading to retained ability to discriminate monkey faces at 9 months (Pascalis et al., 2005). Perceptual narrowing for faces also has an interesting possible link with narrowing for language. Lewkowicz and Ghazanfar (2006) reported that human infants could make cross-modality matches of a monkey vocalization to a picture of a monkey face making that particular sound at 4 and 6 months, but that this ability was lost at 8 and 10 months.

Importantly, the perceptual narrowing effects for faces described above indicate only a *destructive* effect of experience across infancy (i.e., *loss* of initial ability with other-species and other-races). In the domain of language, loss of phonetic discrimination ability within nonexperienced languages has been shown to co-occur with an improvement of phonetic discriminability within the experienced language (Kuhl et al., 2006). Thus, perceptual narrowing for faces might similarly include enhanced ability to discriminate experienced face subtypes: that is, discrimination for own-species own-race faces might start crude and *improve* with practice. Potentially consistent with this prediction, Humphreys and Johnson (2007) showed the physical difference between faces required to produce novelty preference was smaller in 7-month-olds than 4-month-olds, indicating that the older babies could either make finer perceptual discriminations, or keep these in memory longer across the 1-5 item test delay.

Neural systems present at birth are often associated with a *critical* (or *sensitive*) *period* (Sengpiel, 2007), requiring environmental input of the appropriate stimulus type within a specified period after birth to avoid being taken over for other purposes. In a classic example, cats are born with cells tuned to all line orientations, but if raised in an environment containing only vertical lines they lose horizontal-responsive cells and a corresponding lack of behavioral sensitivity to horizontal lines. For faces, Le Grand and colleagues report evidence consistent with a critical period for one important aspect of face perception, holistic processing. Congenital cataract patients, specifically people born with dense cataracts disrupting all pattern vision who had the cataracts removed at

2-28 months of age, were tested at ages ranging between 9 years and adulthood. Despite their many years of post-cataract exposure to faces, patients who had had early bilateral cataracts showed no composite effect for faces (Le Grand et al., 2004). Also, patients who had had right-eye-only or bilateral cataracts – which produce a deficit of input to the right hemisphere due to the wiring of the infant visual system – showed a later deficit in processing spacing information in faces, while patients who had had left-eye-only cataracts did not (Le Grand, Mondloch, Maurer, & Brent, 2003), a pattern consistent with the normal role of the right hemisphere in holistic processing (Rossion et al, 2000). Interestingly, there does not appear to be a critical period for the ability to discriminate faces per se. Anecdotally, the Canadian cataract patients are not functionally prosopagnosic (Daphne Maurer, pers comm), for example reporting even being able to recognize other-race students when teaching English in Korea (Rachel Robbins, pers comm). Formal testing shows good ability to match novel faces (without view change) both in these patients (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002) and in an Indian woman whose congenital cataracts were not removed until *12 years* of age (Ostrovsky, Andalman, & Sinha, 2006). Also, lack of visual experience with faces for the first 6-24 months in Sugita's (2008) monkeys did not destroy discrimination ability. The reason why a requirement for early visual input exists for holistic processing but not face discrimination remains to be resolved. One possibly relevant observation is that holistic processing could perhaps have a particular role in cross-view recognition (McKone, 2008), and the Canadian cataract patients have a specific problem with recognition of once-seen faces across view changes (Geldart et al., 2002; note the Indian patient and Sugita's monkeys were tested on same-view faces only).

The behavioral findings reviewed above – demonstrating abilities present at birth, perceptual narrowing and critical periods – are all consistent with a genetically determined "innate" contribution to infant face recognition. In particular, they argue for an innate contribution to face *individuation.*

Neurally, face individuation in adults is associated with cortical rather than subcortical function. What is the evidence regarding *cortical* face-processing function in infants? There are few available studies, and none in neonates. Results do, however, demonstrate face-selectivity and inversion effects. In infant macaques, Rodman, Scalaidhe and Gross (1993) found that the response magnitude of single units in inferotemporal cortex was lower overall than in adults, but selectivity for form including face selectivity was present at the youngest ages tested, within 2 months of birth. In humans, a PET study of 2.5-month-olds is somewhat suggestive of face-selective activation in the fusiform gyrus (and other cortical regions), although the infants were not neurologically normal, the statistical threshold was extremely lenient ($p < .05$ uncorrected), and the contrast (faces versus blinking diodes) confounds selectivity for faces with responses to visual shape information (Tzourio-Mazoyer et al., 2002). Using ERPs, human 3-month-olds exhibit an "N290" component that has larger amplitude for human compared to monkey faces in the right hemisphere only (Halit, de Haan, & Johnson, 2003) although adult N170 shows the opposite pattern. At 12 months of age, this N290 was higher in amplitude for inverted than upright faces, only for human, not monkey faces (like the adult N170). Although the same study reported that this sensitivity to inversion was not found in 3-month-olds, another analysis of the same data using a different method (Johnson et al., 2005) did claim to find such inversion sensitivity. Further, other ERP components (the P400 and the P1) do show inversion effects at 3 months, the youngest age tested (Halit et al., 2003). Similarly, near infrared spectroscopy (NIRs) responses in 5-8-month-old infants are stronger for upright than inverted faces over the right hemisphere only (Otsuka et al., 2007; note the cortical source of this effect was most likely the STS). Overall, the available neural evidence from infants is consistent with the existence of cortical machinery for processing faces within a few months after birth, and there is no evidence to suggest this is not present earlier.

Taking all findings together, we conclude that infants are born with a rich capacity to represent the structure of upright faces which supports face discrimination, rather than merely drawing attention to faces. Results further show that this representation interacts with experience during infancy in particular ways. A probable critical period suggests holistic processing is 'experience-expectant' (i.e., early environmental input is required for its maintenance). Perceptual narrowing shows early experience restricts the range of faces that can be accommodated: that is, an initial representation of faces is sufficiently broadly tuned to support individuation of all face types including those of other primates, and experience with one subtype of face (own-species, own-race) *removes* this initial ability with other face types (other-species, other-races), at the same time that it possibly improves perceptual tuning for faces of the experienced subtype. Regarding neural origin of face discrimination in infants, there is evidence of relevant cortical representation by mid-infancy, but no data are available regarding whether the discrimination ability present *at birth* is supported by cortical as opposed to subcortical representations.

3.9 Development: Four year-olds to adults

In understanding the interaction of genetic inheritance and learning, investigation of the developmental trajectory of face processing in childhood through adulthood can also be informative. When no change is found in a given behavioral or neural measure of face perception in this period, that argues against extended maturation or learning as necessary for the construction of the adult system. If instead protracted development is observed, this could reflect learning (as often assumed), though crucially it could also reflect biological maturation (Carey et al, 1980), or an interaction of genetic and experiential factors.

3.9.1 Behavioral Measures of Face Identity Perception

For children 4-5 years and older, it is possible, with care, to adapt adult behavioral paradigms directly, and thus to compare child performance with adult performance on exactly the same tasks. For each phenomenon established in adults, two empirical questions are of interest. First, is there some age below which children simply do not show that phenomenon at all? (i.e., is there *qualitative* change with age?). Second, regarding any phenomena that are observed, when are full maturity levels reached? (i.e., is there *quantitative* change with age).

We consider qualitative change first. Early behavioral research appeared to suggest that core perceptual processes involved in face identification did not emerge at all until quite late in development (e.g., 10 years for holistic processing, Carey & Diamond, 1977; Carey et al., 1980). Unfortunately, researchers in the face neuroscience literature (e.g., Gathers, Bhatt, Corbly, Farley, & Joseph, 2004; Aylward et al., 2005; Golarai et al., 2007; Scherf, Behrmann, Humphreys, & Luna, 2007) commonly emphasize only these few early findings, which give an inaccurate representation of the current state of knowledge. In fact, research in the last 15 years has clearly established that *all* standard adult face recognition effects are present in young children. (Indeed, Section 3 showed all phenomena tested – including inversion effects – were present in infancy.)

In child-age studies using adult tasks, every key adult property of face recognition investigated has been obtained at the youngest age tested. With respect to holistic processing, these results include the inversion effect on short- and long-term recognition memory (3 y.o. Sangrigoli & de Schonen, 2004; 4 y.o. Carey, 1981; 5-6 y.o. Brace et al., 2001; 7 y.o. Flin, 1985), the composite effect (4 y.o. de Heering, Houthuys,

& Rossion, 2007; 6 y.o. Carey & Diamond, 1994; 6 y.o. Mondloch, Pathman, Maurer, Le Grand, & de Schonen, 2007), the part-whole effect for upright but not inverted faces (4 y.o. Pellicano & Rhodes, 2003; 6 y.o. Tanaka, Kay, Grinnell, Stansfield, & Szechter, 1998), the part-in-spacing-changed-whole effect for upright but not inverted faces (4 y.o. Pellicano, Rhodes, & Peters, 2006) sensitivity to exact spacing between facial features (4 y.o. McKone & Boyer, 2006; 4 y.o. Pellicano et al., 2006), the perceptual bias to upright in superimposed faces (8 y.o. Donnelly, Hadwin, Cave, & Stevenage, 2003) and the internal-over-external features advantage for familiar face identification (5-6 y.o. Wilson, Blades, & Pascalis, 2007). Regarding face-space coding, results include distinctiveness effects on perception at 4 years (McKone & Boyer, 2006) and on memory at 6-7 years (Gilchrist & McKone, 2003), an other-race disadvantage on recognition memory at 3 years (Sangrigoli & de Schonen, 2004) and a recent conference report of adaptation aftereffects in 4-5 year-olds (Jeffery & Rhodes, 2008). Where early studies did not show effects, this has generally been established to have arisen from methodological problems, the most common one being floor effects on the task in young children (e.g., see Carey et al., 1980 vs. Carey, 1981; or Johnston & Ellis, 1995 vs. Gilchrist & McKone, 2003). Another case of note is the early suggestion that children could not perform face identification *at all* in the presence of distracting paraphernalia (Carey & Diamond, 1977); this finding was overturned (Lundy, Jackson, & Haaf, 2001), by simply making the faces larger. (Also note that even adults are sometimes strongly distracted by paraphernalia, Simons & Levin, 1998). In summary, it is clear that there is no qualitative change in face perception beyond 4-5 years of age; quite possibly, there is none beyond infancy.

The question of whether quantitative change occurs is more difficult to answer. Certainly, performance on just about any experimental task involving faces improves very substantially across childhood and well into adolescence (see Figures 3a and 3b). The crucial issue is how much of this development reflects development in *face perception* (e.g., in holistic processing, or in the fine tuning of face-space), and how much reflects development in other general cognitive factors that are known to improve substantially across this age range and would affect task performance whatever the stimuli (e.g., explicit memory ability, ability to concentrate on the task to instruction). A common bias of face researchers is to assume, given data showing increasing memory for faces with age (e.g., Figure 3a), that it is face perception that is changing, and that the task type – explicit memory – is irrelevant; yet, an implicit memory researcher looking at the same set of data would likely conclude 'explicit memory' is developing and presume the particular stimulus type – faces – is irrelevant.

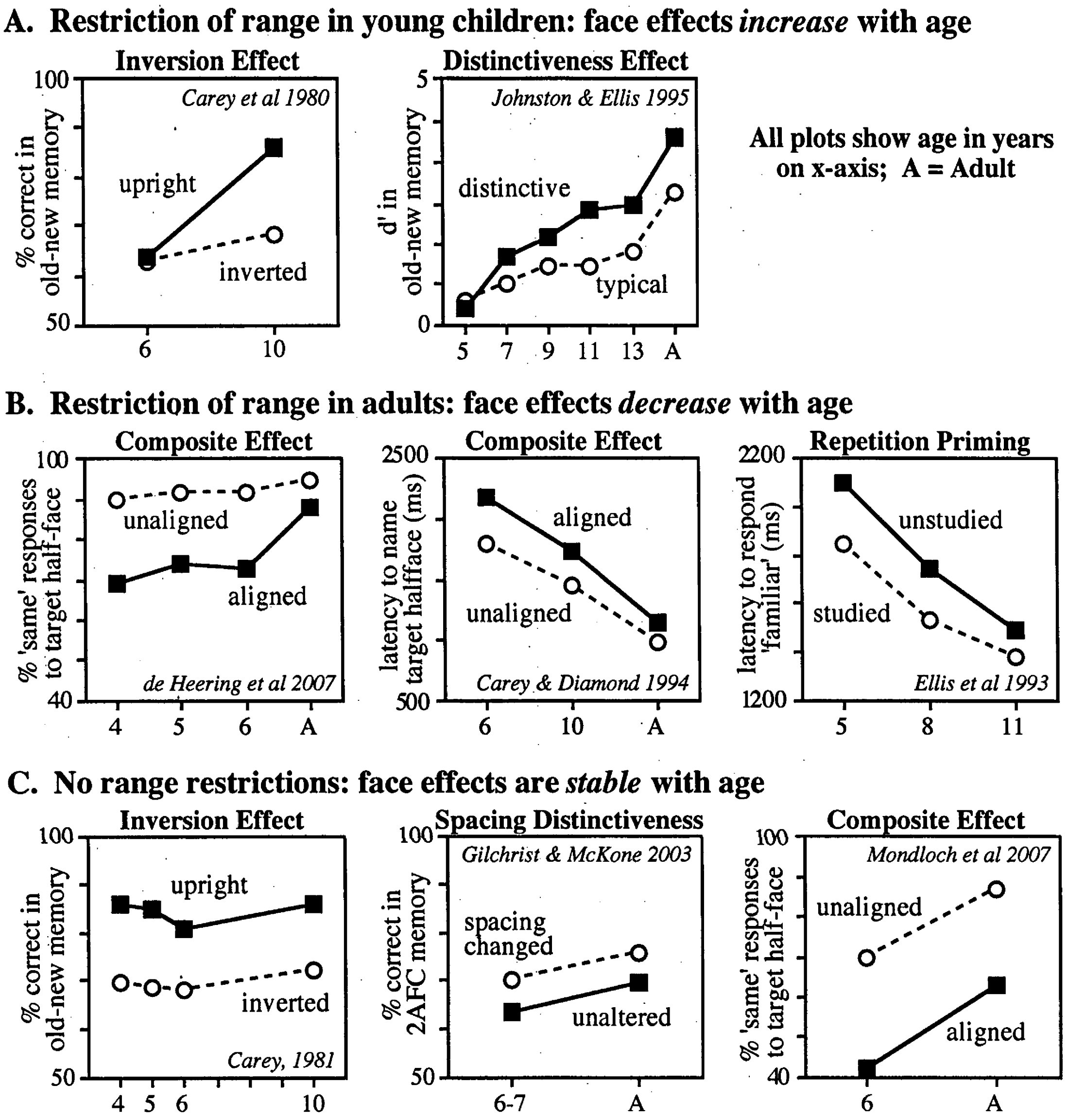


Figure 3. Behavioral face recognition effects in the preschooler to adult age range. A basic finding is of overall improvement with age – higher accuracy or lower reaction time; note that in **C**, the left and middle plots show studies where the researchers deliberately removed this trend by using smaller learning set sizes in younger children. Our major point is that apparent developmental trends in the strength of core effects (size of inversion effect, size of composite effect, ability to represent recently-seen faces in implicit memory, etc) depend on whether, and how, room to show effects is potentially restricted.

Various attempts have been made to overcome the limitations of simply tracking age-related improvement in raw performance. To our minds, however, none of these are methodologically satisfactory, and none produce a clear conclusion regarding whether face perception per se does, or does not, improve between early childhood and adulthood. One approach is to compare *two* conditions across development, for example asking whether the size of the difference between upright and inverted (or typical and distinctive, etc) changes with age (e.g., Carey et al., 1980; Johnston & Ellis, 1995). The results of almost all such studies, however, are confounded with overall 'baseline' changes across age groups, such that (a) when room to show effects is potentially compressed by approaching floor in young children, but is not restricted (i.e., no ceiling effect) in adults, results seem to suggest quantitative *increases* in the effect of interest with age (Figure 3a), but that (b) when room to show effects is restricted by approaching ceiling in adults, but is not restricted in young children (i.e., no floor effects on accuracy, or alternatively use of a reaction time measure), results seem to show quantitative *decreases* with age (Figure 3b). Taking seriously the results of the first type of study as showing quantitative development in face perception (as is commonly done), requires also taking seriously the results of the second type of study– apparently leading to the conclusion that face perception gets consistently *worse* between early childhood and adulthood! A further requirement for valid comparison of rates of development for two stimulus types is that performance be equated for the two types in one or other end-point age group. This is commonly not done. As one example, the Mondloch, Le Grand, & Maurer (2002) finding that sensitivity to feature changes reaches adult levels earlier than spacing changes can be attributed (McKone & Boyer, 2006) simply to the fact that the features changes were easier in adults (that is, performance on an easier stimulus set reaches adult levels before performance on a more difficult stimulus set). Another general issue in studies comparing faces versus objects (e.g., in rate of development, Golarai et al., 2007; or size of inversion effects, Carey & Diamond, 1977; Teunisse & de Gelder, 2003; Aylward et al., 2005), is that, in addition to producing very mixed results, the object classes tested to date (houses, scenes, sculptures, shoes) have not been well matched to faces on basic parameters, such as not sharing a first-order configuration (houses, scenes), or not being natural objects (sculptures, shoes).

Overall, we conclude that current behavioral evidence demonstrates qualitatively adult-like processing of faces in young children, but does not resolve whether processing is quantitatively mature. We note, however, that at least some evidence suggests a conclusion likely to be surprising to many readers, namely that even *quantitative* maturity might be reached by early childhood. The three studies that appear to have the most suitable methodology – in which baselines were matched across age groups (Carey, 1981; Gilchrist & McKone, 2003), or restriction of range problems were otherwise avoided (Mondloch et al., 2007) – all indicate no change in holistic processing (inversion effect, Carey, 1981; composite effect, Mondloch et al., 2007; spacing sensitivity, Gilchrist & McKone, 2003; or distinctiveness effects Gilchrist & McKone, 2003) between early childhood (4-6 years) and adulthood (Figure 3c).

3.9.2 Neural Measures of Face Identity Processing (FFA and N170)

As with behavioral studies, we discuss results of neuroimaging and ERP studies in children with respect to two questions: qualitative development, and quantitative development.

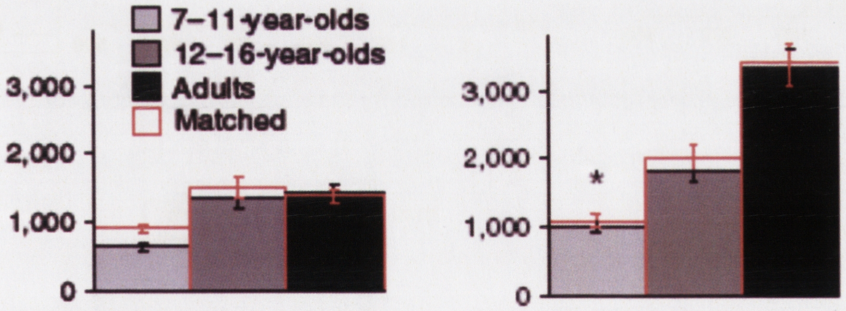
Three studies have used fMRI to scan children age 5 to adult on face and object tasks, enabling these studies to track the existence and size of face-selective regions of cortex. (A fourth study will not be discussed here because it used such liberal criteria to define "FFAs" that the regions so identified were clearly not face-selective even in adults; see Figure 1 d-f in that study, Gathers et al., 2004). Considering *qualitative* effects, evidence of a face-selective FFA has been found in most children at the youngest ages tested. Although no FFA was revealed in young children by group analyses (in which all subjects are aligned in a common space; 5-8 y.o. Scherf et al., 2007; 8-10 y.o. Aylward et al., 2005), in the two studies reporting individual-subject analyses, Scherf et al. found an FFA in 80% of the children in 5-8 year-olds (albeit at a very liberal statistical threshold), and Golarai et al. (2007) found an FFA in 85% of children in their 7-11 year-old group (using a more standard statistical threshold). One study (Passarotti, Smith, DeLano, & Huang, 2007) also reported an inversion effect (higher response to inverted than upright faces) in the region of the right (but not left) FFA in children 8-11 years of age (and an effect in the opposite direction in adults). Regarding ERPs, young children (like infants) show both face-selective responses and inversion effects upon these (see Figures 5 and 6; Taylor, Batty, & Itier, 2004). These fMRI and ERP findings in children add to the infant data to confirm that at least some form of face-specific neural machinery is established early.

Quantitatively, neural machinery involved in face perception demonstrates substantial changes in face-selective neural responses continuing late into development. In all three fMRI studies, the FFA increases markedly in volume between childhood and adulthood (Aylward et al., 2005; Golarai et al., 2007; Scherf et al., 2007), even though total brain volume does not change substantially after age 5. These studies clearly show that the rFFA is still changing late in life, certainly after age 7 and in some studies much later.

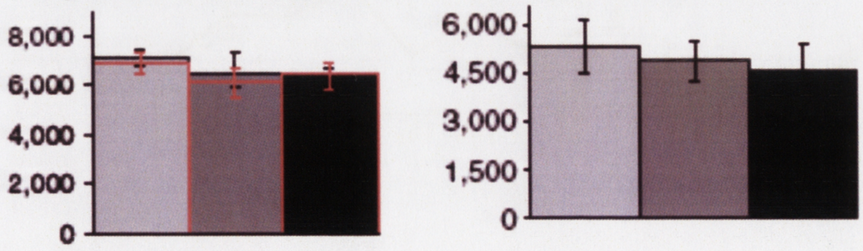
Comparing fMRI data across children and adults is fraught with potential pitfalls. Children move more in the scanner, and are less able to maintain attention on a task. These or other differences between children and adults could in principle explain the change in volume of the rFFA. However, notably, control areas identified in the same scanning sessions do not change with age. For example object-responsive regions and the scene-selective "parahippocampal place area" in the right hemisphere or rPPA (Epstein & Kanwisher, 1998) did not change in volume from childhood to adulthood (Golarai et al., 2007; Scherf et al., 2007) although somewhat surprisingly Golarai et al. found that the lPPA did increase in volume with age. These findings are reassuring that the changes in the rFFA with age are not due to across-the-board changes in the ability to extract good functional data from young children.

Golarai et al. (2007) asked how changes in the rFFA relate to changes in behavioral face recognition over development (Figure 4). Right FFA size was correlated (separately in children and adolescents but not in adults) with face recognition memory, but not with place or object memory. Conversely, lPPA size was correlated (in all age groups independently) with place memory but not with object or face memory. This double dissociation of behavioral correlations clearly associates the rFFA with changes in face recognition measured behaviorally.

A) Left FFA B) Right FFA



C) Right mid-fusiform gyrus D) Right LOC E)



E) Face-selective right STS E) Right PPA

Figure 4. Developmental data from Golarai et al. (2007): Mean volume across subjects in each age group of individually-defined left (A) and right (B) FFA, (C) anatomically-defined right mid-fusiform gyrus, (D) functionally-defined right LOC, and functionally-defined face-selective right STS (E) and right place-selective PPA (F). Red bars indicated values in subsets of subjects matched for BOLD-related confounds.

ERP findings are consistent with the evidence from fMRI that the cortical regions involved in face recognition continue to change well into the teenage years. Face-related ERPS show gradual changes in scalp distribution, latency, and amplitude into the mid-teen years (Figures 5 and 6). Both the early P1 component and the later N170 component show gradual decreases in latency from age 4 to adulthood. Regarding neural inversion effects, late developmental changes are found with both fMRI and ERP (see Figure 5), including a reversal of the direction of the inversion effect between children and adults in both methods (Taylor et al., 2004; Passarotti et al., 2007). Future research might best approach this question by measuring not just mean responses to upright versus inverted faces, but instead using identity-specific adaptation to ask when the better discrimination of upright than inverted faces seen in adulthood (Yovel & Kanwisher, 2005; Mazard et al., 2006).

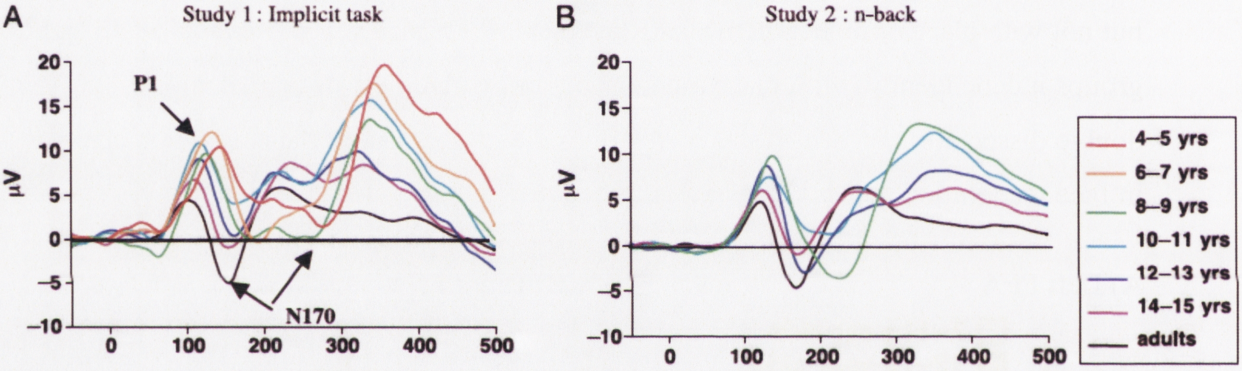


Figure 5. ERPs from right posterior temporal scalp locations in response to face stimuli, separately for each age group, from Taylor e t al. (2004).

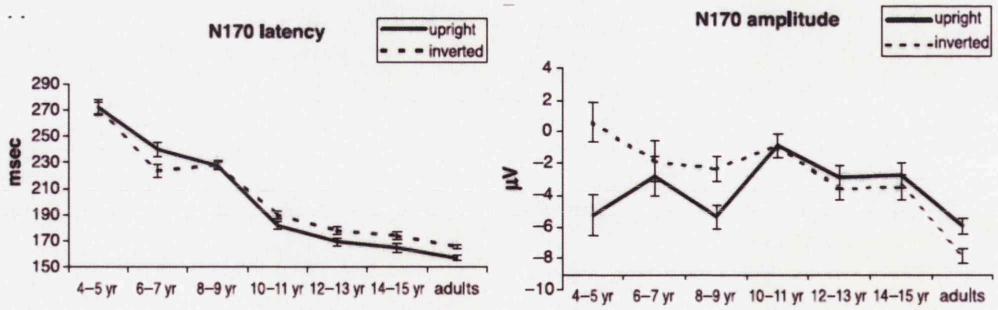


Figure 6. Mean N170 latency (left) and amplitude (right) for upright and inverted faces as a function of age, from Taylor et al. (2004).

3.9.3 Comparing Development for Behavioral and Neural Measures

Taking the findings from the 4-to-adult range together with the infant literature, we can draw the following conclusions. First, the results regarding *qualitatively* adult-like face processing appear to agree well across behavioral and neural measures; that is, just as all behavioral face recognition effects have been obtained in the youngest age groups tested, face-selective neural machinery as revealed by fMRI, ERPs, NIRs and single-cell recording has also been found in the youngest children and infants tested. Nonetheless, fMRI data are not available for children younger than 5-8 (pooled together), and the ERP studies in infants and children often go in opposite directions from adults. For example, and the inversion effect on the N170 switches polarity between childhood and adulthood, as shown in Figure 6, despite maintaining the same polarity in behavior.

Second, the evidence for quantitative development is less clear. It may be that the improvements with age on behavioral tasks do reflect ongoing development of face perception itself and, if so, this could agree neatly with the increasing size of the FFA. As we have noted, however, findings such as those shown in Figures 3b and 3c suggest that behavioral face perception may be fully mature early, and that ongoing behavioral improvements with age reflect changes in other, more general, cognitive factors. This view would produce an apparent discrepancy – behavioral maturity arising well before maturity of relevant cortical regions – that would need to be resolved. If this is the case, two ideas might worth exploring. It may be that the measured size of the FFA in children is affected by top-down strategic processing which (for some unknown reason) affects faces and not objects. Another possibility is that the FFA might play some role in the long-term storage of individual faces (e.g., it shows repetition priming, Pourtois, Schwartz, Seghier, Lazeyras, & Vuilleumier, 2005; Williams, Berberovic, & Mattingley, 2007) and that the increased size of the FFA could arise simply because people continue to learn faces across life; this idea would have to propose that the number of new faces learned is much greater than the number of new objects.

3.10 Conclusion

For decades, conventional wisdom has held that face recognition arises very slowly in development, and that experience is the primary engine of this development.

The new evidence reviewed here refutes this hypothesis. Impressive face recognition abilities are present within a few days of birth, and are present in monkeys who have never seen faces before. Some form of inherited genetic influence is also indicated by Polk et al's imaging study of twins, and by the fact that developmental prosopagnosia can run in families. Qualitatively, behavioral findings indicate establishment of *all* adult-like face recognition effects by 4 years at the latest, and in infancy wherever tested; the striking breadth of this evidence is summarised in Figure 7. The available evidence also indicates early initial establishment of face-selective neural machinery at the cortical level; again see Figure 7. It is not, however, that experience plays no role in development. Perceptual narrowing of the range of facial subtypes for which discrimination is possible reveals a destructive role for experience. Further, there is a requirement for early-infancy input (consistent with a critical period) for the development of holistic face processing but (mysteriously) not face discrimination.

Three major questions remain for future research. First, it will be critical to determine whether face perception *per se* improves quantitatively after age 4, or whether instead improvement in performance after this age reflects improvement in domain-general mechanisms. Second, if face perception itself does improve quantitatively after age 4, what role does experience play in this improvement? A final critical challenge will be to understand the relationship between cognitive and neural development, especially the substantial increase in the size of the FFA.

	Newborns / deprived	<= 3 months	Later infancy	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	Adults
Behavioral Properties												
Ability to discriminate individual faces	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺
Inversion effect on discrimination (looking time or recognition memory)	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺
Composite-like effect, upright not inverted	▨	▨	☺	▨	▨	▨	▨	▨	▨	▨	▨	☺
Composite effect	▨	▨	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺
Part-whole effect, upright not inverted	▨	▨	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺
Part-in-spacing-altered-whole effect, upright not inverted	▨	▨	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺
Sensitivity to spacing changes	☺	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺
Inversion effect on spacing sensitivity	▨	▨	☺	▨	▨	☺	☺	☺	☺	☺	☺	☺
Perceptual bias to upright in superimposed faces	▨	▨	▨	▨	▨	▨	☺	☺	☺	▨	▨	☺
Distinctiveness effects	▨	▨	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺
Adaptation aftereffects	▨	▨	▨	☺	☺	▨	▨	▨	☺	☺	☺	☺
Attractiveness preference, upright not inverted	☺	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	☺
Neural Properties												
Face-selective cells, macaques	▨	☺	▨	▨	▨	▨	▨	▨	▨	▨	▨	☺
Face-selective ERPs	▨	☺	▨	☺	☺	☺	☺	☺	☺	☺	☺	☺
FFA present	▨	▨	▨	▨	☺	☺	☺	☺	☺	☺	☺	☺
Some type of inversion effect on neural response	▨	?	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺
Perceptual Narrowing												
Looking time discrimination of other race/species faces	☺	☺	X	▨	▨	▨	▨	▨	▨	▨	▨	X

Figure 7. For each property of face processing, we indicate for each age group whether that property is *qualitatively* present (☺), debatable (?), not present (X), or not yet tested (grey). Deprived = monkeys deprived of face input from birth. Note: All references can be found in text except: Inversion effect on spacing sensitivity aged 6 years-adult (Mondloch et al., 2002), Adaptation aftereffect aged 9 years-adult (Pellicano, Jeffery, Burr, & Rhodes, 2007).

3.11 Acknowledgements

We thank Mark Johnson for useful comments and Bettiann McKay for help with the manuscript. Preparation of this chapter was supported by NEI grant 13455 and a grant from the Ellison Foundation to NK and by grant DP0450636 from the Australian Research Council to EM.

3.12 Bibliography

Aylward, E. H., Park, J. E., Field, K. M., Parsons, A. C., Richards, T. L., Cramer, S. C., & Meltzoff, A. N. (2005). Brain activation during face perception: Evidence of a developmental change. *Journal of Cognitive Neuroscience,* 17(2), 308-319.

Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience,* 8(6), 551-565.

Bernstein, M. J., Young, S. G., & Hugenberg, K. (2007). The cross-category effect: Mere social categorization is sufficient to elicit an own-group bias in face recognition. *Psychological Science,* 8, 706-712.

Brace, N. A., Hole, G. J., Kemp, R. I., Pike, G. E., Van Duuren, M., & Norgate, L. (2001). Developmental changes in the effect of inversion: Using a picture book to investigate face recognition. *Perception, 30,* 85-94.

Bruce, V., Henderson, Z., Newman, C., & Burton, M. A. (2001). Matching identities of familiar and unfamiliar faces caught on CCTV images. *Journal of Experimental Psychology: Applied,* 7(3), 207-218.

Burton, A. M., Wilson, S., Cowan, M., & Bruce, V. (1999). Face recognition in poor-quality video: Evidence from security surveillance. *Psychological Science,* 10(3), 243-248.

Bushnell, I. W. R. (2001). Mother's face recognition in newborn infants: Learning and memory. *Infant and Child Development,* 10, 67-74.

Carbon, C. C., Strobach, T., Langton, S., Harsányi, G., Leder, H., & Kovács, G. (2007). Adaptation effects of highly familiar faces: immediate and long lasting. *Memory and Cognition,* 35(8), 1966-1976.

Carey, S. (1981). The development of face perception. In G. Davies, H. D. Ellis & J. Shepherd (Eds.), *Perceiving and remembering faces* (pp. 9-38). New York: Academic Press Inc.

Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science,* 195, 312-314.

Carey, S., & Diamond, R. (1994). Are faces perceived as configurations more by adults than by children? *Visual Cognition, 2/3,* 253-274.

Carey, S., Diamond, R., & Woods, B. (1980). Development of face recognition - A maturational component? *Developmental Psychology,* 16(4), 257-269.

Cohen, L. B., & Cashon, C. H. (2001). Do 7-month-old infants process independent features of facial configurations? *Infant and Child Development,* 10, 83-92.

de Haan, M., Johnson, M. H., Maurer, D., & Perrett, D. I. (2001). Recognition of individual faces and average face prototypes by 1- and 3-month-old infants. *Cognitive Development,* 16, 659-678.

de Heering, A., Houthuys, S., & Rossion, B. (2007). Holistic face processing is mature at 4 years of age: Evidence from the composite face effect. *Journal of Experimental Child Psychology, 96*, 57-70.

DeGutis, J. M., Bentin, S., Robertson, L. C., & D'Esposito, M. (2007). Functional plasticity in ventral temporal cortex following cognitive rehabilitation of a congenital prosopagnosic. *Jouranl of Cognitive Nueroscience,* 19(11), 1790-1802.

Desimone, R., Albright, T. D., Gross, C. G., & Bruce, C. (1984). Stimulus-selective properties of inferior temporal neurons in the macaque. *Journal of Neuroscience,* 4(8), 2051-2062.

Donnelly, N., Hadwin, J. A., Cave, K., & Stevenage, S. (2003). Perceptual dominance of oriented faces mirrors the distribution of orientation tuning in inferotemporal neurons. *Cognitive Brain Research,* 17, 771-780.

Duchaine, B., Germine, L., & Nakayama, K. (2007). Family resemblance: Ten family members with prosopagnosia and within-class object agnosia. *Cognitive Neuropsychology,* 24(4), 419-430.

Duchaine, B. C., & Weidenfeld, A. (2003). An evaluation of two commonly used tests of unfamiliar face recognition. *Neuropsychologia,* 41(6), 713-720.

Ellis, H. D., Sheperd, J. W., & Davies, G. M. (1979). Identification of familiar and unfamiliar faces from internal and external features: Some implications for theories of face recognition. *Perception,* 8(4), 431-439.

Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature,* 392(6676), 598-601.

Farroni, T., Johnson, M. H., Menon, E., Zulian, L., Faraguna, D., & Csibra, G. (2005). Newborns' preference for face-relevant stimuli: Effects of contrast polarity. *Proceedings of the National Academy of Sciences of the United States of America, 102*(47), 17245-17250.

Flin, R. H. (1985). Development of face recognition: An encoding switch? *British Journal of Psychology, 76*, 123-134.

Foldiak, P., Xiao, D., Keysers, C., Edwards, R., & Perrett, D. I. (2004). Rapid serial visual presentation for the determination of neural selectivity in area STSa. *Progress In Brain Research,* 144, 107-116.

Gathers, A. D., Bhatt, R. S., Corbly, C. R., Farley, A. B., & Joseph, J. E. (2004). Developmental shifts in cortical loci for face and object recognition. *NeuroReport,* 15(10), 1549-1553.

Geldart, S., Mondloch, C. J., Maurer, D., de Schonen, S., & Brent, H. P. (2002). The effect of early visual deprivation on the development of face processing. *Developmental Science,* 5(4), 490-501.

Gilchrist, A., & McKone, E. (2003). Early maturity of face processing in children: Local and relational distinctiveness effects in 7-year-olds. *Visual Cognition,* 10(7), 769-793.

Golarai, G., Ghahemani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D., & Grill-Spector, K. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience,* 10, 512-522.

Goren, C. C., Sarty, M., & Wu, P. Y. K. (1975). Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics,* 56(4), 544-549.

Grueter, M., Grueter, T., Bell, V., Horst, J., Laskowski, W., Sperling, K., Halligan, P. W., Ellis, H. D., & Kennerknecht, I. (2007). Hereditary prosopagnosia: the first case series. *Cortex,* 43(6), 734-749.

Halgren, E., Raij, T., Marinkovic, K., Jousmaki, V., & Hari, R. (2000). Cognitive response profile of the human fusiform face area as determined by MEG. *Cerebral Cortex* 10(1), 69-81.

Halit, H., de Haan, M., & Johnson, M. H. (2003). Cortical specialisation for face processing: face-sensitive event-related potential components in 3- and 12-month-old infants. *NeuroImage,* 19(3), 1180-1193.

Hayden, A., Bhatt, R. S., Reed, A., Corbly, C. R., & Joseph, J. E. (2007). The development of expert face processing: Are infants sensitive to normal differences in second-order relational information? *Journal of Experimental Child Psychology,* 97, 85-98.

Humphreys, K., & Johnson, M. H. (2007). The development of "face-space" in infancy. *Visual Cognition, 15*(5), 578-598.

Jacques, C., d'Arripe, O., & Rossion, B. (2007). The time course of the inversion effect during individual face discrimination. *Journal of Vision,* 7(8), 1-9.

Jacques, C., & Rossion, B. (2006). The speed of individual face categorization. *Psychological Science,* 17(6), 485-492.

Jeffery, L., & Rhodes, G. (2008). Aftereffects reveal enhanced face-coding plasticity in young children, *Vision Sciences Society*). Naples, Florida.

Johnson, M. H. (2005). Subcortical face processing. *Nature Reviews Neuroscience, 6,* 766-774.

Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' preferential tracking of face-like stimuli and its subsequent decline. *Cognition,* 40(1-2), 1-19.

Johnson, M. H., Griffin, R., Csibra, G., Halit, H., Farroni, T., de Haan, M., Tucker, L. A., Baron-Cohen, S., & Richards, J. (2005). The emergence of the social brain network: evidence from typical and atypical development. *Development and Psychopathology,* 17(3), 599-619.

Johnston, R. A., & Ellis, H. D. (1995). Age effects in the processing of typical and distinctive faces. *The Quarterly Journal of Experimental Psychology,* 48A(2), 447-465.

Kanwisher, N., Mc Dermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience,* 17(11), 4302-4311.

Kanwisher, N., & Yovel, G. (in press). Cortical Specialization for Face Perception in Humans. In J. T. Cacioppo & G. G. Berntson (Eds.), *Handbook of Neuroscience for the Behavioral Sciences*). Hoboken, NJ: J. Wiley and Sons.

Kelly, D. J., Quinn, P. C., Slater, A., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science,* 18(12), 1084-1089.

Kennerknecht, I., Pluempe, N., & Welling, B. (2008). Congenital prosopagnosia--a common hereditary cognitive dysfunction in humans. *Frontiers in Bioscience,* 1(13), 3150-3158.

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritanim, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science, 9*(2), F13-F21.

Kuhl, P. K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences of the United States of America,* 100, 9096-9101.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2003). Expert face processing requires visual input to the right hemisphere during infancy. *Nature Neuroscience,* 6(10), 1108-1112.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science,* 15(11), 762-768.

Leopold, D. A., Bondar, I. V., & Giese, M. A. (2006). Norm-based face encoding by single neurons in the monkey inferotemporal cortex. *Nature,* 442(7102), 572-575.

Leopold, D. A., O' Toole, A. J., Vetter, T., & Blanz, V. (2001). Prototype-referenced shape encoding revealed by high-level aftereffects. *Nature Neuroscience,* 4(1), 89-94.

Lewkowicz, D. J., & Ghazanfar, A. A. (2006). The decline of cross-species intersensory perception in human infants. *Proceedings of the National Academy of Sciences of the United States of America, 103*(17), 6771-6774.

Liu, J., Harris, A., & Kanwisher, N. (2002). Stages of processing in face perception: an MEG study. *Nature Neuroscience,* 5(9), 910-916.

Logie, R. H., Baddeley, A. D., & Woodhead, M. M. (1987). Face recognition, pose and ecological validity. *Applied Cognitive Psychology,* 1, 53-69.

Lundy, B. L., Jackson, J. W., & Haaf, R. A. (2001). Stimulus properties, attentional limitations, and young children's face recognition. *Perceptual and Motor Skills,* 92, 919-929.

Martini, P., McKone, E., & Nakayama, K. (2006). Orientation tuning of human face processing estimated by contrast matching on transparency displays. *Vision Research,* 46(13), 2102-2109.

Maurer, D., Le Grand, R., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences, 6*(6), 255-260.

Mazard, A., Schiltz, C., & Rossion, B. (2006). Recovery from adaptation to facial identity is larger for upright than inverted faces in the human occipito-temporal cortex. *Neuropsychologia,* 44(6), 912-922.

McCarthy, G., Luby, M., Gore, J., & Goldman-Rakic, P. (1997). Infrequent events transiently activate human prefrontal and parietal cortex as measured by functional MRI. *Journal of Neurophysiology,* 77(3), 1630-1634.

McKone, E. (2008). Configural processing and face viewpoint. *Journal of Experimental psychology. Human perception and performance,* 34(2), 310-327.

McKone, E., Aitkin, A., & Edwards, M. (2005). Categorical and coordinate relations in faces, or Fechner's law and face space instead? *Journal of Experimental Psychology: Human Perception and Performance,* 31(6), 1181-1198.

McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology,* 94(2), 134-162.

McKone, E., Kanwisher, N., & Duchaine, B. C. (2007). Can generic expertise explain special processing for faces? *Trends in Cognitive Sciences,* 11(1), 8-15.

Meissner, C. A., & Brigham, J. C. (2001). Thirty years of investigating the own-race bias in memory for faces: A meta-analytic review. *Psychology, Public Policy, & Law,* 7(1), 3-35.

Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception,* 31, 553-566.

Mondloch, C. J., Pathman, T., Maurer, D., Le Grand, R., & de Schonen, S. (2007). The composite face effect in six-year-old children: Evidence of adult-like holistic face processing. *Visual Cognition,* 15(5), 564-577.

Morton, J., & Johnson, M. H. (1991). CONSPEC and CONLERN: A two-process theory of infant face recognition. *Psychological Review,* 98(2), 164-181.

Ostrovsky, Y., Andalman, A., & Sinha, P. (2006). Vision following extended congenital blindness. *Psychological Science,* 17(12), 1009-1014.

Otsuka, Y., Nakato, E., Kanazawa, S., Yamaguchi, M. K., Watanabe, S., & Kakigi, R. (2007). Neural activation to upright and inverted faces in infants measured by near infrared spectroscopy. *NeuroImage,* 34, 399-406.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296*, 1321-1323.

Pascalis, O., de Haan, M., Nelson, C. A., & de Schonen, S. (1998). Long-term recognition memory for faces assessed by visual paired comparison in 3- and 6-month-old infants. *Journal of Experimental Psychology: Learning, Memory and Cognition,* 24(1), 249-260.

Pascalis, O., de Schonen, S., Morton, J., Deruelle, C., & Fabre-Grenet, M. (1995). Mother's face recognition by neonates: A replication and an extension. *Infant Behavior and Development,* 18, 79-85.

Pascalis, O., Scott, L. S., Kelly, D. J., Shannon, R. W., Nicholson, E., Coleman, M., & Nelson, C. A. (2005). Plasticity of face processing in infancy. *Proceedings of the*

National Academy of Sciences of the United States of America, 102(14), 5297-5300.

Passarotti, A. M., Smith, J., DeLano, M., & Huang, J. (2007). Developmental differences in the neural bases of the face inversion effect show progressive tuning of face-selective regions to the upright orientation. *NeuroImage,* 34(4), 1708-1722.

Pellicano, E., Jeffery, L., Burr, D., & Rhodes, G. (2007). Abnormal adaptive face-coding mechanisms in children with autism spectrum disorder. *Current Biology,* 17(17), 1508-1542.

Pellicano, E., & Rhodes, G. (2003). Holistic processing of faces in preschool children and adults. *Psychological Science, 14*(6), 618-622.

Pellicano, E., Rhodes, G., & Peters, M. (2006). Are preschoolers sensitive to configural information in faces? *Developmental Science,* 9(3), 270-277.

Perrett, D. I., Mistlin, A. J., Chitty, A. J., Smith, P. A., Potter, D. D., Broennimann, R., & Harries, M. (1988). Specialized face processing and hemispheric asymmetry in man and monkey: evidence from single unit and reaction time studies. *Behavioural Brain Research,* 29(3), 245-258.

Pinsk, M. A., DeSimone, K., Moore, T., Gross, C.G., & Kastner, S. (2005). Representations of faces and body parts in macaque temporal cortex: a functional MRI study. *Proceedings of the National Academy Science, U.S.A.,* 102(19), 6996-7001.

Polk, T. A., Park, J., Smith, M. R., & Park, D. C. (2007). Nature versus nurture in ventral visual cortex: a functional magnetic resonance imaging study of twins. *Journal of Neuroscience,* 27(51), 13921-13925.

Pourtois, G., Schwartz, S., Seghier, M. L., Lazeyras, F., & Vuilleumier, P. (2005). Portraits or people? Distinct representations of face identity in the human visual cortex. *Journal of Cognitive Neuroscience,* 17(7), 1043-1057.

Puce, A., Allison, T., Asgari, M., Gore, J. C., & McCarthy, G. (1996). Differential sensitivity of human visual cortex to faces, letterstrings, and textures: A functional magnetic resonance imaging study. *Journal of Neuroscience,* 16(16), 5205-5215.

Rhodes, G., Brake, S., & Atkinson, A. P. (1993). What's lost in inverted faces? *Cognition,* 47, 25-57.

Robbins, R., & McKone, E. (2003). Can holistic processing be learned for inverted faces? *Cognition,* 88, 79-107.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition,* 103(1), 34-79.

Rodman, H. R., Scalaidhe, S. P., & Gross, C. G. (1993). Response properties of neurons in temporal cortical visual areas of infant monkeys. *Journal of Neurophysiology,* 70(3), 1115-1136.

Rossion, B., Dricot, L., Devolder, A., Bodart, J., Crommelinck, M., de Gelder, B., & Zoontjes, R. (2000). Hemispheric asymmetries for whole-based and part-based face processing in the human fusiform gyrus. *Journal of Cognitive Neuroscience,* 14(5), 793-802.

Rotshtein, P., Henson, R. N., Treves, A., Driver, J., & Dolan, R. J. (2005). Morphing Marilyn into Maggie dissociates physical and identity face representations in the brain. *Nature Neuroscience,* 8(1), 107-113.

Sai, F. Z. (2005). The role of the mother's voice in developing mother's face preference: Evidence for intermodal perception at birth. *Infant and Child Development,* 14, 29-50.

Sangrigoli, S., & de Schonen, S. (2004). Effect of visual experience on face processing: a developmental study of inversion and non-native effects. *Developmental Science,* 7(1), 74-87.

Sangrigoli, S., Pallier, C., Argenti, A.M., Ventureyra, V.A., & de Schonen, S. (2005). Reversibility of the other-race effect in face recognition during childhood. *Psychological Sciences,* 16(6), 440-444.

Saxe, R., Brett, M., & Kanwisher, N. (2006). Divide and conquer: a defense of functional localizers. *Neuroimage,* 30(4), 1088-1096.

Scherf, K. S., Behrmann, M., Humphrey, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science,* 10(4), F15-F30.

Schiltz, C., & Rossion, B. (2006). Faces are represented holistically in the human occipito-temporal cortex. *NeuroImage,* 32, 1385-1394.

Sengpiel, F. (2007). The critical period. *Current Biology,* 17, R742-R743.

Simion, F., Macchi Cassia, V., Turati, C., & Valenza, E. (2003). Non-specific perceptual biases at the origins of face processing. In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood: Current perspectives* (pp. 13-25). New York: Nova Science Publisher, Inc.

Simion, F., Valenza, E., Umilta, C., & Dalla Barba, B. (1998). Preferential orienting to faces in newborns: A temporal-nasal asymmetry. *Journal of Experimental Psychology: Human Perception and Performance, 24*(5), 1399-1405.

Simons, D., J, & Levin, D. T. (1998). Failure to detect changes to people during real-world interaction. *Psychonomic Bulletin and Review,* 5(4), 644-649.

Slater, A., Quinn, P. C., Hayes, R., & Brown, E. (2000). The role of facial orientation in newborn infants' preference for attractive faces. *Developmental Science,* 3(2), 181-185.

Sugita, Y. (2008). Face perception in monkeys reared with no exposure to faces. *Proceedings of the National Academy of Sciences of the United States of America,* 105(1), 394-398.

Tanaka, J. W., & Farah, M. (1993). Parts and wholes in face recognition. *The Quarterly Journal of Experimental Psychology,* 46A(2), 225-245.

Tanaka, J.W., Kay, J. B., Grinnell, E., Stansfield, B., & Szechter, L. (1998). Face recognition in young children: When the whole is greater than the sum of its parts. *Visual Cognition,* 5, 479-496.

Tanaka, J. W., & Sengco, J. A. (1997). Features and their configuration in face recognition. *Memory and Cognition,* 25(5), 583-592.

Taylor, M. J., Batty, M., & Itier, R. J. (2004). The faces of development: a review of early face processing over childhood. *Journal of Cognitive Neuroscience,* 16(8), 1426-1442.

Teunisse, J. P., & de Gelder, B. (2003). Face processing in adolescents with autistic disorder: the inversion and composite effects. *Brain and Cognition,* 52(3), 285-294.

Tsao, D. Y., Freiwald, W. A., Knutsen, T. A., Mandeville, J. B., & Tootell, R. B. (2003). Faces and objects in macaque cerebral cortex. *Nature Neuroscience,* 6(9), 989-995.

Tsao, D. Y., Freiwald, W. A., Tootell, R. B. H., & Livingstone, M. S. (2006). A cortical region consisting entirely of face-selective cells. *Science, 311*, 670-674.

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

Turati, C., Macchi Cassia, V., Simion, F., & Leo, I. (2006). Newborns' face recognition: Role of inner and outer facial features. *Child Development,* 77(2), 297-311.

Tzourio-Mazoyer, N., de Schonen, S., Crivello, F., Reutter, B., Aujard, Y., & Mazoyer, B. (2002). Neural correlates of woman face processing by 2-month-old infants. *NeuroImage,* 15, 454-461.

Valentine, T. (1991). A unified account of the effects of distinctiveness, inversion, and race in face recognition. *The Quarterly Journal of Experimental Psychology,* 43A(2), 161-204.

Valentine, T., & Bruce, V. (1986). The effects of distinctiveness in recognising and classifying faces. *Perception,* 15, 525-535.

Webster, M. A., & MacLin, O. H. (1999). Figural aftereffects in the perception of faces. *Psychonomic Bulletin and Review,* 6(4), 647-653.

Williams, M. A., Berberovic, N., & Mattingley, J. B. (2007). Abnormal FMRI adaptation to unfamiliar faces in a case of developmental prosopamnesia. *Current Biology,* 17(14), 1259-1264.

Wilson, R. R., Blades, M., & Pascalis, O. (2007). What do children look at in an adult face with which they are personally familiar? *British Journal of Development Psychology,* 25, 375-382.

Winston, J. S., Vuilleumier, P., & Dolan, R. J. (2003). Effects of low-spatial frequency components of fearful faces on fusiform cortex activity. *Current Biology,* 13(20), 1824-1829.

Yin, R. K. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81*(1), 141-145.

Young, A. W., Hellawell, D., & Hay, D. C. (1987). Configurational information in face perception. *Perception,* 16, 747-759.

Yovel, G., & Duchaine, B. (2006). Specialized face perception mechanisms extract both part and spacing information: evidence from developmental prosopagnosia. *Journal of Cognitive Neuroscience,* 18(4), 580-593.

Yovel, G., & Kanwisher, N. (2005). The neural basis of the behavioral face-inversion effect. *Current Biology,* 15(24), 2256-2262.

3.13 Relevant literature published after this manuscript was accepted

The final version of McKone, Crookes and Kanwisher (in press) was written in June 2008. Four additional studies have since appeared which are of relevance to one of the primary questions addressed in this chapter, namely the youngest age at which all standard adult face recognition effects are present in children. These papers do not change the conclusions drawn in our chapter; that is, it is still the case that all adult-like behavioural effects have been found at the youngest age tested.

The specific details are as follows. Two of the studies (Macchi Cassia, Kuefner, Picozzi, & Vescovo, 2009a; Macchi Cassia, Picozzi, Kuefner, Bricolo, & Turati, 2009b) clearly push the age of the presence of *holistic processing* on adult-like tests back to 3 years. Previously, the inversion effect for faces had been demonstrated in only one study at 3 years (Sangrigoli & de Schonen, 2004), and for other standard holistic processing effects (part-whole, composite) the earliest tests were at 4 years. Macchi Cassia et al. (2009a) confirmed an inversion effect for faces in 3-year-olds, using a short term memory task. Further, Macchi Cassia et al. (2009b) found that 3-year-olds demonstrated the adult pattern for the composite effect for faces versus cars: that is, an accuracy advantage for misaligned over aligned halves for faces but *not* for cars.

The other two studies are the first published tests of adaptation aftereffects for face attractiveness (Anzures, Mondloch, & Lackner, 2009) and identity (Nishimura, Maurer, Jeffery, Pellicano, & Rhodes, 2008) in children as young as 8 years. Previously, the youngest age at which the identity aftereffect had been tested (and demonstrated) was 9 years, and the attractiveness aftereffect had not been tested in children at all. Anzures et al. (2009) demonstrated that aftereffects on attractiveness ratings of distorted (i.e., "spherized") faces, following adaptation to a distorted face, were qualitatively similar in 8 year-olds and adults. Nishimura et al. (2008) demonstrated that identity aftereffects in the Leopold, O'Toole, Vetter & Blanz (2001) identity-adaptation procedure were qualitatively similar in 8-year-olds and adults.

Two additional papers have also appeared relevant to the question of neural development. Pelphrey, Lopez and Morris (2009) localised the FFA in children aged 7 to 11 years supporting the qualitative presence of adult-like neural mechanisms. While no change in selectivity was observed with age the FFA did appear to increase in volume with age although no statistics were reported. In the second paper Kuefner, de Heering, Jacques, Palmero-Soler and Rossion (in press) compared the ERP responses for faces and cars in 5-16 year-olds. They confirmed the qualitative presence of the adult N170 component in children. Quantitatively no face specific development was observed in any aspect of the electrophysiological response.

3.14 Minor corrections to the published paper

It is acknowledged that Haig (1984) demonstrated sensitivity to spacing changes before Rhodes et al., (1993) and McKone et al., (2005). The citation on page 19 should therefore read: "evidence of strong *sensitivity to spacing changes* (e.g., distance between eyes) in upright faces (e.g., Haig, 1984; Rhodes, Brake, & Atkinson, 1993; McKone, Aitkin, & Edwards, 2005)".

With regards to tests of holistic processing on page 19 it should be noted that in studies by Rossion and colleages the composite effect when tested inverted is greatly reduced but not absent. Hence the statement should be qualified to: "All these holistic effects are specific to upright faces: they are not found or are greatly reduced for inverted or scrambled faces (Young et al., 1987; Tanaka & Sengco, 1997; Robbins & McKone, 2003; Martini et al., 2006)..."

The statement about the ERP component the N170 on page 21 should have included reference to earlier papers. The citation should therefore read: "A negative-going ERP response peaking about 170 ms after stimulus onset over posterior temporal sites (N170) has been widely replicated to be face-selective (e.g., Bentin, Allison, Puce, Perez, & McCarthy, 1996; Halgren, Raij, Marinkovic, Jousmaki, & Hari, 2000; Liu, Harris, & Kanwisher, 2002)." Similarly the statement about the increase in the N170 on page 21 has an incorrect citation. It should read: "This peak is delayed by 10 ms, and is larger in amplitude, for inverted faces relative to upright faces (Rossion et al., 1999)."

It should have been stated that the prosopagnosic in the DeGutis et al., (2007) study referred to on page 22 was an adult *developmental* prosopagnosic.

The statement on page 29 regarding perceptual narrowing that "experience with one subtype of face (own-species, own-race) *removes* this initial ability with other face types (other-species, other-races)" fails to acknowledge that there maybe ongoing plasticity throughout childhood which leads to greater flexibility. Hence, discrimination of other-race faces may be learned if experience is gained within childhood. These ideas are discussed in Section 8.4.8 of the general discussion.

The following sentence on page 36 should have included a reference to an ERP adaptation study by Jacques, d'Arripe & Rossion (2007): "Future research might best approach this question by measuring not just mean responses to upright versus inverted faces, but instead using identity-specific adaptation to ask when the better discrimination of upright than inverted faces seen in adulthood (Jacques, d'Arripe & Rossion, 2007; Yovel & Kanwisher, 2005; Mazard et al., 2006)."

CHAPTER 4 – EARLY MATURITY OF FACE RECOGNITION: NO CHILDHOOD DEVELOPMENT OF HOLISTIC PROCESSING, NOVEL FACE ENCODING, OR FACE-SPACE

4.1 Context statement

The previous chapter concluded with three major questions for future research. The present chapter addresses one of these questions: Does functional face perception *per se* improve quantitatively after age 4-5 years, or does improvement in performance after this age instead reflect improvement in domain-general mechanisms? This question is the key to one of the major aims of this thesis – to investigate the role of extended experience, continuing into adolescence, in establishing quantitative maturity of the core face perception abilities. Evidence of quantitative development of face-specific mechanisms with age would be predicted by the view that extended experience with faces does play a role in this development. In contrast, evidence of *no* quantitative change with age would argue that extended experience with faces is *not* the origin of the "special" processing of faces.

The three new experiments and comprehensive literature review in this chapter attempt to disentangle face-specific perceptual development from general cognitive development, in order to assess quantitative change across age in three basic abilities: the ability to perform holistic processing; the ability to encode perceptual representations of novel faces; and the ability to represent faces in face-space.

4.2 Publication status

This chapter comprises a paper accepted for publication in February 2009. It appears in print as:

Crookes, K. & McKone, E. (2009). Early maturity of face recognition: No childhood development of holistic processing, novel face encoding, or face-space. *Cognition, 111*(2), 219-247.

The accepted version of this paper was finalised in February 2009. Discussion of three relevant papers published since that date is provided following presentation of the accepted manuscript.

4.3 Author contributions

4.3.1 Literature review

- **Crookes** was responsible for the literature review, including literature searches, reading papers, understanding methods and results, summarising findings, and noting methodological issues.

4.3.2 Conceived and designed the experiment

- All experiments were conceived and designed by **Crookes** in conjunction with McKone.

4.3.3 Programming and Testing

- **Crookes** programmed all the tasks and created the new stimuli for Experiment 3
- **Crookes** arranged all the child testing in schools including ethics clearance from the education department, contacting principals and liaising with classroom teachers
- **Crookes** collected all the child data and the majority of the new adult data (a few adult participants were tested by research assistant Stefan Horarik while **Crookes** was off-site testing in schools).[1]

4.3.4 Data analysis

- **Crookes** was responsible for deciding what statistical analysis would be performed.
- McKone suggested a few additional analyses.
- **Crookes** performed all the data analysis.

4.3.5 Theory development

- **Crookes** and McKone worked together to develop the arguments and theories presented

4.3.6 Writing

- **Crookes** wrote the paper and produced all the tables and figures
- McKone then edited and refined the paper

---

[1] Examiners should note that: (1) as stated in the paper, data for the "performance matched adult" group in Experiment 2 were taken from Robbins and McKone (2007) and were not collected by me; and (2) 48 of the 64 child participants in Experiment 3B were previously included and examined in my Honours thesis (2004).

Cognition 111 (2009) 219–247

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Early maturity of face recognition: No childhood development of holistic processing, novel face encoding, or face-space

Kate Crookes *, Elinor McKone

Department of Psychology, The Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 29 July 2008
Revised 8 February 2009
Accepted 17 February 2009

Keywords:
Face recognition
Development
Children
Holistic processing
Configural processing
Novel faces
Face-space
Implicit memory
Repetition priming

ABSTRACT

Historically, it was believed the perceptual mechanisms involved in individuating faces developed only very slowly over the course of childhood, and that adult levels of expertise were not reached until well into adolescence. Over the last 10 years, there has been some erosion of this view by demonstrations that all adult-like behavioural properties are *qualitatively* present in young children and infants. Determining the age of maturity, however, requires *quantitative* comparison across age groups, a task made difficult by the need to disentangle development in face perception from development in all the other cognitive factors that affect task performance. Here, we argue that full quantitative maturity is reached early, by 5–7 years at the latest and possibly earlier. This is based on a comprehensive literature review of results in the 5-years-to-adult age range, with particular focus on the results of the few previous studies that are methodologically suitable for quantitative comparison of face effects across age, plus three new experiments testing development of holistic/configural processing (faces versus objects, disproportionate inversion effect), ability to encode novel faces (assessed via implicit memory) and face-space (own-age bias).

1. Introduction

The ability to recognise a person from their facial appearance – that is, the process of visual discrimination of faces – is essential to human social interaction. There has thus been longstanding interest in the developmental course of face recognition, and particularly the question of when children's perceptual ability matures to adult levels.

Infant studies demonstrate remarkable face recognition abilities very early in life. Newborns can recognise their mother (Bushnell, 2001; Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995), discriminate individual identity of novel faces with hair (Pascalis & de Schonen, 1994; Turati, Macchi Cassia, Simion, & Leo, 2006) and without hair (Turati et al., 2006), and recognise identity of novel faces across viewpoint changes (Turati, Bulf, & Simion, 2008; also see Pascalis, de Haan, Nelson, & de Schonen, 1998, in 3-month-olds). Infants younger than 6–9 months can even individuate faces from races and species with which they have no prior experience (Kelly et al., 2007; Pascalis, de Haan, & Nelson, 2002).

Despite this early proficiency, all laboratory studies in children show dramatic development, continuing throughout childhood and into adolescence. Children's recognition memory for faces in experimental settings improves greatly from approximately 5 years and approaches adult levels only in later adolescence (e.g., Blaney & Winograd, 1978; Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Ellis & Flin, 1990; Flin, 1980, 1985; Johnston & Ellis, 1995). This is not merely a memory phenomenon. Performance on perceptual face discrimination tasks, such as same-different decision, also improves strongly between 5 years and adulthood (e.g., Carey et al., 1980; Mondloch, Dobson, Parsons, & Maurer, 2004; Mondloch, Le Grand, & Maurer, 2002).

The question we address here is *why* this protracted development in children's task performance occurs. From

---

* Corresponding author. Tel.: +61 2 61254106; fax: +61 2 61250499.
E-mail address: Kate.Crookes@anu.edu.au (K. Crookes).

0010-0277/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2009.02.004

the literature, we identify two general theories. The first is a *face-specific perceptual development theory*, which proposes that an important contributing factor is ongoing development of face-specific perceptual mechanisms (e.g., holistic processing, tuning of face-space dimensions). The second is a *general cognitive development theory*, which proposes that face perception itself is mature in early childhood, and that all development of task performance thereafter reflects improvements in general cognitive mechanisms such as concentration, visual attention, and explicit memory ability.

The first of these theories has been historically the most popular, but the second has been supported by a number of recent findings, leading to controversy and a currently open question. Our aim here is to discriminate between the two theories, considering primarily the 5 years to adult age range, and addressing the fundamental question of whether children's identity-related *face perception* is, or is not, fully mature in early childhood.

Our article is structured as follows. First, we describe the two theories. Second, we provide a brief summary of the now well-established evidence that there is no *qualitative* change in face perception between children and adults. Third, we review the very extensive literature relevant to the question of whether there is *quantitative* improvement in face perception: here, we argue that methodological difficulties in comparing across age groups are present in almost all studies, but note that the handful of studies with the most appropriate methodology all favour early perceptual maturity. Fourth, we present three new experiments focussing on quantitative comparison across ages of two very important aspects of face perception – the strength of holistic/configural processing, and the ability to encode novel faces – and also present some data relevant to the development of face-space. These studies, using three independent techniques, converge with each other and with the previous literature to argue that face perception is quantitatively mature at 5–7 years.

1.1. Face-specific perceptual development theory

Recall the phenomenon we are trying to explain is the dramatic improvement in laboratory face task performance across childhood and adolescence. The first theory of this improvement (e.g., Aylward et al., 2005; Carey & Diamond, 1977; Carey et al., 1980; Cohen Kadosh & Johnson, 2007; Ellis, 1992; Humphreys & Johnson, 2007; Mondloch et al., 2002; Nishimura, Maurer, Jeffery, Pellicano, & Rhodes, 2008; Scherf, Behrmann, Humphreys, & Luna, 2007) we will refer to as the *face-specific perceptual development* theory. Although acknowledging infants' early proficiency, this theory argues face perception itself continues to develop into late childhood, and that this is due to extended experience with faces. Ongoing improvements in face coding contribute directly to improvements on perceptual tasks such as face discrimination, and are also presumed to support improvements in memory by, for example, allowing more robust encoding of novel faces, or more exact comparison to distractors at retrieval.

Regarding the exact nature of any change in face perception, three specific proposals can be identified. One is that improvements might occur in *holistic/configural* processing (henceforth referred to as *holistic* processing). The exact nature of this 'special' style of face processing is not fully understood, but it is widely agreed to include (a) strong perceptual integration of information across the whole face, and (b) processing of the "second-order" ways in which exact spacing between facial features deviates from the basic shared first-order configuration found in all faces (i.e., two eyes, above nose, above mouth). One theory proposes perceptual integration and coding of spacing information are independent subcomponents (Maurer, Le Grand, & Mondloch, 2002); another proposes a single integrated representation of all facial information that includes spacing information within it (and, indeed, local feature shape; McKone, in press; Tanaka & Farah, 1993; Yovel & Duchaine, 2006). Importantly, both theories agree holistic processing is strongly sensitive to stimulus inversion; in the Maurer et al. (2002) theory, this applies to all subcomponents.

In adults, holistic processing is associated with several standard paradigms. Faces produce *disproportionate inversion effects* on recognition memory. All objects are remembered more poorly if studied and tested upside-down compared to upright, but the inversion effect is much larger for faces (25% decrement) than for a wide range of other object classes (2–10%, Diamond & Carey, 1986; Robbins & McKone, 2007; Scapinello & Yarmey, 1970; Yin, 1969). The standard assumption is this occurs because holistic processing operates only for upright faces, a conclusion supported by methods that assess processing style directly. In the *composite effect* (Young, Hellawell, & Hay, 1987), aligning the top half of one face (e.g., George Bush) with the bottom half of another (e.g., Tony Blair) produces a percept of a 'new person', and it is more difficult to name the top half for aligned than misaligned composites. In the *part-whole effect* (Tanaka & Farah, 1993), memory for a face part (Bill's nose) is much poorer in isolation (Bill's nose versus John's nose) than in the context of the original whole face (Bill's nose in Bill's face versus John's nose in Bill's face). In the *part-in-spacing-changed-whole* variant (Tanaka & Sengco, 1997), memory for a face part (Bill's nose) is poorer in a spacing-changed version of the whole face (Bill's nose in Bill's face with the eyes moved further apart) than in the unaltered whole face, consistent with much other evidence of excellent sensitivity to exact spacing between features in upright faces (e.g., McKone, Aitkin, & Edwards, 2005; Rhodes, Brake, & Atkinson, 1993). These holistic effects occur for upright faces, but are absent or substantially reduced for inverted faces, scrambled faces, and objects including houses, cars, dogs and 'greebles', both in novices and experts (for reviews see McKone, Kanwisher, & Duchaine, 2007; Robbins & McKone, 2007).

Turning to children, an early developmental theory argued holistic processing first emerged at around 10 years (Carey et al., 1980). More recently, it has been argued that some aspects of holistic processing are mature in young children, but other aspects continue to develop into adolescence due to extended experience with faces. Proposals about exactly which aspects of holistic processing develop include Carey and Diamond's (1994, p. 270) "mystery factor", and Mondloch et al.'s (2002) proposal of sensitivity to spacing between features.

A second version of face-specific perceptual development theory is that development could occur in 'face-space' (Ellis, 1992; Humphreys & Johnson, 2007; Johnston & Ellis, 1995; Nishimura et al., 2008; Valentine, 1991), namely a multi-dimensional space in which dimensions code physical properties differentiating faces, each individual is a point, and the centre is the average face. Face-space has been used to explain several properties of adult face recognition, including *typical versus distinctive face* effects (Valentine & Bruce, 1986), *caricature effects* (Rhodes, Brennan, & Carey, 1987), *preference for attractive faces* (attractive faces are more average; Rhodes, Sumich, & Byatt, 1999), and *adaptation aftereffects* (Leopold, O'Toole, Vetter, & Blanz, 2001). Also, *the other-race effect* – poorer individuation for other-race individuals than own-race individuals – is often attributed to face-space dimensions being tuned to suit the most frequently observed face type (own-race faces), leading to tight clustering and confusion errors for other-race faces (Valentine, 1991).

Regarding development, a key assumption of most face-space theories is that the dimensions of face-space are determined through experience, and tuning continues throughout life. Theoretically, it has been proposed children might use fewer dimensions than adults, or the same dimensions but differently weighted, or might code discriminations along each dimension less finely, or that the occupation of children's face-space by fewer familiar exemplars might functionally affect face perception (Humphreys & Johnson, 2007; Johnston & Ellis, 1995; Nishimura et al., 2008). Given that face-space dimensions are also argued to respond rapidly to the 'diet' of faces to which one has been exposed (Rhodes et al., 2005), another possible age-related (although not strictly *developmental*) change is that children's face-space could be better tuned for child faces, while adult's face-space could be better tuned for adult faces, presuming there are differences between age groups in relative rate of recent exposure to each face type (Cooper, Geldart, Mondloch, & Maurer, 2006).

A third version of development in face-specific processes is *development in the ability to perceptually encode a novel face*. Carey (1992, p. 95) argued "young children do not form representations of newly encountered faces as efficiently as do adults". Thus, even if children's holistic processing and face-space coding were adult-like early, decrements in young children might show up on the more difficult task of encoding the appearance of a once-seen face (and/or generalising it across viewpoint change, Mondloch, Geldart, Maurer, & Le Grand, 2003).

To summarise, the face-specific perceptual development theory argues that the improvement seen on face tasks between 5 years and adulthood results substantially from changes within the face perception system (although of course it does not rule out additional contributions from general cognitive development). Possible sources of the face perception development could include changes in: aspects of holistic processing; face-space; and perceptual encoding of novel faces.

1.2. General cognitive development theory

The second theory (Carey, 1981; Gilchrist & McKone, 2003; McKone & Boyer, 2006; Mondloch, Maurer, & Ahola, 2006; Pellicano, Rhodes, & Peters, 2006; Want, Pascalis, Coleman, & Blades, 2003) we will refer to as the *general cognitive development theory*. This argues the improvement seen on face tasks after some early age – perhaps 4–5 years, possibly even earlier – is due entirely to the development of general cognitive factors. Depending on the task, such factors might include: memory ability; ability to use deliberate task strategies; ability to concentrate on the task and avoid distractions; ability to narrow the focus of visual attention; ability of early visual processes to make fine discrimination in line alignment (vernier acuity); and general neural processing speed affecting reaction time (e.g., speed of early visual inputs to face recognition areas, speed of motor responses). All these factors are known to improve substantially across childhood, and most improve further into adolescence (Betts, Mckay, Maruff, & Anderson, 2006; Bjorklund & Douglas, 1997; Flavell, 1985; Kail, 1991; Pastò & Burack, 1997; Skoczenski & Norcia, 2002).

Importantly, the *general cognitive development theory* argues that perceptual coding of faces is fully mature early. All the subsequent development on experimental task performance can be explained by development of other factors.

1.3. Evaluating the two theories

There is no doubt that general cognitive factors, other than face perception, can contribute to the improvement with age seen on experimental tests. Consider the following examples. Mondloch and colleagues found weaker development (i.e., younger children's performance was improved) in face discrimination tasks that used simultaneous presentation (Mondloch et al., 2004) as compared to sequential presentation (Mondloch et al., 2002), suggesting a memory contribution to the development seen on the sequential task. Lundy, Jackson, and Haaf (2001) found that children's apparent inability to match identity of faces in the presence of distracting paraphernalia (Diamond & Carey, 1977) disappeared when the faces were simply made larger; this shows that difficulties with narrowing the focus of visual attention, or poorer visual acuity, can contribute to poor performance in children. Finally, sustained attention – that is, concentration under instruction – improves at least until 10 years (Betts et al., 2006). Thus, even in the best designed and most child friendly task, temporary lapses of concentration will almost certainly occur more often in young children than in adults. Lapses will reduce children's accuracy by adding a noise component, even in the absence of any age-related changes in face perception.

The open question is whether, once these general factors are accounted for, there is any development in face perception *per se*. To address this question, researchers need to know first whether there is any *qualitative* change in face perception with age (i.e., whether there is an age below which some core aspect of adult face processing does not exist at all), and also whether there is any *quanti-*

tative change (i.e., whether there is an age below which, although an effect is present, it is not yet fully mature in strength). The face-specific perceptual development theory would be supported by evidence of either qualitative and/or quantitative development of face perception. The general cognitive development theory, in contrast, predicts no change, either qualitatively or quantitatively.

1.4. Qualitative change?

Twenty-five years of research has clearly established there is no *qualitative* change in face perception in the 5 years to adult age range. Almost all face effects present in adults have been tested in developmental studies. In all cases, the relevant effects have been obtained in young children or infants.

With respect to holistic processing, results in 4–6 year-olds include: inversion effects on recognition memory (Brace et al., 2001; Carey, 1981), the composite effect (Carey & Diamond, 1994; de Heering, Houthuys, & Rossion, 2007; Mondloch, Pathman, Maurer, Le Grand, & de Schonen, 2007), the part-whole effect (Pellicano & Rhodes, 2003; Tanaka, Kay, Grinnell, Stansfield, & Szechter, 1998), sensitivity to exact spacing between facial features (McKone & Boyer, 2006; Pellicano et al., 2006) and the advantage for internal over external features in familiar face identification (Wilson, Blades, & Pascalis, 2007). Infants demonstrate inversion effects (Turati, Sangrigoli, Ruel, & de Schonen, 2004; Turati et al., 2006), a composite-like effect (Cohen & Cashon, 2001) and sensitivity to exact spacing between features even within the natural range of variability (Hayden, Bhatt, Reed, Corbly, & Joseph, 2007).

Regarding face-space coding, findings include distinctiveness effects (4 year-olds McKone & Boyer, 2006), attractiveness effects for upright but not inverted faces (<1-week-old Slater, Quinn, Hayes, & Brown, 2000), caricature effects (4–6 year-olds Ellis, 1992; 6 year-olds Chang, Levine, & Benson, 2002), the other-race effect (9 month-olds Kelly et al., 2007; 3 year-olds Sangrigoli & de Schonen, 2004), and adaptation aftereffects at 8 years (the youngest age group tested, Nishimura et al., 2008).

Finally, young children can encode a novel face into memory after a single learning trial. They can perform above chance on sequential matching of faces for same view images (3 year-olds Sangrigoli & de Schonen, 2004) and view-changed images (6 year-olds Mondloch et al., 2003), and also at longer delays (e.g., 4 year-olds Carey, 1981). Infants tested following several learning exposures show coding of novel faces, both within- and across-views, even when tested as newborns (Turati et al., 2006, 2008).

1.5. Quantitative change?

Given this evidence that all core adult-like face processing effects are *qualitatively* present at an early age, to decide between the two theories we therefore need to know if there is any *quantitative* change in face-specific processing with age. This is a substantially more difficult question to address, and is the topic of the bulk of this article.

Five specific approaches relevant to testing for quantitative change can be identified in the literature. The first three focus on the 'special' aspect of processing faces – namely, holistic processing as found for faces and not other objects. These approaches include: (a) tracking across age the size of holistic processing effects (e.g., inversion, composite); (b) comparing the rate of development of recognition memory for faces with that for objects; and (c) comparing holistic processing for faces versus objects in children via the disproportionate inversion effect and tracking any changes in the amount of disproportion with age. The fourth approach (d) tracks the size of face-space effects across age. The final approach (e) tracks the ability to perceptually encode faces using implicit rather than explicit memory tests.

1.5.1. Do standard holistic processing effects increase quantitatively with age?

A common approach has been to chart the size of standard holistic processing effects (inversion effect, composite effect, etc) across childhood, the argument being that if holistic processing is strengthening with age then effects will increase in size. Many studies have found that effects do increase significantly with age (e.g., Carey & Diamond, 1977; Carey et al., 1980; Mondloch et al., 2002; Sangrigoli & de Schonen, 2004), leading the authors of these papers and many other researchers (e.g., Aylward et al., 2005; Cohen Kadosh & Johnson, 2007) to support the face-specific perceptual development theory. However, almost all relevant studies suffer from a logical problem which arises when comparing the size of effects across age groups when overall performance levels also change with age, meaning effects are being calculated with respect to different baselines.

To illustrate the logical issue that arises with baseline differences, particularly when floor and ceiling effects are present, we present results in Fig. 1 from a wide range of studies that contained different patterns of baseline performance changes with age. Note that in these studies, the trends apparent regarding size of holistic processing effect were not always significant (we were unable to restrict our review to significant effects because many studies did not report the age × condition interaction for the particular part of their design we have illustrated), and we later discuss which actual *conclusion* should be favoured regarding development of inversion, part-whole, composite and so on. For the moment, however, we wish merely to raise the methodological issue.

In the most common situation, accuracy in a baseline 'comparator' condition (e.g., upright, in an inversion study) improves with age and there are restriction of range problems in the youngest age group (performance approaches floor) but not in the older groups (performance well away from ceiling). As illustrated in Fig. 1A, this situation seems always to produce results in which the face perception effect of interest is numerically larger in older participants than in younger participants (e.g., inversion effect: Carey & Diamond, 1977; Carey et al., 1980; Sangrigoli & de Schonen, 2004; part-whole effect: Pellicano & Rhodes, 2003; Tanaka et al., 1998). Where such changes have been significant, researchers have then claimed evidence of develop-

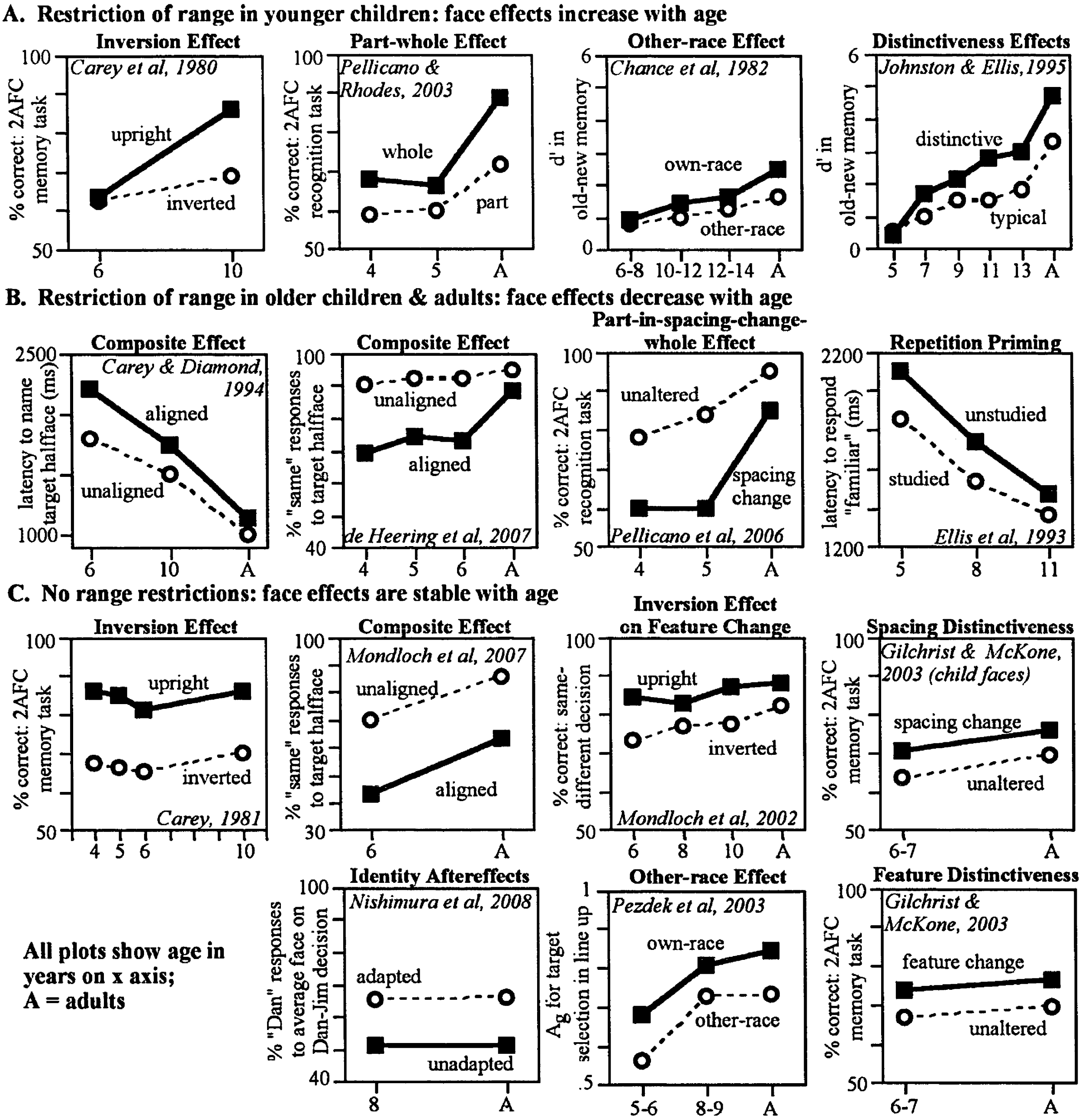


Fig. 1. Results of previous studies tracking across age the size of face effects related to holistic processing (inversion, composite, part-whole, spacing), face-space (distinctiveness, other-race, identity aftereffect), and face encoding (repetition priming). (A) Representative sample of a large number of studies which suffer restriction of range in younger age groups, but not older age groups. Superimposed on the overall developmental improvement in task performance, these studies find trends in which face effects (e.g., strength of holistic processing) apparently *increase* with age. (B) Studies with restriction of range in older groups but not younger groups. Results show trends in which face effects apparently *decrease* with age. (C) Complete set of studies where range is not restricted in either younger or older groups. Results suggest *no quantitative change* with age. *Notes*: (1) We defined potential for restriction of range as the average of the two conditions tested falling in the lower or upper quartile of the 50–100% scale range for 2AFC tasks (i.e., approximately $\leqslant 63\%$ or $\geqslant 87\%$), or $d' < .85$; for reaction times measures, where maximum and minimum cannot be not known, we rely on the general observation that differences between conditions are usually smaller when mean reaction time is faster (note: the two RT studies shown did not report *SEMs*). (2) The reason why some studies in part C show no overall improvement in performance with age is that methods deliberately took out this effect (e.g., by using smaller learning set sizes in younger groups). (3) This is an expanded version of a previously published figure (McKone, Crookes, & Kanwisher, 2009, Fig. 3).

ment in face perception. However, rather than reflecting development of holistic face processing, these results could reflect merely less room to show the effect in younger children.

This hypothesis is supported by the few published studies (some of which are illustrated in Fig. 1B) where room to show effects was restricted in adults rather than in children. In the part-whole paradigm, Pellicano et al. (2006)

found part-whole and part-in-spacing-altered-whole effects were numerically (but not significantly) larger in 4–5 year-olds than adults, in a study in which accuracy approached ceiling for adults. In Carey and Diamond (1994), the composite effect (aligned–unaligned difference) was *larger* in 6-year-olds than in adults; this study used reaction time as the response measure and, with reaction times, it is commonly found that effects tend to be smaller when responses are faster overall (as occurs in adults). De Heering et al. (2007) also showed a larger composite effect in 4-, 5- and 6-year-olds than in adults; they used an accuracy measure with task difficulty designed to suit the children, leading to performance for adults being close to ceiling. Similarly, Macchi Cassia, Picozzi, Kuefner, Bricolo, and Turati (2009) found a composite effect that was larger in 5-year-olds than in adults, significantly so on reaction times, and approaching significance on accuracy, which was very near ceiling in adults. Note that if we followed the standard logic commonly applied to developmental face studies, these results could be taken to indicate that holistic face processing ability consistently *declines* across childhood! This is a conclusion that researchers have been rightly hesitant to draw.

One way to avoid these problems of interpretation is to equate performance in some comparator condition across age groups. Two studies have taken this approach (see Fig. 1C). In each case, the measure was recognition memory accuracy, and comparator condition levels of performance were equated across age groups by having younger children learn the items in smaller sets than older participants. Both studies show the same pattern: the inversion effect (Carey, 1981) and the enhancements of memory from spacing-change increases in distinctiveness (Gilchrist & McKone, 2003) are the same size in young children as in adults. There are two further studies in which comparator condition performance was not deliberately equated but, instead, limits on the potential range of response were avoided because scores were simultaneously away from floor in children and from ceiling in adults. Mondloch et al. (2007) found the size of the composite effect was the same in 6-year-olds as in adults. Mondloch et al. (2002) found the size of the inversion effect (on discrimination of feature changes) was stable between 6 years and adulthood.

So, what is the correct conclusion to be drawn from these various studies? We suggest results are more consistent with early maturity of holistic processing than with ongoing development. Our first point is that, to our knowledge, no studies have shown a significant increase in a holistic processing effect (inversion, spacing sensitivity, etc) with age *except* where this can be potentially accounted for by restriction of range in the youngest age groups. Second, results of the part-whole procedure strongly argue for no age-related change: of three relevant studies, two had (mild) range restriction in the youngest *children* and the third had range restriction in *adults*, yet all showed the same results, with no significant change in part-whole effect with age (Pellicano & Rhodes, 2003; Pellicano et al., 2006; Tanaka et al., 1998). Third, the four studies in which baselines were matched (Carey, 1981; Gilchrist & McKone, 2003), or restriction of range problems were otherwise avoided (Mondloch et al., 2007; inversion effect for feature changes in Mondloch et al., 2002), all appear to use the most suitable methodology, and all indicate no change in holistic processing with age.

A final, rather different, approach to holistic processing has compared the development for spacing changes (e.g., different distance between the eyes) versus local feature changes (e.g., different eyes), based on the (controversial) theory that only spacing changes tap holistic processing and feature changes do not. Results from three studies using this procedure (Freire & Lee, 2001; Mondloch et al., 2002; Mondloch et al., 2004) obtained slower development for detection of spacing changes than for detection of feature changes, a finding the authors interpreted as evidence of a specific delay in the development of holistic processing, independent of task-general limitations. Unfortunately, however, in all cases the feature changes were not difficulty-matched to the spacing changes. For adults, the feature task was easier, leaving the results open to the interpretation that performance in an easier task simply matured earlier than performance in a more difficult task. When McKone and Boyer (2006) equated spacing and feature changes for effects on perception in adults, 4–5 year-olds were equally sensitive to both change types, indicating no specific deficit in spacing sensitivity.[1]

Overall, we suggest current evidence favours the view that holistic processing does *not* develop quantitatively with age. Crucially, application of the common logic that size of effects can be interpreted directly while ignoring baseline changes with age leads to one conclusion – that holistic processing improves with age – in studies in which range of response is restricted in young children, but to the opposite conclusion – that holistic processing can *worsen* with age – in studies in which range of response is restricted in adults. It is clear, therefore, that such methodology cannot be suitable for valid quantitative comparison across age groups.

We note, however, that there is still a need for further research. Mondloch et al.'s (2007) study stands alone as the only test to avoid range-restriction problems while both using a task widely accepted by all researchers as assessing holistic processing (inversion effects on feature changes would be argued by some not to tap holistic processing) and using exactly the same procedure for children and adults. Carey (1981) and Gilchrist and McKone (2003) extend the range of holistic processing measures tested; however, the interpretation of these studies as supporting early quantitative maturity of holistic processing rests on the assumption that altering learning set sizes across age groups does not alter the reliance of face encoding on holistic processing.[2] At present, there is no direct evidence this assumption is valid, and it may be that it is not, particularly if set sizes become extremely small (e.g., focussing on

---

[1] The preschoolers' performance on spacing changes was relatively poor (also see Mondloch & Thomson, 2008) but this finding alone does not distinguish between poor holistic processing and poor general cognitive abilities.

[2] We thank Susan Carey and Daphne Maurer for drawing our attention to the fact that set size might be an important variable.

a single local feature could perhaps become a viable learning strategy[3]).

1.5.2. Does rate of memory development differ for faces and objects?

Want et al. (2003) argued that, without a comparison object stimulus, it is impossible to know how much of children's development in face memory is due to general cognitive development and how much is due to face-specific factors. When both faces and objects are tested, our two theories – face-specific perceptual development, or general cognitive development – make opposite predictions. Development of 'special' holistic processing for faces predicts memory should improve faster with age for faces than for objects. Purely general cognitive development would be indicated by equal rates of improvement across age.

Only a few studies have compared face and object memory development. Carey and Diamond (1977) found memory for faces improved between 6 and 10 years, whereas memory for houses was stable. Likewise, Golarai et al. (2007) found face memory improved between childhood (7–11 years) and adolescence (12–16 years) and again between adolescence and adulthood, while memory for places (indoor and outdoor scenes) also improved but at a lesser rate, and memory for objects (abstract sculptures) remained stable, suggesting special development for faces. In contrast, Aylward et al. (2005) found no change in memory performance for faces or houses between younger children (8–10 years) and older children (12–14 years); this suggests no special development for faces.[4]

Overall, the findings from these studies are mixed, with two apparently favouring the face-specific perceptual development theory, and one apparently favouring the general cognitive development theory. The more important problem, however, is that all of these studies suffer from a potential problem with their selection of a comparison stimulus. Faces, as a stimulus class, share a first-order configuration; that is, features are always arranged the same way: two eyes above a nose above a mouth. In contrast, houses do not share a first-order configuration, and nor do scenes or sculptures. Another difference is that, due to their genetic variability, faces vary on a very large number of dimensions. Man-made objects, in contrast, vary on a smaller number of dimensions which can make a strategy based on single features (e.g., focussing on window shape) very effective. Because deliberate strategy use changes with age, development of general cognitive abilities might thus affect faces and man-made object classes differently.

We argue that, to meaningfully compare developmental trajectories of recognition memory, the object class should be matched to faces on key variables. At a minimum, all exemplars within the object class should share first-order configuration. Ideally, the stimuli should also be natural objects, vary genetically, and not be unusually likely to encourage strategic, single feature based discrimination (e.g., there would be little value in using poodles with wildly different haircuts).

1.5.3. Does disproportion in the inversion effect for faces versus objects increase with age?

The third approach combines a test of holistic processing with a comparison of faces versus objects. For adults, the inversion effect on memory is much larger for faces than for objects. While many studies have now shown that children display an inversion effect for faces (e.g., Brace et al., 2001; Carey, 1981; Flin, 1985; Sangrigoli & de Schonen, 2004) only three studies have compared the size of the inversion effect for faces with that for nonface objects. Such a comparison is necessary to be able to say if the inversion effect for faces is in fact disproportionately large (and therefore even qualitatively adult-like).

The three studies demonstrate 9–10 year-olds show the qualitatively adult pattern, specifically a larger inversion effect for faces than houses (Aylward et al., 2005; Carey & Diamond, 1977) and shoes (Teunisse & de Gelder, 2003). Only one study also tested younger children (Carey & Diamond, 1977), finding evidence suggesting a disproportionate inversion effect in 8-year-olds but not 6-year-olds.

Turning to quantitative change, the question is whether disproportion in the inversion effect for faces (defined as *inversion effect for faces* minus *inversion effect for objects*) increases with age. Carey and Diamond (1977) reported a significant increase in disproportion between 6 and 10 years, suggesting development of holistic processing. The two studies that have tested 9–10 year-olds and an older group (12–14 year-olds Aylward et al., 2005; adults Teunisse & de Gelder, 2003) did not report statistical analyses comparing across the age groups. Aylward et al. (2005) appear to find increasing disproportion with age, again supporting the face-specific perceptual development theory, although this finding was entirely the result of an unusual pattern in which reversal of the inversion effect for houses (better with inverted than upright houses) is present in the older but not younger children. Teunisse and de Gelder (2003) appear to find no change in disproportion between 9–10 year-olds and adults, supporting the general cognitive development theory, although ceiling effects for the objects in both age groups mean this conclusion may be unreliable.

Overall, evidence is again mixed, and in two cases open to basic questions regarding its validity. Also, the comparison stimuli (houses and shoes) were not well matched to faces. Finally, baseline matching is also an important consideration here. To fairly compare the size of the inversion effects for faces and objects across age, performance in a comparator condition (e.g., accuracy in the inverted condition) needs to be matched both *across age* and *across stimulus class*. In the only study to test children younger than 9–10 years, this was not done (Carey & Diamond, 1977).

1.5.4. Do face-space effects increase quantitatively with age?

Quantitative comparison across age groups has been attempted for several face-space phenomena. Interpretation

---

[3] Although note that this would predict *weak* inversion and spacing effects in young children, which was not the pattern obtained.

[4] Two additional studies testing faces versus motorbikes (Kylliäinen, Braeutigam, Hietanen, Swithenby, & Bailey, 2006) and shoes (Teunisse & de Gelder, 2003) are not discussed here because scores approached ceiling in all ages and stimulus classes.

of results often suffers from the same issues regarding restriction of range as raised with respect to holistic processing.

For distinctiveness effects, Johnston and Ellis (1995) found the memory advantage for distinctive compared to typical faces increased between 5 years and adulthood, but range was restricted by proximity to floor in young children and not in adults (Fig. 1A). In the same article, reaction times in face–nonface decision suggested relative restriction of range in *adults*, and correspondingly a tendency was found towards *smaller* distinctiveness effects in adults than young children. Gilchrist and McKone (2003) equated baselines across age groups and found distinctiveness effects (deriving from both spacing and feature changes) were as large in 6–7 year-olds as in adults (Fig. 1C; although again note this study involved altering learning set size across age groups). In a task requiring subjects to choose the most distinctive face of a pair, where pairs varied in strength of distinctiveness difference (determined from adult ratings), McKone and Boyer (2006) found quite a high correlation between the proportion of 4–5 year-olds choosing the higher-rated face for particular pairs and the proportion of adults making the same choice; this argues *ordering* of perceived distinctiveness of *individual* faces is similar between children and adults.

For the other-race effect, Chance, Turner, and Goldstein (1982) found the memory advantage for own-race compared to other-race faces increased between 6–8 years and adults; however, performance was poor in the youngest group (Fig. 1A; also see Sangrigoli & de Schonen, 2004, between 3 and 5 years). When restriction of range was less of a problem, Pezdek, Blandon-Gitlin, and Moore (2003) found the other-race effect was as large in 5–6 year-olds as in adults (Fig. 1C). Corenblum and Meissner (2006) also state they found (means and statistics were not reported) no age-related change in strength of the other-race effect for 9-year-olds versus adults.

For the caricature effect, Chang et al. (2002) found sensitivity to caricatures increased across 6-, 8-, 10-year-olds and adults, but accuracy was at chance in 6-year-olds. However, a second experiment, testing reaction times to name caricatures versus anti-caricatures, found equal-sized caricature effects in all age groups.

Finally, in the Leopold et al. (2001) identity-adaptation procedure, Nishimura et al. (2008) found the adaptation aftereffect – the shift in perception of the average face as measured by the increase in 'Dan' responses on a Dan/Jim decision following adaptation to 'anti-Dan' – to be equal in size in 8-year-olds (the youngest age group tested) and adults (Fig. 1C). Note that this procedure avoids restriction of range problems in that '% Dan' scores in the baseline unadapted condition are expected to be 50% for both children and adults.

Overall, we conclude there is no reliable evidence of quantitative development in face-space effects with age. All apparent evidence in favour of such development can be attributed to restriction of range problems in the younger age groups. There have been relatively few studies that have avoided these problems, but those that do favour the general cognitive development theory.

1.5.5. *Implicit memory for faces*

The fifth approach to the question of quantitative development of face-specific processing has been to use implicit memory tasks – repetition priming – to test the ability to perceptually encode faces. Unlike explicit memory tasks (e.g., old–new recognition memory), which assess conscious recollection, implicit memory is not affected by deliberate memory strategies. Disruption of strategy use by moderate divisions of attention at encoding affect explicit but not implicit memory (e.g., Murphy, McKone, & Slee, 2003; Parkin, Reid, & Russo, 1990[5]). Correspondingly, research in other domains has demonstrated that implicit measures can reveal strong encoding of material for which explicit memory tests would have suggested encoding was poor or absent (e.g., in classic amnesia, Cermak, Talbot, Chandler, & Wolbarst, 1985; in Attention Deficit/Hyperactivity Disorder, Aloisi, McKone, & Heubeck, 2004). Thus, potentially, children might reveal levels of face encoding ability closer to those of adults when assessed with implicit rather than explicit retrieval tests.

Only one previous study has examined development of implicit memory for faces. Results do not differentiate between our theories. Ellis, Ellis, and Hosie (1993) measured reaction time in familiar–unfamiliar decision. Priming for recently-studied classmate faces compared to unstudied classmate faces was largest in 5-year-olds, smaller in 8-year-olds and smaller again in 11-year-olds and adults, but this apparent *decrease* in perceptual encoding ability for faces with age was superimposed on a strong overall change in reaction times with age that produced potential restriction of range in older age groups (Fig. 1B). It is thus impossible to know from this study whether face encoding ability decreased with age, remained stable, or even whether range restrictions might have masked an increase with age. Also note the study tested encoding of *familiar* faces (classmates) only, not ability to encode novel faces.

1.6. *Evaluation of previous literature*

Regarding *quantitative development*, our review has shown that, although there are a large number of studies tracking performance on face tasks in the 5 years to adult range, the interpretation of the great majority of findings is limited by recurring methodological issues. The few studies that do not suffer these problems suggest a conclusion we suspect will be surprising to many readers. This is that face perception itself is mature in early childhood, and that all subsequent improvements in task performance (e.g., as seen in increasing overall accuracy and decreasing overall reaction time in Fig. 1A and B) can be attributed to general cognitive factors. In supporting this conclusion, we have argued that particular attention should be paid to the results illustrated in Fig. 1C. Strikingly, all seven findings suggest the same conclusion. Whether it is with respect to the composite effect, spacing changes, inversion effects, distinctiveness effects, the other-race effect, or adaptation aftereffects, all studies using methodology suitable for

---

[5] Note even implicit memory can be affected if division of attention is so severe that the stimulus cannot be perceived properly (Mulligan, Duke, & Cooper, 2007).

quantitative comparison across age groups suggest *no* change in the size of face perception effects with age.

1.7. Three new experiments

So, why does performance on face tasks reach adult levels so late in development? Is it due to late maturity in face-specific perceptual processes? Or merely to late maturity of general cognitive factors that affect performance on face tasks? We now present three new experiments, designed to more compellingly differentiate between these two theories, which avoid the methodological problems of previous studies identified in our review.

Between them, our experiments, (a) provide converging evidence from three quite different techniques, (b) address the validity of two potentially key studies (Carey, 1981, and Gilchrist & McKone, 2003) by testing whether changing learning set size alters reliance on holistic processing, (c) assess development of holistic processing, using measures (inversion effects, and faces versus objects) that combine all putative subtypes of such processing; (d) provide the first assessment of childhood development in the perceptual ability to encode novel faces; and (e) provide some data relevant to development of face-space aspects of face perception. Throughout, the age range of interest is from early childhood to adulthood, and the youngest group of children tested (5–6 years in two experiments, 7 years in the other) was selected because pilot testing revealed these were the youngest children who could both reliably understand the task instructions and perform sufficiently above floor level to avoid restriction of range issues.

The first two experiments address developmental change in holistic processing. Experiment 1 compared rate of development of recognition memory for faces with that for objects. Improvements on previous methodology included providing the first test using an object class appropriately matched to faces (Labrador dogs), and selecting stimuli to match face and dog performance in 5–6 year-olds, so that developmental trends beyond this age could be fairly compared. Experiment 2 examined size of inversion effect for faces versus Labradors. This experiment provided the first test of whether children show a disproportionate inversion effect for faces compared to a well-matched object class, and compared the size of the disproportion in 7-year-olds to that in two groups of adults: one to whom the children's overall performance levels had been matched by manipulating learning set size; and the other for whom there was no variation in set size.

Experiment 3 tested development of implicit versus explicit memory for faces. This provides the first test of children's perceptual ability to encode once-seen novel faces. Our experiment avoided restriction of range problems by equating 'baseline' performance (i.e., for unstudied faces) across age groups; note the method used to do this did not alter the *encoding* phase in any way, but adjusted only the difficulty of the task used during the subsequent test phase. Experiment 3 also provided data relevant to the development of children's face-space, by including a manipulation of the age of the face and testing for own-age advantages in explicit versus implicit memory.

2. Experiment 1 – development of recognition memory for faces versus Labrador dogs

In adults, faces receive both holistic and part-based processing, while objects are not processed holistically and receive only part-based processing. The lack of holistic processing for objects has been demonstrated specifically for the class of Labrador dogs. Robbins and McKone (2007) found that Labradors (see example stimuli in Fig. 2) produce: much smaller inversion effects than do faces on recognition memory; no inversion effect at all on simultaneous same-different pair discrimination; and, most directly, no composite effect (in a method that produced a clear composite effect for faces). In adults, the holistic processing for faces is widely presumed to contribute positively to memory for faces, explaining, for example, why it is that when face and Labrador stimuli are matched for discriminability in the inverted orientation, memory in the upright orientation is much better for faces than for dogs (Robbins & McKone, 2007). The logic underlying Experiment 1, therefore, is that if there is late ongoing development in the strength of holistic processing then the developmental trend on a memory task should be steeper for faces than dogs.

Methodologically, Labradors are a class which, like faces, share a first-order configuration (head at one end, tail at the other and four legs underneath) and vary genetically on a large number of dimensions. We also pilot tested to select stimuli that produced matched performance for faces and dogs in the youngest age group tested (5–6 year-olds). This allows fair comparison of rates of development across the three older groups. Experiment 1 tested only upright stimuli, so matching was performed in the upright orientation.

Predictions were as follows. If holistic processing is stronger in adults than in children (i.e., the face-specific perceptual development theory), then developmental curves should diverge after 5–6 years, with a steeper increase across age for faces than for dogs. Importantly, this same prediction arises if *any* putative subcomponent of holistic processing – such as spacing sensitivity (Mondloch et al., 2002) or a 'mystery factor' (Carey & Diamond, 1994) – develops with age. Alternatively, if holistic processing is quantitatively mature in young children (i.e., the general cognitive development theory), memory for faces should improve with age at the same rate as memory for dogs. Importantly if this pattern is obtained, it would demonstrate that *no* putative subcomponent of holistic processing improves with age.[6]

2.1. Method

2.1.1. Participants

Eighty-five participants comprised nineteen 5–6 year-olds (mean 5.97 years; range 5.0–7.0; 5 male), twenty-two 7–8 year-olds (mean 8.42 years; range 7.5–9.0; 10 male), twenty 9–10 year-olds (mean 9.89 years; range

---

[6] Meaning that it is then not necessary to test each subcomponent separately.

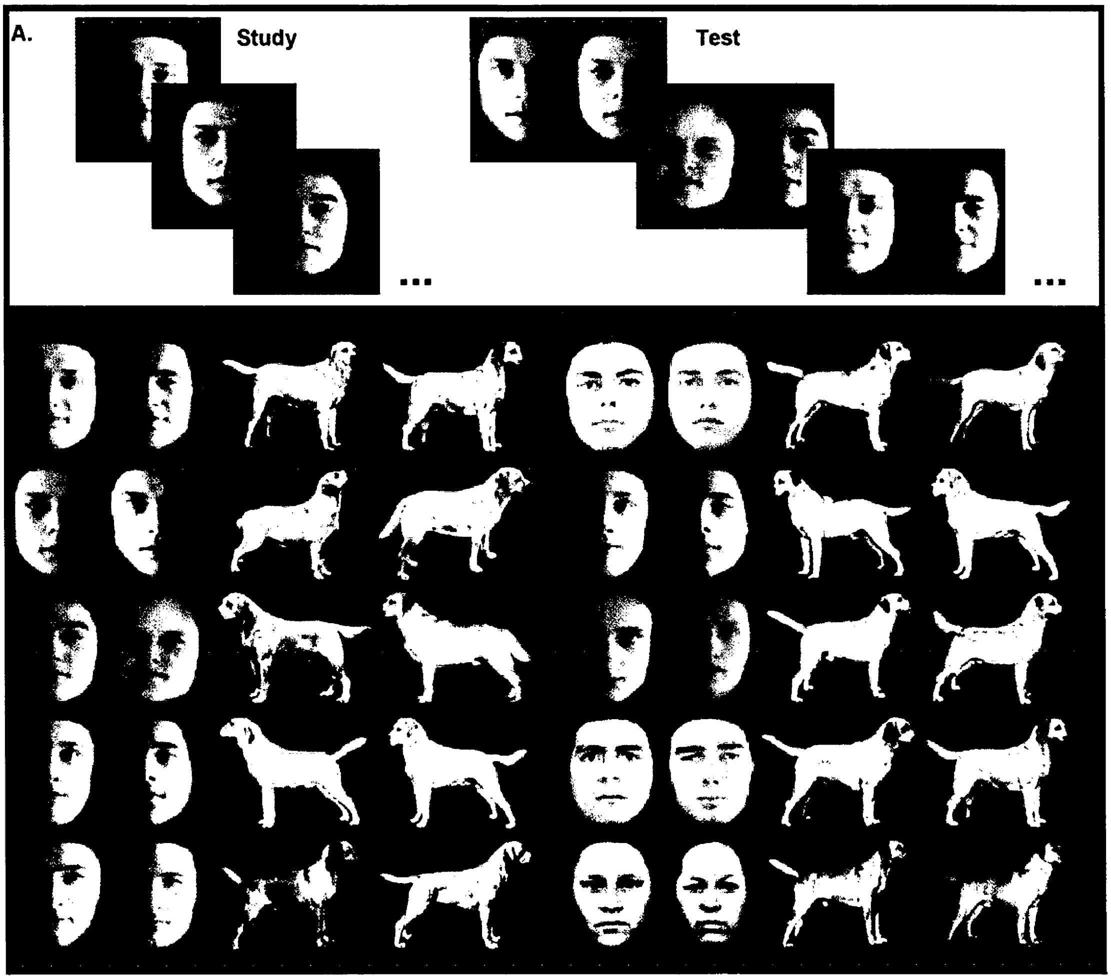


Fig. 2. (A) Procedure for Experiments 1 and 2. In a given block, participants learned 5 faces (or dogs), and later did a recognition memory test on 5 pairs (each showing one old and one new item). (B) Stimulus pairs from a sample block in Experiment 1, where *upright* memory performance was matched across faces and dogs. (C) Stimulus pairs from a sample block in Experiment 2 where, this time, *inverted* memory performance was matched across faces and dogs. Note, to match performance inverted, the physical similarity between the two items of each pair (e.g., lighting, exact stance/outline, and shape of particular parts) appears closely matched between faces and dogs. To match performance upright, in contrast, it was necessary to make the faces *more* physically similar (across the block) than in Experiment 2, and the dogs *less* physically similar (both across the block and within each pair).

9.1–10.8; 7 male); and twenty-four adults (mean 22.96 years; range 18.5–38.6; 10 male). Children were accessed through holiday programs and schools in middle-class districts in Canberra. Parental consent was obtained. Adults were members of the Australian National University (ANU) community paid $3 for the 15 min experiment. All participants were Caucasian (the same race as the face stimuli).

2.1.2. Design

The task was two alternative forced choice (2AFC) recognition memory (see Fig. 2). Stimulus class (faces versus dogs) was manipulated within-subjects. There were 4 study-test cycles: 2 of faces, 2 of dogs. In each, the study phase presented 5 items, followed by a test phase with 5 pairs. Each test pair comprised one item seen during the study phase (old) and one unstudied item (new). Subjects chose the old item, guessing if necessary. The dependent measure was accuracy. Chance is 50%.

2.1.3. Materials

Stimuli were canonical-view greyscale photographs of faces and yellow Labradors. Specific stimuli were a subset of faces and dogs used by Robbins and McKone (2007) Experiment 1, presented against a uniform grey background. Dogs (Fig. 2B) were 20 side-view photographs of male and female Labradors. Lack of holistic processing applies to these particular images (Robbins & McKone, 2007). Dogs were 4.9–5.9 cm from nose to tail (average 5.7 cm) by 3.7–4.4 cm from head to paws (average 4.1 cm) corresponding to 9.3° horizontal by 6.7° vertical at the viewing distance of 35 cm. Faces (Fig. 2B) were 20 front view photographs of Caucasian males all from the University of Ljubljana CVL and CV, PTER, Velenje database (http://lrv.fri.uni-lj.si/facedb.html). Faces had neutral expression, no facial hair or glasses, and any distinguishing features removed (e.g., birthmarks). They excluded hair and ears but retained chin and cheeks so each face had a different outline shape (like the dogs). Face were 3.1–3.8 cm at the widest point (average 3.4 cm) by 4.2–4.6 cm at the tallest point (average 4.4 cm), corresponding to 5.6° by 7.3°.

Stimuli were organised into 10 pairs of faces (i.e., enough for two blocks) and 10 pairs of dogs. Within each pair, one item was assigned to the studied condition for half the participants while the other remained unstudied, counterbalanced across participants. Processing of all regions of the faces/dogs was encouraged by the fact that, with blocks comprising 5 study items and 10 test items, no single feature (e.g., tail position) or photographic feature (e.g., contrast) of a particular photograph was unique in the set (see Fig. 2B). The particular pairings of old–new items, and the pairs included in each block, were selected based on pilot testing to give class matching and appropriate accuracy (approximately 65%) in 5–6 year-olds.

2.1.4. Procedure

2.1.4.1. General. Stimuli were presented on an iMac computer using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993). Participants were tested individually. For adults, trials began automatically following completion of the previous trial. Adults entered their own responses via the keyboard. For children, the experimenter controlled stimulus presentation; stimuli were displayed only when the child was concentrating. Responses were entered by the experimenter, who sat behind the child to avoid biasing responses.

2.1.4.2. Block order. Order of face and dog blocks was face-dog-face-dog or vice versa. Assignment of face (dog) subsets to either the first or second block of that stimulus class was counterbalanced across participants.

2.1.4.3. Practice phase. There was one practice block using the same procedure as the actual task but with very easy stimuli comprising brightly coloured cartoon dinosaurs differing substantially in colour and shape (e.g., after studying a purple stegosaurus, a test pair might comprise the same purple stegosaurus and a green pterosaur). This explained the task to participants, and screened individuals who did not understand the task or showed serious disruptions of concentration. All children scored 100%; one adult was excluded for not achieving 100%, and replaced. Feedback and encouragement were provided to child participants.

2.1.4.4. Study phases. On each trial, a fixation cross appeared for 1000 ms for adults, or until the experimenter judged the child was concentrating for children, followed by the stimulus for 5000 ms. Participants were told to remember the item and rate "how nice each person/dog is" on a three point scale ("nice", "not nice" or "in the middle"). Presentation order of items was randomised for each participant.

2.1.4.5. Test phases. Test followed study after 15 s. On each trial, a fixation cross for 1000 ms for adults, or until concentrating for children, was followed by a stimulus pair shown simultaneously 13.3 cm (21.5°) apart at the same height until response. Adults pressed one key if the left item was "old", another if the right was "old". Child participants pointed to the "old" stimulus. There was no feedback. The old item was on the right 50% of the time. Presentation order was randomised for each participant.

2.1.4.6. Repeat for remaining blocks. A 30 s break followed each test phase. Subjects were given a longer break if required (e.g., children who appeared distracted). The study-test cycle was then repeated for the next block (4 cycles in total).

2.2. Results

Fig. 3 shows recognition memory accuracy as a function of age group, for faces and Labrador dogs. Memory accuracy was matched for faces and dogs in the youngest age group (5–6 year-olds), $t < 1$. Importantly, this matching was obtained in the context of performance in this age group being comfortably as well as significantly above chance for both stimulus classes; faces $M = 64.74\%$, $t(18) = 3.68$, $p < .005$; dogs $M = 64.21\%$, $t(18) = 3.49$, $p < .005$.

Turning to the comparison of rates of development for faces and dogs, a 4 (age group) × 2 (stimulus class) analysis of variance (ANOVA) found a significant main effect of age group, $F(3,81) = 21.93$, $MSE = 217.03$, $p < .001$, but no main effect of stimulus class, $F < 1$, $MSE = 155.69$, and, most importantly, no interaction, $F < 1$, $MSE = 155.69$. This indicates that there was no difference between faces and dogs in the rate at which memory improved with age. Given that ANOVA is not sensitive to the order of the age groups, we also confirmed this conclusion with the more powerful technique of trend analysis. There was no significant interaction between stimulus class and any age trends (linear, quadratic, cubic, all $ps > .4$). Finally, a priori t-tests were used to compare faces and dogs at each age group in turn: these confirmed no differences between stimulus classes; all child group $ts < 1$, adults $t(23) = 1.56$, $p > .1$. The lack of difference between faces and dogs in adults could possibly be attributed to a ceiling effect; crucially, however, face-specific perceptual development theory also predicts faster development for faces than dogs *across the 5–10 year age range* (Carey & Diamond, 1977), where there were no ceiling or floor problems.

We also plotted, for child participants, a scatterplot of exact age versus memory performance for faces (Fig. 4A) and dogs (Fig. 4B). The strength of the correlation between age-in-months and memory was the same for faces ($r = .40$) and dogs ($r = .39$). Moreover, the slopes of the lines of best fit (i.e., the linear trend across age) were the same in both cases (faces = .31%-accuracy improvement per month, dogs = .28%-accuracy improvement per month). This provides further support for the conclusion that memory for dogs develops at the same rate as memory for faces.

2.3. Discussion

Experiment 1 has provided a clear result. There was no indication of any difference in the rate of development for faces compared to dogs beyond 5–6 years. That is, there was no *special* development for faces. Of the three previous studies comparing memory development for faces versus

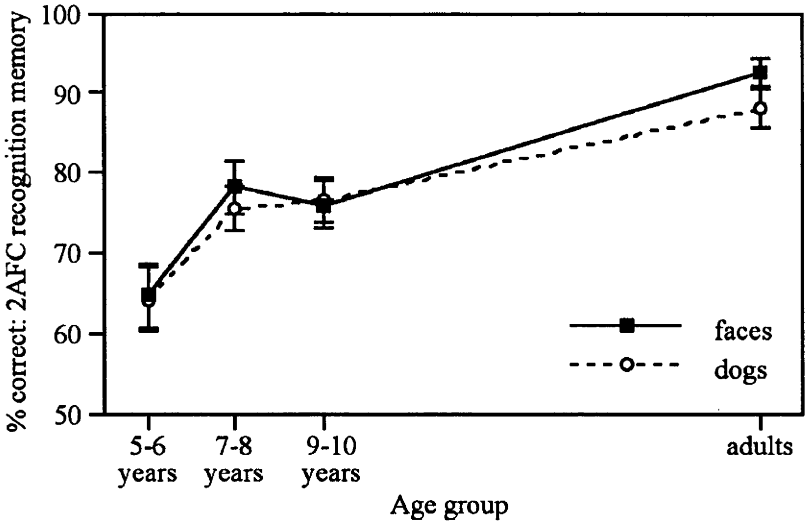


Fig. 3. Experiment 1: recognition memory results for faces versus dogs, showing no difference in rate of development with age. Error bars show ±1 *SEM*.

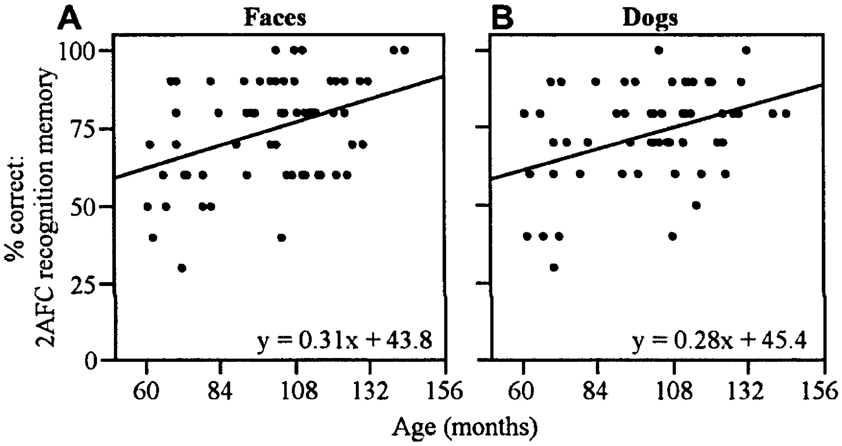


Fig. 4. Experiment 1: recognition memory plotted against exact age in months for child participants. The formula given on each plot is for the line of best fit.

objects, our results agree with one study (Aylward et al., 2005), and conflict with two others (Carey & Diamond, 1977; Golarai et al., 2007), but note ours is the only study to use an object class appropriately matched to faces on stimulus characteristics, and to match performance (comfortably above floor) for faces and objects at the beginning of the age range tested.

Results of Experiment 1 argue against the face-specific perceptual development theory. If an increase in the strength of *any* aspect of holistic processing had occurred between the ages of 5 years and adulthood, then we would have expected memory for faces to improve with age at a faster rate than memory for dogs. This did not occur. Results are, instead, consistent with the general cognitive development theory. The identical rates of improvement for faces and dogs argue the development observed arises from general factors. Given that we used an explicit memory task, two relevant factors are deliberate memory strategy use at encoding and retrieval, and level of interest in and attention to the faces at encoding. An additional factor, relevant to all tasks, is ability to maintain concentration on every trial.[7]

3. Experiment 2 – development of the disproportion in the inversion effect for faces versus Labrador dogs

Experiment 2 approached the differentiation of the two theories by looking at holistic face processing via the disproportionate face inversion effect. The first aim was to examine the qualitative pattern in 7-year-olds; that is, whether this age group shows the adult pattern of a larger

---

[7] An alternative explanation of the equal rate of increase for faces and dogs is that the relatively small learning set size (5 items at a time) produced an unusual reliance on part-based processing for *faces*. This possibility, however, is refuted by results of Experiment 2, which show a large inversion effect for faces, but not dogs, in young children using the same learning procedure.

inversion effect for faces than for Labrador dogs. No previous studies have tested for disproportionate inversion effects in children by comparing faces to a well-matched object class.

The second aim was to perform quantitative comparisons on the *disproportion* in the inversion effect between children and adults. Specifically, the question was whether the amount by which the inversion effect for faces was greater than for dogs (disproportion score = inversion effect for faces – inversion effect for dogs) was any smaller in children than in adults. If holistic processing, or any subtype of holistic processing, strengthens with age (i.e., the face-specific perceptual development theory), then the disproportion score should increase with age. For example, if inversion effects for dogs were similar in size for children and adults, then inversion effects for faces should be larger in adults than children. Or, if inversion effects for dogs increased with age (because *part*-based processing of upright dogs improved with increasing exposure to this orientation, as for dog experts in Robbins & McKone, 2007), then the inversion effect for faces should increase *faster* than the inversion effect for dogs. In contrast, if all aspects of holistic processing are fully mature in young children (i.e., the general cognitive development theory), then (a) 7-year-old children should show a larger inversion effect for faces than dogs, and (b) the size of this disproportion should not change with age.

To test these predictions, we compared 7-year-olds to two groups of adults. Data for a *performance-matched* adult group were taken from Robbins and McKone (2007): these adults had learned the stimulus items in larger sets than the children (15-item sets instead of 5-item sets). We also tested a new group of *procedure-matched* adults, under exactly the same circumstances as the children (i.e., 5-item sets). This group was included to explore effects of learning set size on pattern of inversion effects. We expected this group to perform better than children. However, because there were no restrictions of range issues, this group provided a direct test of whether changing learning set size alters reliance on holistic processing. If we obtain the same results by comparing children to *procedure-matched* adults as we do by comparing children to *performance-matched* adults, this will substantially strengthen our conclusions. A finding of equal disproportion scores in adults with 15-item and 5-item sets would further validate comparison across age groups in the two prior studies that varied set size between children and adults (see Fig. 1C), noting that these studies used reasonably similar set sizes to the present study (10-item for 10-year-olds versus 6-item for 5-year-olds in Carey, 1981; 30-item for adults versus 7- or 8-item for 6–7 year-olds in Gilchrist & McKone, 2003, upright condition).

3.1. Method

3.1.1. Participants – children and procedure-matched adults

The 39 new participants, from pools described in Experiment 1, comprised seventeen 7-year-olds (mean 7.20 years; range 7.1–7.4; 10 male), and twenty-two adults to provide the procedure-matched group (mean 22.91 years; range 18.3–30.7; 11 male). Adults received $5 for the 30 min experiment.

3.1.2. Design – children and procedure-matched adults

Stimulus class (faces, dogs) and orientation (upright, inverted) were varied within-subjects. There were 12 study-test cycles, 3 each of: faces upright; faces inverted; dogs upright; dogs inverted. Study phases showed 5 learning items one at a time. Test phases showed 5 pairs. Subjects chose the old item, guessing if necessary.

The face and dog sets had previously been matched for discriminability in the inverted condition for adult participants (Robbins & McKone, 2007) allowing quantitative comparison of the size of the inversion effect across stimulus type.[8] Pilot testing was used to select presentation conditions such that 7-year-olds' memory performance for both inverted face and dog sets was matched to that of the adults in Robbins and McKone (2007, Experiment 1, data from young adult dog-novices).

3.1.3. Materials – children and procedure-matched adults

The specific items, and pairings of items, were exactly as used by Robbins and McKone (2007, Experiment 1). Faces (Fig. 2C) were 60 front view Caucasian males and females. Dogs (Fig. 2C) were 60 side view male and female yellow Labradors. Here, faces were 3.1–3.8 cm wide (average 3.4 cm) by 4–4.6 cm high (average 4.4 cm), averaging 5.6° horizontal by 7.3° vertical at the experimental viewing distance of 35 cm. Dogs were 4.9–6.0 cm wide (average 5.7 cm) by 3.5–4.6 cm high (average 4.2 cm), averaging 9.3° by 6.9°.

Stimuli were organised into 30 pairs of faces (i.e., enough for three blocks upright and three blocks inverted) and 30 pairs of dogs. For each subject, 15 pairs (i.e., three blocks of 5 pairs) from each stimulus class were assigned to the upright orientation and the other 15 pairs to the inverted orientation, counterbalanced across subjects. Particular pairs were randomly assigned to blocks for each participant. Within each pair, one item was assigned to the studied condition for half the participants while the other remained unstudied, counterbalanced across participants.

3.1.4. Procedure – children and procedure-matched adults

3.1.4.1. General. As in Experiment 1.

3.1.4.2. Condition order. The three blocks of a particular condition (e.g., three blocks of upright faces) were completed consecutively. Four orders of conditions were used: (1) faces upright, faces inverted, dogs upright, dogs inverted; (2) faces inverted, faces upright, dogs inverted, dogs upright; (3) dogs upright, dogs inverted, faces upright, faces inverted; (4) dogs inverted, dogs upright, faces inverted, faces upright.

---

[8] We chose *inverted* as the baseline using the logic that matching in this orientation was the best way to ensure *part*-based similarity within sets was matched. There is no reason to think results would change if we had matched on upright instead. Carey (1981) matched upright faces across ages, and results regarding development of face inversion effects were the same as revealed here in Experiment 2. Further, in adults, the disproportionate inversion effect is obtained regardless of whether faces and objects are matched inverted (Robbins & McKone, 2007) or upright (e.g., faces versus costumes in Yin, 1969).

3.1.4.3. Practice, study and test phases. As in Experiment 1.

3.1.4.4. Repeat for remaining blocks. Following a break of 30 s (or longer if required), the study-test cycle was then repeated for the next block (12 cycles in total). Children were given a long break (at least 20 min) midway through the experiment.

3.1.5. Procedure – performance-matched adults from previous study

Procedure for Robbins and McKone (2007) Experiment 1 was identical to the present except as follows. Each condition (e.g., upright faces) was given as one single block of 15 study stimuli followed by 15 test pairs. The viewing distance was slightly longer (45 cm), making faces 4.3° by 5.6° and dogs 7.2° by 5.3°. At study participants were simply asked to remember the stimuli: there was no encoding question. Between study and test, participants did 1 min of multiplication problems.

3.2. Results

3.2.1. Disproportionate inversion effects within each age group

To validly compare inversion effects across stimulus class, it was important to demonstrate matching for face and dog accuracy, at levels not influenced by floor effects, in the inverted orientation. For the performance-matched adults, this had already been done by Robbins and McKone (2007). For the 7-year-olds, memory for inverted faces and inverted dogs did not differ, $t < 1$, and was at a level comfortably as well as significantly above chance for both stimulus classes: inverted faces $M = 64.31$, $t(16) = 4.58$, $p < .001$; inverted dogs $M = 65.88$, $t(16) = 5.68$, $p < .001$. For the procedure-matched adults, successful matching was also achieved: inverted faces $M = 72.12$, inverted dogs $M = 70.00$, $t < 1$.

The first major finding was that all three groups show a disproportionate inversion effect for faces (Fig. 5). For

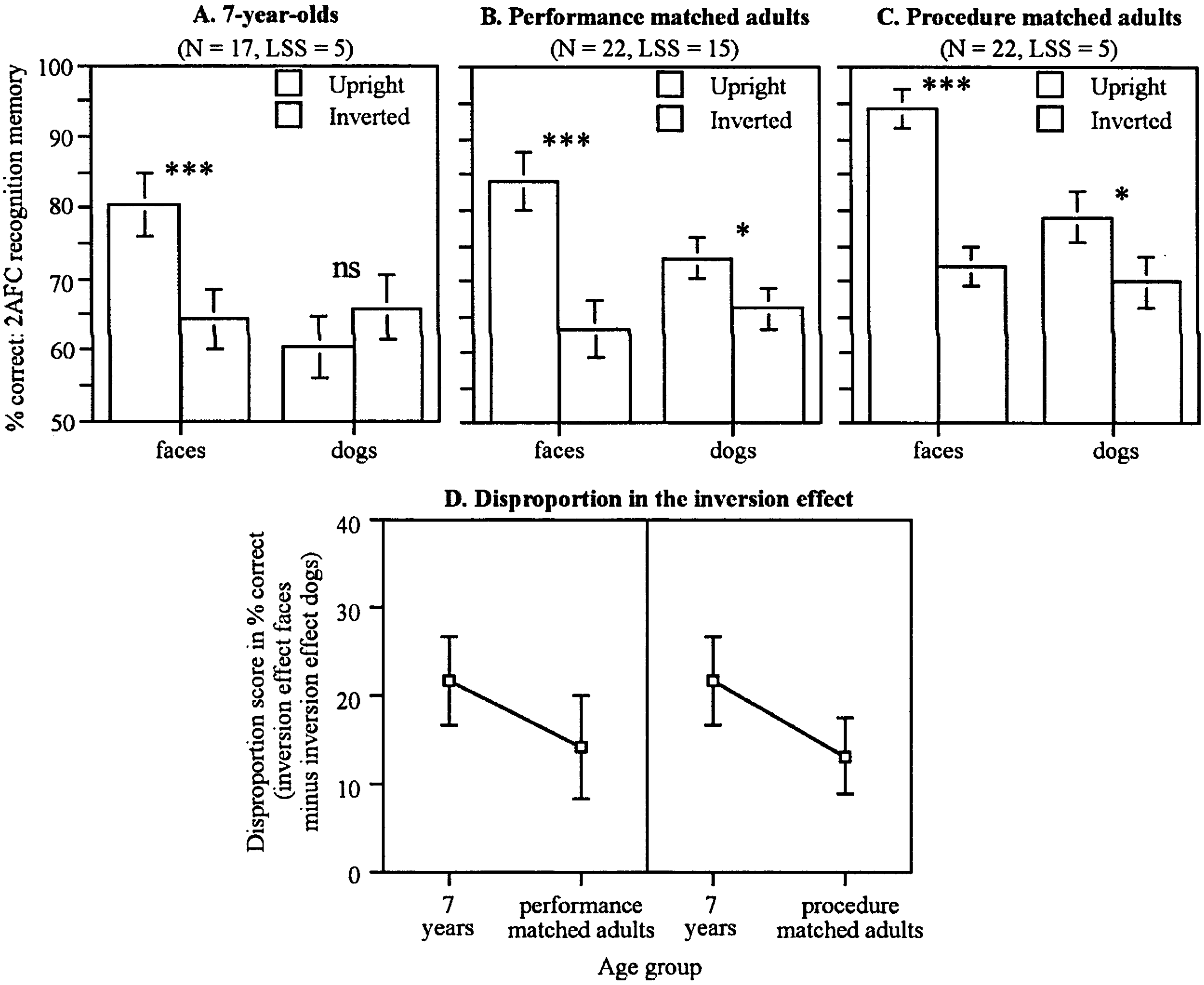


Fig. 5. Experiment 2: (A–C) seven-year-olds show the adult-like pattern of a much larger inversion effect for faces than objects (dogs); moreover, (D) the amount by which the inversion effect is larger for faces than dogs (disproportion measure) does not increase with age. Data for 'performance-matched adults' are from Robbins and McKone (2007, Experiment 1, young-adult dog novices). Error bars in (A–C) are appropriate for the within-subjects comparison of upright versus inverted conditions (i.e., ±1 *SEM* of the upright – inverted difference scores). Error bars in (D) show ±1 *SEM*. $^{***}p < .005$, $^{*}p < .05$, ns $p > .05$. LSS = Learning set size.

7-year-olds (Fig. 5A), the difference between upright and inverted was significant for faces, $t(16) = 3.66$, $p < .005$, but not dogs $t(16) = 1.21$, $p > .2$. A significant interaction between stimulus class and orientation, $F(1,16) = 18.85$, $MSE = 104.89$, $p < .005$, confirmed the inversion effect (upright–inverted) was significantly larger for faces (16.08%) than dogs (−5.49%).

For the performance-matched adults (Fig. 5B), Robbins and McKone (2007) had previously shown the inversion effect was significantly larger for faces than dogs. For the procedure-matched adults (Fig. 5C), stimulus class again interacted significantly with orientation, $F(1,21) = 9.05$, $MSE = 103.15$, $p < .01$, with a larger inversion effect for faces (22.12%) than dogs (9.09%).

3.2.2. Development: seven-year-olds versus performance-matched adult group

Our specific aim in matching child performance to that of the Robbins and McKone (2007) adults was to match on the inverted stimuli. This was successfully accomplished: memory accuracy did not differ for children and adults for either inverted faces (child $M = 64.31$, adult $M = 63.33$, $t < 1$) or inverted dogs (child $M = 65.88$, adult $M = 66.36$, $t < 1$). We also note that an ANOVA comparing the children (Fig. 5A) to the Robbins and McKone (2007) adults (Fig. 5B) across *all* conditions found no main effect of age, $F(1,37) = 3.15$, $MSE = 201.64$, $p > .05$.

Given the successful performance match, we can conduct direct quantitative comparison of the size the disproportion in inversion effects. Crucially, the ANOVA showed no 3-way interaction between stimulus class, orientation and age, $F < 1$, $MSE = 150.93$. That is, age did not influence the extent to which the face inversion effect was larger than the dog inversion effect. This indicates that holistic processing was not weaker in children than in adults. Indeed, the nonsignificant trend was in the reverse direction: calculation of the disproportion score (inversion effect for faces minus inversion effect for dogs, Fig. 5D) indicated a tendency to a larger disproportion in children (21.57%) than adults (13.94%).

We also conducted an a priori test of the size of the inversion effect for faces. This did not change with age (children's face inversion effect = 16.08%, adult's face inversion effect = 20.91%, $t < 1$).

3.2.3. Development: seven-year-olds versus procedure-matched adult group

Given that ceiling effects did not limit range of scores in the procedure-matched adult group (i.e., the average of upright and inverted for faces was only 83.18%; Fig. 5C), it seemed reasonable to perform quantitative comparison of this group to the 7-year-olds. ANOVA again showed no 3-way interaction between stimulus class, orientation and age $F(1,37) = 1.68$, $MSE = 103.90$, $p > .2$, confirming there was no change in the size of the disproportion of the inversion effect with age (Fig. 5D). Again, the trend was in the direction reverse to that predicted by an age-related increase in holistic processing: children's disproportion score = 21.57%, adults' disproportion score = 13.03%. A priori comparison of the size of the inversion effect specifically for faces also showed no age-related change: children's face inversion effect = 16.08%, adults' face inversion effect = 22.12%, $t(37) = 1.22$, $p > .2$.

The ANOVA revealed a significant main effect of age, $F(1,37) = 21.85$, $MSE = 217.02$, $p < .001$, reflecting the fact that adults were more accurate overall than children. This is as would be expected in a memory task when learning set size is the same for both groups.

3.2.4. Effects of changing set size: comparing the two adult groups

To assess whether changes in learning set size influenced pattern of inversion effects in adults, the performance-matched group (set size = 15) was compared to the procedure-matched group (set size = 5). There was no 3-way interaction between stimulus class, orientation and group, $F < 1$, $MSE = 144.58$. The disproportion score was almost exactly the same for the two groups (13.94% performance-matched versus 13.03% procedure-matched). So too was the size of the inversion effect for faces (20.91% performance-matched versus 22.12% procedure-matched). Thus, altering learning set size did not alter the reliance on holistic processing.

3.3. Discussion

Results of Experiment 2 again favour *the general cognitive development theory* of age-related improvement in performance on face tasks. Support for early quantitative maturity is both direct – from our own developmental findings – and indirect, regarding the interpretation of two key previous studies.

Directly, results comparing children to adults showed no evidence of development in the strength of holistic processing between 7 years and adulthood. If there had been quantitative development in holistic processing – or, importantly, in any proposed subtype of holistic processing such as spacing sensitivity (Mondloch et al., 2002) or the 'mystery factor' (Carey & Diamond, 1994) – then we would have predicted that inversion effects for faces, relative to inversion effects for objects, would be smaller in children than in adults. This was not observed. Instead, (a) 7-year-olds showed an inversion effect for faces that was substantially larger than that for dogs, (b) the amount of this disproportion did not change with age, (c) the basic inversion effect for faces did not change with age, and (d) these results held regardless of whether the child group was compared to adults with matched levels of *performance* (i.e., who learned items in larger sets), or to adults tested with a matched *procedure* (given there were no restriction of range issues). Our results thus provide strong support for early perceptual maturity of *all aspects of* holistic processing.

Our results are consistent with one previous study (Teunisse & de Gelder, 2003) and in conflict with two others (Aylward et al., 2005; Carey & Diamond, 1977). Importantly, however, ours is the first study to compare inversion effects for faces with those for a well matched object class (dogs, rather than the man-made classes of houses and shoes). Further, all three previous studies were affected by one or more additional problems, including ceiling effects for the object class, an unexpected reversed inversion effect for objects in older but not younger groups, lack of statistics comparing across age groups, and/or failure to match performance in a comparator condition simultaneously across both age and stimulus class.

The *indirect* support for the general cognitive development theory comes from set size results. Comparison of our two adult groups showed no effect of learning 15 items at a time, versus 5 items at a time, on either inversion effects for faces or the amount by which the inversion effect for faces was disproportionately larger than the inversion effect for dogs. This shows that changing learning set size, at least within a moderate range of set sizes, does not alter the reliance of memory on holistic processing. This finding has important implications for the interpretation of two key previous studies. As shown in Fig. 1C, Carey (1981) showed that sensitivity to face inversion did not change between 4 years and adulthood, and Gilchrist and McKone (2003) showed that sensitivity to spacing changes was as strong in 6–7 year-olds as in adults. However, to equate performance in a comparator condition (upright, or no-spacing-change) across age groups, both studies used larger set sizes in adults than in children, and so interpretation of these results as evidence for early quantitative maturity of holistic processing relies on the assumption that this procedure does not alter the reliance on holistic processing. This assumption has now been tested, and found to hold. Thus, the results of Carey (1981) and Gilchrist and McKone (2003) can now be taken to provide strong support for the general cognitive development theory.

Finally, the *qualitative* similarity in inversion effects between children and adults is relevant to the interpretation of equal rates of development for faces versus dogs in Experiment 1. Present results confirm development does not alter processing strategies for either upright faces (holistic in both children and adults) or upright dogs (part-based in both age groups).

The overall conclusion supported by Experiments 1 and 2, and the previous literature, is that there is no quantitative development beyond the ages of 5–7 years in the *holistic processing* aspect of face perception. Results are consistent with the idea that the overall improvements in task performance for faces reflect late maturity of general cognitive abilities which affect task performance regardless of stimulus category.

At this stage, however, it still remains possible there might be perceptual changes in *face-space*, or in ability to *perceptually encode a novel face*. These issues are addressed in Experiment 3.

4. Experiment 3 – the development of implicit and explicit memory for own- and other-age faces

In common with many previous studies, our Experiments 1 and 2 tested performance on *explicit* memory tasks, namely tasks in which participants are required to consciously recollect whether or not they have seen a particular face before in the experiment. As expected, when all age groups were tested using a common procedure, both experiments showed substantial age-related increases in memory for faces. Importantly, however, this finding does not necessarily show the ability of the *face perception system* to encode a novel face – that is, to add a new exemplar – improves with age. Explicit memory tasks have a rich range of other sources from which development could derive. They are strongly affected by availability of attention to the task, participants' metamemory skills (e.g., knowledge of how much effort must be applied during learning to obtain a suitable test outcome, Flavell & Wellman, 1977), and deliberate top-down strategies during the retention phase ("I saw someone who looked like my friend Bill, so I will rehearse 'Bill Bill Bill' to help me remember") or at retrieval ("Here's a guy who looks like George Bush. I remember there was a guy that looked George Bush in the study phase. But, that guy had a weirdly big nose, and this guy doesn't, so this one must be 'new'."). Adults have substantial advantages over young children in all these abilities.

A more direct way to test ability to perceptually encode faces, independent of general cognitive ability, is to assess encoding with *implicit* memory tests. Such tests measure *repetition priming*, defined as more accurate and/or faster responses to items recently studied than to 'baseline' unstudied items, on tasks that do not require reference to the earlier study phase. For example, repetition priming for (familiar) faces can be measured in a famous–nonfamous decision task as the speed difference between famous faces seen at study and famous faces not seen at study.

As long as researchers avoid "explicit contamination" on the task (i.e., subjects finding and using a strategy by which they can improve their test responses by deliberate reference to information from the study phase; Schacter, Bowers, & Booker, 1989), implicit memory measures provide a very pure method of tapping perceptual encoding. Several sources of evidence support this claim. Removing resources for deliberate strategic processing by dividing attention at study reduces explicit but not implicit memory (e.g., Parkin et al., 1990). Neuroimaging evidence shows repetition priming (reflected as reduced BOLD response in fMRI, or decreased bloodflow in PET) occurs in high-level perceptual processing areas relevant to the stimulus domain – such as the Visual Word Form Area for written words, or the Fusiform Face Area (FFA) for faces – without hippocampal contributions as occur for explicit memory (Pourtois, Schwartz, Seghier, Lazeyras, & Vuilleumier, 2005; Schacter, Alpert, Savage, Rauch, & Albert, 1996). Finally, implicit memory shows patterns of development that directly track the state of the underlying perceptual system. Where strong perceptual knowledge is established in early childhood (spoken words, common objects), implicit memory is at full adult levels at 5–6 years. In contrast, where perceptual knowledge begins and matures much later (written words), implicit memory continues to increase into late childhood (Carlesimo, Vicari, Albertoni, Turriziani, & Caltagirone, 2000; Murphy et al., 2003).

In Experiment 3, we provide the first investigation of development of implicit memory for novel faces. If the ability of the face perception system to add a new face develops between 5 years and adulthood, repetition priming will increase in size with age. (Also note the developmental trend should be less steep for the implicit version than for an explicit memory version of the task, given that additional factors contribute to explicit memory development.) Alternatively, if there is no development of perceptual face encoding ability and all age-related improvement on the explicit memory version of the task can be attributed to *general cognitive development*, then repetition priming should be as strong in young children as in adults.

We also included a face-age manipulation (child versus adult). This allowed us to test for age-related changes in face-space coding, by contrasting a possible own-age advantage across explicit and implicit memory tasks. In everyday life, children see more children's faces than adults' faces (at least at school), while our adults would be expected to see many more adults' faces than children's faces. If face-space better codes the type of faces seen most often (Rhodes et al., 2005), then any own-age advantage (e.g., children showing better memory for child faces than adult faces) found in explicit memory should also be found when perceptual encoding is assessed directly via implicit memory. Alternatively, if any own-age advantage on the explicit memory task is attributable merely to increased social interest in peers leading in turn to greater attention (similar to other own-social-group advantages in explicit memory, Bernstein, Young, & Hugenberg, 2007), and there is no difference in *perceptual* encoding, then any own-age advantage should disappear on the implicit memory task.

Experiment 3 is divided into explicit memory (Experiment 3A) and implicit memory (Experiment 3B). The two versions of the experiment were almost identical in the learning phase, but differed substantially in the test phase.

5. Experiment 3A – explicit memory

The aims of Experiment 3A were to (a) provide comparison data on the developmental trend in explicit memory for the particular face stimuli to be used in the implicit version, and (b) to assess the existence or otherwise of an own-age advantage in children and/or adults. In this explicit version of the task, we wished to have full allowance for involvement of deliberate memory strategies. We thus employed a recognition memory task in which participants knew before learning there would be a later memory test (allowing study and rehearsal strategies to be useful) in addition to being tested using explicit retrieval instructions (allowing retrieval strategies to be useful). Except for the use of intentional learning, the study phase of the explicit version was identical to the subsequent implicit version.

Three points regarding the own-age versus other-age manipulation deserve some elaboration. First, it was not entirely clear that an own-age advantage would be obtained even in explicit memory. Only two previous studies have tested own-age effects in child subjects where there was evidence that child and adult face stimulus sets were matched for discriminability. Gilchrist and McKone (2003) crossed participant age (6–7 years versus adult) with face-age (child versus adult), and found no other-age effects. However, Anastasi and Rhodes (2005) reported an own-age advantage in child participants aged 5–8 years (i.e., children showed better memory for child faces than young-adult faces).

Second, it was theoretically important to test for an own-age advantage separately in children and in adults. If attentional biases are the origin of explicit memory own-age advantages, the effect might be apparent only in children. Adults should be good at directing attention equally to all faces, consistent with the implied expectations of the experimenter, while children might either be unaware of these expectations or be unable to use top-down control to overcome a stronger natural interest in peer faces than adult faces. A similar idea can be proposed to explain Firestone, Turk-Browne, and Ryan's (2006) finding that explicit memory showed no own-age bias in young adults (who have good attentional control), but did show an own-age bias in *older* adults (who have poorer attentional control).

Third, we defined 'own'-age broadly to simply mean child versus adult status, rather than attempting to match exact age within children.[9] Our face stimuli were first graders (mostly 6–7 years). Although these stimuli were most closely matched in age to the 5–6 year-old participant group, both the 5–6 year-old (Kindergarten) and 10–11 year-old group (5th grade) have everyday exposure to 6–7 year-olds at school.

5.1. Method

5.1.1. Participants

The 56 new participants, from pools described in Experiment 1, were twenty *5–6 year-olds* (mean 6.3 years, range 5.5–6.9; 11 male), sixteen *10–11 year-olds* (mean 11.1 years, range 10.5–11.7; 6 male), and twenty *adults* (mean 24.1 years, range 18.5–31.7; 5 male). Adults received $5 or $6 for the 30 min test.

5.1.2. Design

Procedure was the same for all three age groups. Each subject was tested on both child face stimuli and adult face stimuli, in two separate study-test blocks. In each block, participants studied 15 faces and performed 30 recognition trials with faces presented one at a time for "old" or "new" decision. All faces were upright.

5.1.3. Materials

5.1.3.1. Face stimuli. Faces were front view greyscale photographs of novel Caucasian males with neutral expressions and no facial hair or glasses. The 60 child faces (age range 6–7 years with a few 5-year-olds) were from a database of photographs taken locally (Gilchrist & McKone, 2003). The 60 adult faces (approximate age range 18–30 years) were from University of Ljubljana CVL and CV, PTER, Velenje database (http://lrv.fri.uni-lj.si/facedb.html), Harvard Vision Laboratory Face Database (Tong & Nakayama, 1999) and local photographs (Gilchrist & McKone, 2003). Adobe Photoshop 5.5 was used to remove distin-

---

[9] Partly because we could not obtain local face stimuli precisely matching our subject ages (the local education department no longer allows photographing of children).

Table 1
Experiment 3A: explicit memory. Mean (& *SEM*) percent "old" responses.

Participant age	Face stimuli	Studied normal[a] (i.e., *hits*)	Unstudied normal (i.e., *false alarms*)	Corrected recognition (*hits* – *false alarms*)
5–6 years	Child	57.7 (2.9)	40.7 (3.3)	17.0 (4.2)
	Adult	54.3 (2.9)	45.7 (3.3)	8.7 (3.9)
	All	56.0 (2.3)	43.2 (3.0)	12.8 (3.0)
10–11 years	Child	73.3 (4.3)	35.8 (3.3)	37.5 (4.3)
	Adult	67.5 (4.2)	39.6 (3.9)	27.9 (4.3)
	All	70.4 (3.4)	37.7 (3.2)	32.7 (3.0)
Adults	Child	77.0 (3.0)	21.7 (2.8)	55.3 (4.2)
	Adult	79.3 (2.6)	23.3 (2.7)	56.0 (4.0)
	All	78.2 (2.5)	22.5 (2.0)	55.7 (3.3)

[a] Experiment 3A used only normal faces; labels "studied normal" and "unstudied normal" are used to allow comparison with Experiment 3B.

guishing features (e.g., birthmarks), crop faces within an oval window to exclude hair and ears, and match brightness and contrast within each source set. Viewing distance was 40 cm (with chinrest). Adult faces were 6.44° horizontal by 8.58° vertical; child faces 7.15° by 8.58°.

5.1.3.2. Stimulus list construction. The 60 faces were randomly divided into four lists of 15 (Lists A, B, C & D; need for four rather than two was driven by requirements of the implicit version of the experiment). For any given subject, 15 faces (e.g., List A) were presented at study. At test participants saw the 15 *studied* plus 15 *unstudied* faces (e.g., List A & B). For half the subjects in each age group, Lists A and B were used (studied-unstudied status counterbalanced across subjects), while Lists C and D remained unused. For the other half, Lists C and D were used.

5.1.4. Procedure

5.1.4.1. General. As in Experiment 1.

5.1.4.2. Study phase. On each trial, a fixation cross for 1000 ms for adults, or until concentrating for children, was followed by the face for 5000 ms. Participants judged "how nice each person is". Adults rated niceness on a 9-point scale. Children responded "nice", "not nice" or "in the middle". Participants were told they would be asked to remember the faces later on, and they would therefore need to look carefully at each face. Faces were in a different random order for each subject.

5.1.4.3. Distractor phase. Study-test delay was approximately 4 min. Filler task content was adjusted for each age group: 5–6 year-olds chose a sticker, did a drawing and named their favourite animals and colours; 10–11 year-olds did a spoken category exemplar generation task; adults did a written category exemplar generation task.

5.1.4.4. Test phase. On each trial, a fixation cross for 1000 ms for adults, and until concentrating for children, was followed by a face presented until response. Participants responded "old" or "new". Test faces were in a different random order for each participant. There was no feedback on response.

5.1.4.5. Repeat for second face-age. A break of at least 5 min followed the first test. The second cycle repeated the study-distractor-test procedure with the stimulus set for the remaining face-age (e.g., adult faces if the participant had seen child faces first).

5.2. Results

5.2.1. Improvement in explicit memory with age

Table 1 shows percentage "old" responses for studied faces (*hits*) and unstudied faces (*false alarms*). Explicit memory scores were calculated in two ways. The primary measure was corrected recognition (*hits–false alarms*), which is directly analogous to the subsequent implicit memory measure, repetition priming (*studied–unstudied*). We also calculated discriminability (d') for old versus new. Results from the two measures did not differ in any way. Only corrected recognition is discussed.

Regarding whether explicit memory develops with age, a 3 (age group) × 2 (face-age) ANOVA revealed a significant main effect of age group, $F(2,53) = 50.30$, $MSE = 365.28$, $p < .001$. Follow-up t-tests revealed significantly better performance in 10–11 year-olds than 5–6 year-olds, $t(34) = 4.64$, $p < .001$, and significantly better performance in adults than 10–11 year-olds, $t(34) = 5.05$, $p < .001$. Thus, as expected, explicit memory for unfamiliar faces improved between 5–6 years and 10–11 years and continued to develop between 10–11 years and adulthood (see Fig. 6).

5.2.2. Own-age bias in explicit memory?

Fig. 6 appears to indicate an own-age bias in children; that is, the two child groups tended to be better with child faces than with adult faces. Collapsing the two child groups together to maximise statistical power, children remembered child faces significantly better than adult faces, $t(35) = 2.21$, $p < .05$, replicating the own-age advantage in child participants found by Anastasi and Rhodes (2005).[10]

Fig. 6 shows no suggestion of any own-age advantage for the adult group of participants. Adults showed no differences between the two face sets, $t < 1$.

---

[10] The face-age by participant age interaction was not significant. Justification for analysing the own-age effect separately for child and adult participants is primarily theoretical. Statistical justification also comes from an overall Experiment 3 ANOVA: face-age for children interacted significantly with memory type (see Experiment 3B), requiring fully exploring the effects of face age in children in explicit memory.

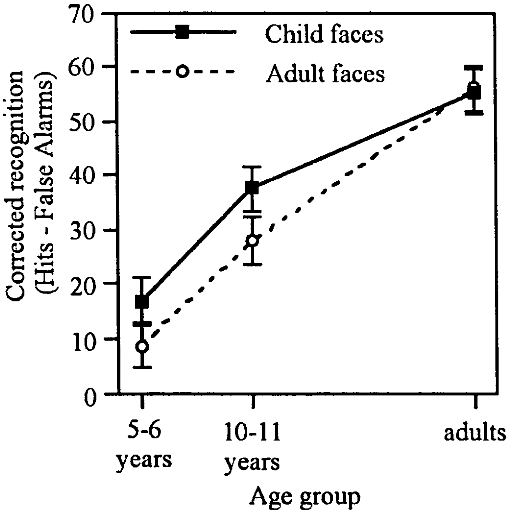


Fig. 6. Experiment 3A: explicit memory results expressed as corrected recognition scores (% "old" responses for studied normal faces *minus* % "old" responses for unstudied normal faces). Findings show (a) the expected developmental increase in explicit memory for both child and adult faces and (b) better memory for peers' faces than adults' faces in children. Error bars show ±1 *SEM*.

5.3. Discussion

Explicit memory for faces increased strongly with age from 5–6 years to adulthood. This confirms the standard finding, and provides a trend against which implicit memory development could be compared in Experiment 3B.

We also demonstrated an own-age advantage on explicit memory for our stimuli in child participants. This provides the basis to test, via implicit memory in Experiment 3B, whether this effect derives from social attentional factors or from changes in perceptual face-space coding deriving from recent experience.

6. Experiment 3B – implicit memory

Experiment 3B assessed children's ability to perceptually encode novel faces using an implicit measure of retention. Predictions were as follows. If the age-related increase in explicit memory and/or the own-age bias in Experiment 3A are the result of face-specific perceptual changes (i.e., the *face-specific perceptual development* theory) we would expect to find that repetition priming shows an increase with age and/or an own-age advantage in children (i.e., greater priming for child faces than adult faces). If, however, the findings of Experiment 3A are solely the result of general cognitive development we would expect to observe *no* age-related development and *no* own-age advantage on implicit memory.

Experiment 3B was designed to satisfy several important methodological criteria. The first was to minimise strategic memory contributions, thus giving the purest measure of perceptual encoding. At study, there was no instruction to learn for a subsequent memory test. At test, the measure was repetition priming, there was no requirement to recall from the study phase, and post-test questionnaire responses were used in adults to exclude participants who reported making deliberate reference to that phase to support their responses (i.e., showed "explicit contamination").

The second was to develop a test-phase task that assessed priming for *novel* faces. This is more difficult than it might seem. The common familiarity decision task produces strong priming effects for familiar faces, but no (or sometimes reverse) priming effects for novel faces (e.g., Young, McWeeny, Hay, & Ellis, 1986), presumably because the perceptual advantage arising from repetition is offset by the increased decisional difficulty of saying 'unfamiliar' to a repeated novel face. There appears to be no task that both avoids this problem and also makes very explicit reference to the individual identity of items, a factor important in obtaining large priming effects for novel items.[11] Goshen-Gottstein and Ganel (2000) were able to find a small but significant priming effect for novel faces in adults on sex decision (3.93% reduction in reaction time for studied compared to unstudied items). Here, we tried a task intended to require as strong an access to identity-related shape coding of the whole face as possible. Faulkner, Rhodes, Palermo, Pellicano, and Ferguson (2002) distorted faces by compressing or expanding them, and observed significant semantic priming from names to familiar faces on a normal-distorted decision task. We used this task to assess repetition priming for novel faces.

Fig. 7 shows the procedure. As for the explicit memory version of the task, all faces were normal in format in the learning phase. Further, at test, priming was assessed only for "normal" (unaltered) faces: that is, the strength of implicit memory was assessed by measuring the advantage in decision accuracy for *normal* faces when they had earlier been studied compared to unstudied. Distorted format faces were introduced at test only, merely to allow a decision response on the normal faces.

Our third methodological criterion was that baseline accuracy (i.e., for the *unstudied normal* condition) should be equated across age groups, *without altering the learning* or retention phases. Matching baselines allowed fair comparison of the size of the repetition priming effect across age groups. Doing so by altering only the test-phase ensured that (a) all age groups had equal opportunity to encode the faces (i.e., same learning time per face, same number of faces to learn), and (b) all age groups were equated for length of time the initial encoding must be retained before testing (i.e., same study-test delay). Under these conditions, a finding that priming increases with age would indicate adults are better than children at making a new face familiar; in contrast, stable priming across age groups would indicate children can save just as strong a trace of a novel face from a single exposure as adults.

Difficulty of test phase decision was equated across ages by altering stimulus presentation duration plus distortion level of the *distorted* faces (Fig. 7C). For adults, pilot testing determined that a relatively mild distortion level and very brief presentation (200 ms per face) gave nor-

---

[11] In studies of priming for novel *words*, large priming effects can be achieved by using naming as the task (e.g., McKone, 1995); but, novel faces cannot be named.

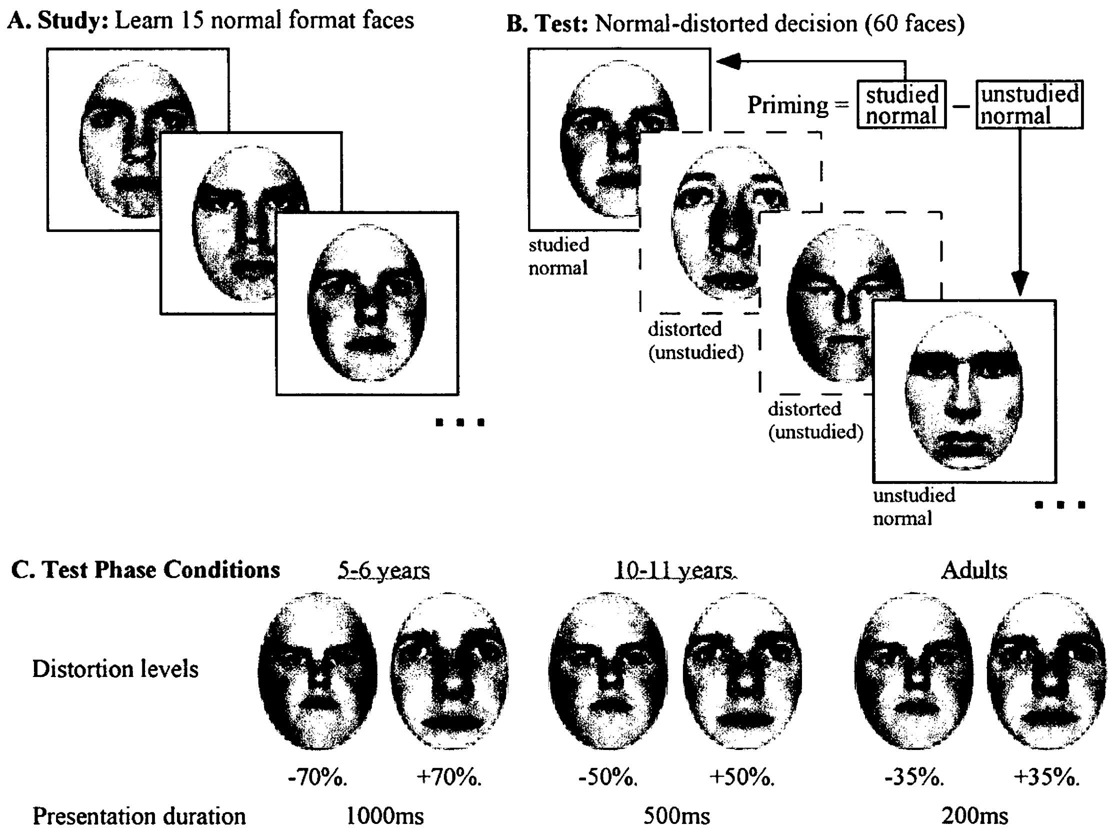


Fig. 7. Experiment 3B: procedure for the implicit memory task. (A) Participants learned 15 normal-format faces at study (the same as for the explicit memory task). (B) At test, repetition priming was assessed for normal-format faces in normal-distorted decision. (C) At test, baseline performance for unstudied normal-format faces was matched across age groups by adjusting both distortion levels of distorted format faces and presentation durations.

mal-decision accuracy for unstudied faces at the desired value (65–70%, i.e., comfortably above floor, but low enough that there was room for studied faces to produce higher accuracy without reaching ceiling). Younger age groups received higher distortion levels, and longer presentation durations, than older groups.[12]

6.1. Method

6.1.1. Participants

The 96 new participants, from pools described in Experiment 1, were thirty-two 5–6 year-olds (mean 5.9 years, range 4.8–6.8; 11 male), thirty-two 10–11 year-olds (mean 10.8 years, range 10.1–11.4; 11 male), and thirty-two adults (mean 22.0 years, range 18.0–29.1; 14 male). Payment was as for Experiment 3A.

6.1.2. Design

As for Experiment 3A, except the test phase added *unstudied distorted* faces to the *studied normal* and *unstudied normal* faces (see Fig. 7B). Distorted face data were not relevant to memory measures.

6.1.3. Materials

6.1.3.1. Stimuli. Normal-format faces were as in Experiment 3A. A distorted version of each was created using the Photoshop "spherize" tool. To prevent adaptation to one direction of distortion (Webster & MacLin, 1999), half the faces were "positively" distorted (expanded) and half "negatively" distorted (contracted). Distortion levels were ±35% for adults, ±50% for 10–11 year-olds, and ±70% for 5–6 year-olds (in Photoshop 5.5 for Macintosh).

6.1.3.2. Stimulus list construction. The four lists of 15 faces (Lists A, B, C & D) were as in Experiment 3A. A given participant saw 15 normal-format faces (e.g., List A) at study. At test they saw these 15 faces again in normal format (*studied normal*), plus 15 other faces (e.g., List B) in normal format (*unstudied normal*) and 30 faces (e.g., Lists C & D) in distorted format (*unstudied distorted*). Lists assigned to the different conditions were counterbalanced across subjects.

6.1.4. Procedure

6.1.4.1. General. As in Experiment 1.

6.1.4.2. Study phase. As in Experiment 3A, except participants were not told to remember the faces.

6.1.4.3. Distractor and practice phase. Study-test delay was again approximately 4 min. Filler tasks were shorter ver-

---

[12] The need to do this demonstrates that children's task performance on normal-distorted decision improves with age. As with all such simple improvement findings, this effect could arise from either face perception or general cognitive abilities.

Table 2
Experiment 3B: implicit memory. Mean (& *SEM*) percent "normal" responses.

Participant age group	Face stimuli	Studied normal (SN)	Unstudied normal (UN)	Unstudied distorted (UD)	Priming (SN–UN)
5–6 years	Child	71.5 (3.1)	65.8 (3.2)	10.7 (1.6)	5.6 (2.7)
	Adult	69.6 (2.8)	64.8 (3.5)	10.1 (1.3)	4.8 (3.0)
	All	70.5 (2.5)	65.3 (2.8)	10.4 (1.2)	5.2 (1.9)
10–11 years	Child	77.3 (2.8)	74.4 (2.7)	14.6 (2.2)	2.9 (2.1)
	Adult	72.3 (3.0)	67.5 (3.2)	16.6 (1.9)	4.8 (3.2)
	All	74.8 (2.4)	70.9 (2.3)	15.6 (1.8)	3.8 (1.9)
Adults	Child	70.6 (2.7)	66.2 (2.9)	28.3 (1.8)	4.4 (2.9)
	Adult	69.0 (2.6)	66.2 (3.1)	28.0 (1.9)	2.7 (3.4)
	All	69.8 (2.2)	66.2 (2.5)	28.2 (1.5)	3.5 (2.6)

sions of those used in Experiment 3A. The last part of the filler period was practice for the test task, using faces not on any list. It comprised 10 practice trials with unlimited presentation duration, then 10 trials at the experimental presentation duration, with feedback.

6.1.4.4. Test phase. On each trial, a fixation cross for 1000 ms for adults, and until concentrating for children, was followed by the face for 200 ms for adults, 500 ms for 10–11 year-olds, and 1000 ms for 5–6 year-olds. Participants responded "normal" or "distorted". There was a different random order for each participant, and no feedback.

6.1.4.5. Repeat for second face-age. As in Experiment 3A.

6.1.4.6. Explicit contamination questionnaire. Uninstructed use of deliberate memory strategies was assessed after the experiment using a standard questionnaire type (McKone & Slee, 1997). We excluded and replaced 4 adults who reported trying to use remembering a face from the study phase as a cue to its normal-distorted status (e.g., "If I had seen it before I knew it was normal"). The questionnaire was not administered to the child groups. We tried a simplified version for 10–11 year-olds, but they did not have the metamemory skills to understand the questions.

6.2. Results

6.2.1. Increase in implicit memory with age?

Table 2 shows percentage "normal" responses. We first needed to confirm that baseline performance (unstudied normal condition) was matched across age groups. A 3 (age group) × 2 (face-age) ANOVA found no main effect of age group, $F(2,93) = 1.43$, $MSE = 407.57$, $p > .2$, or face-age, $F(1,93) = 1.55$, $MSE = 215.34$, $p > .2$, and no significant interaction, $F(2,93) = 1.02$, $MSE = 215.34$, $p > .3$. Thus, baselines were successfully equated, and analysis of priming could proceed.

Implicit memory was calculated as *priming = studied normal – unstudied normal.* Fig. 8 shows priming for child and adult faces separately (Fig. 8A), and collapsed across face-age (Fig. 8B). A 3 (age group) × 2 (face-age) ANOVA revealed no main effect of age of participant, $F < 1$, $MSE = 291.99$. Thus, there was no increase in implicit memory with age. Indeed, the slight trend was, if anything, in the opposite direction (Fig. 8). A priori *t*-tests also

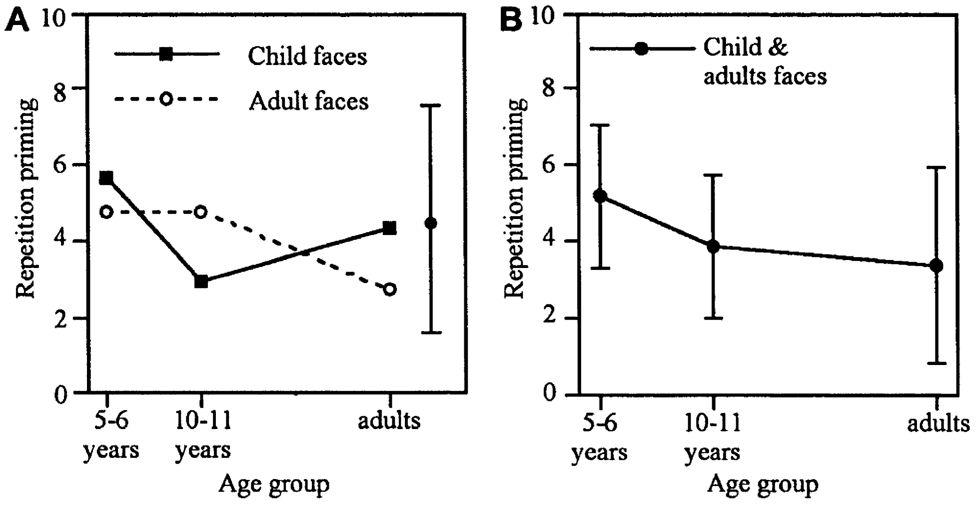


Fig. 8. Experiment 3B: implicit memory results expressed as priming scores (% "normal" responses to studied normal faces *minus* % "normal" responses to unstudied normal faces) for: (A) each face-age stimulus set separately and, (B) collapsed across the two face-age sets. Note the lack of increase in implicit memory with age. Error bars show (A) ±1 average *SEM*, (B) ±1 *SEM* for each condition.

showed no difference in priming scores between 5–6 year-olds and 10–11 year-olds, $t < 1$, or between 10–11 year-olds and adults, $t < 1$. The mean priming score across all age groups was 4.20%, which was significantly above zero, $t(95) = 3.44$, $p < .002$. A priori t-tests also confirmed priming was significantly above zero in each group of children: for 5–6 year-olds, $t(31) = 2.77$, $p < .01$; 10–11 year-olds, $t(31) = 2.06$, $p < .05$. In summary, priming was present in young children, and did not increase with age.[13]

Finally, comparison to results of Experiment 3A revealed the lack of age-related development on implicit memory to be a significantly different pattern from the age effect on explicit memory (participant age × memory type interaction, $F(2,138) = 36.62$, $MSE = 161.42$, $p < .001$).

6.2.2. A different definition of baselines?

Above, we took "matched baselines" to mean matched accuracy for unstudied *normal* faces, because studied items were normal faces. On this basis, all age groups showed similar priming. However, this analysis ignores the unstudied *distorted* items and, as shown in Table 2, the adult groups were poorer than the child groups in this condition. Correspondingly, d' discriminability for unstudied normal-distorted decision was better in children (5–6 year-olds = 1.80, 10–11 year-olds = 1.74) than adults (1.05). If d' were chosen as the baseline, only the two child groups were well matched. Might this jeopardise our conclusion of no development in implicit memory? We argue not. Priming did not increase between the 5–6 year-olds and the 10–11 year-olds (Fig. 8), despite the fact that these two groups, at least, were baseline matched on both unstudied normal accuracy *and* unstudied normal-distorted discrimination, and despite the strong development of explicit memory over this age range (Fig. 6).[14]

6.2.3. Overall differences in priming between face-age sets?

ANOVA revealed no main effect of face-age on priming, $F < 1$, $MSE = 244.20$. Indeed, mean priming was almost identical for child faces (4.3%, $SEM = 1.5\%$) and adult faces (4.1%, $SEM = 1.8\%$). This is important methodologically. If priming had differed between face sets, then it could have been suggested that the Experiment 3A finding in explicit memory of an own-age advantage for child but not adult subjects was due merely to the child face stimuli being more perceptually discriminable or easier to encode than the adult face stimuli (i.e., scores for child faces were artificially pushed up overall compared to scores for adult faces). However, the implicit memory results confirm child and adult faces sets were well matched.

6.2.4. Own-age advantage in implicit memory for child participants?

Fig. 8A shows no suggestion of any own-age advantages. Most importantly, the own-age advantage in explicit memory for child participants (Experiment 3A) disappeared in implicit memory. Combining the two child age groups to maximise power revealed no difference between priming for the child and adult face sets, $t < 1$. Tests for 5–6 year-olds and 10–11 year-olds independently also showed no face set difference (both ts < 1). Thus, children showed as much priming for adult faces as for child faces. The lack of own-age advantage obtained in children for implicit memory also differed significantly from the own-age advantage found in Experiment 3A for explicit memory: for a combined 5–6 and 10–11 year-old group, there was a face-age × memory type interaction, $F(1,94) = 3.98$, $MSE = 273.86$, $p < .05$.

For completeness, there was no face-age × participant age interaction, $F < 1$, $MSE = 244.20$. There was also no own-age advantage for the adult participants, $t < 1$.

6.3. Discussion

Encoding novel faces is a very important skill that had previously been suggested (Carey, 1981; Carey, 1992) to be particularly poorly developed in young children. Experiment 3B has provided the first direct test of encoding *within children's face perception system*, using implicit memory to examine this independent of deliberate strategies and attentional factors that contribute strongly to explicit memory.

The major finding was that there was no change in repetition priming with age. This shows the ability of young children's face perception system to describe, and store, a novel face – that is, to make an new face familiar – is as good as that in adults. Our finding is particularly strong given that the same learning and retention conditions were used for all age groups (i.e., all groups had equal learning set size, equal presentation time at study, and equal study-test delay).

Our second finding was that the own-age advantage for child participants in explicit memory (Experiment 3A) disappeared when encoding was tested with implicit retrieval. Indeed, children's priming for adult faces was as strong as adults' priming for adult faces (Fig. 8A). This shows that the explicit memory results did not represent poor perceptual encoding of adult faces, and that the explicit own-age bias cannot be interpreted as evidence for a perceptual face-space better tuned to the most frequently experienced ages of faces. Instead, a plausible explanation of the explicit own-age bias is that children aged 5–11 years were more socially interested in peers than in adults, and thus paid more attention to child face stimuli.

Overall, Experiment 3 has added tests of novel face encoding and face-space aspects of face recognition to our earlier tests of holistic processing. The conclusion is the same as previously, namely that children's perceptual processing of faces is fully quantitatively mature at 5–6 years. Further, by contrasting explicit memory for faces with implicit memory for faces, Experiment 3 has provided

---

[13] It has been suggested to us that lack of development might have arisen because priming was (as expected) relatively small even in adults. However, this criticism is not compelling. Small priming in adults, in the context of underlying development, should have made it extremely difficult to obtain any priming effect at all in children, yet children showed an effect that was, if anything, slightly larger than that in adults.

[14] It was not possible to re-run the experiment simultaneously matching all age groups on both baseline measures: children had a bias to respond "distorted" that we were unable to alter in several attempts, while adults' responses were unbiased.

a very direct confirmation that the development that occurs in memory for faces after 5 years is due to development of *memory* factors, not development of face perception.

7. General discussion

Our results showed: (1) memory for faces and dogs improved at the same rate between 5–6 years and adulthood; (2) the disproportion in the inversion effect for faces versus dogs was just as large in 7-year-olds as in adults; (3) reducing the learning set size (from 15 to 5 faces) did not reduce the strength of holistic processing; (4) implicit memory for faces did not change with age from 5–6 years to adulthood; and (5) an own-age bias in explicit memory for child participants disappeared in implicit memory. These findings converge to argue that, although there is dramatic improvement in performance on laboratory face tasks between early childhood and adulthood, this development can be attributed to general cognitive development, rather than to face-specific perceptual development.

7.1. Development of holistic processing

Does holistic processing increase in strength between 5 years and adulthood? From our review of the previous literature, we concluded that the four studies with the most appropriate methodology for addressing this question all favoured no developmental change (see Fig. 1C), as did studies of the part-whole effect (Pellicano & Rhodes, 2003; Pellicano et al., 2006; Tanaka et al., 1998). We also argued that other studies were ambiguous as regards interpretation. The field has shown a tendency to selectively cite those results suggesting an *increase* in holistic processing strength with age (e.g., Fig. 1A), but we showed that this interpretation is weak due to restriction of range to show effects in younger children, failure to match conditions for which developmental trends are compared (e.g., feature versus spacing, faces versus objects) for difficulty at either end-point age group, and failure to compare faces to well-matched object classes. We also showed that some findings apparently suggest a *decrease* in holistic processing strength with age (Fig. 1B) and argued that, if we accept that this can be explained by the obvious methodological limitation in these studies (i.e., restriction of range in some age group/s) then the same logic must also be applied to invalidate similar studies showing an increase. We therefore concluded that no previous studies demonstrated development in holistic processing, and that in contrast there was a moderate amount of evidence supporting early quantitative maturity.

The present study has added considerably to this evidence. Our experiments avoided restriction of range issues, and we contrasted faces with a well-matched object class. If holistic processing had increased in strength with age, then we should have observed (a) face memory diverging from dog memory in older age groups in Experiment 1, and (b) the amount by which the inversion effect for faces was larger than dogs increasing with age in Experiment 2. Neither of these results was obtained (Figs. 3 and 5).[15]

Our results have also added to the evidence by clarifying the interpretation of Carey (1981) and Gilchrist and McKone (2003). The interpretation of those studies as supporting no developmental change in holistic processing relies on the assumption that decreasing the learning set size in young children relative to adults does not reduce the reliance of memory on holistic processing. Our Experiment 2 results validate this assumption, by showing that altering learning set size in the approximate range used by Carey and by Gilchrist and McKone had no influence on either the size of the inversion effect for faces, or the amount by which the inversion effect for faces was disproportionate relative to that for dogs.

Taking our results together with the previous studies, we therefore conclude there is now strong evidence that holistic processing is at adult levels of strength in early childhood. This conclusion derives from converging findings from multiple standard measures (inversion effect, composite effect, part-whole effect, spacing sensitivity, faces versus objects). Crucially, it also applies to all putative subtypes of holistic/configural processing. In contrast to earlier suggestions (Maurer et al., 2002; Mondloch et al. 2002), results now favour early maturity even of the 'second-order relational' aspect of holistic/configural processing (i.e., sensitivity to spacing between features). Gilchrist and McKone (2003) specifically tested spacing sensitivity, and found it was as strong in 6–7 year-olds as in adults (Fig. 1C). Three other experiments have used methods that combine *all* putative subcomponents of holistic/configural processing (i.e., faces versus objects, upright faces versus inverted faces) and where it can therefore be concluded that the findings of no overall development in holistic/configural processing must reflect no development of *any* subcomponent (present Experiment 1; present Experiment 2; Carey, 1981).[16]

Our overall conclusion is that holistic processing within the face system should be considered fully mature in early childhood, at least under relatively unspeeded conditions. By the term *fully mature* we mean that holistic processing is: qualitatively present; quantitatively at adult strength; and that these properties apply to all standard measures and all putative subtypes of holistic/configural processing.

---

[15] Note again that this is unlikely to be due to mere lack of statistical power. Experiment 1 produced small error bars, and the lack of age effect on the face-dog difference was obtained in the context of highly significant other effects (i.e., overall developmental increase in memory). In Experiment 2, the age-related change in the disproportion score trended in the *reverse* direction to that predicted by an increase in holistic face processing, and again this result was obtained in the context of other effects that were clearly significant (e.g., inversion x stimulus class interactions).

[16] It thus seems age-related increases on spacing tasks must have generic rather than face system sources (e.g., improvements in vernier acuity, concentration, explicit memory, and/or strategies relevant to change-detection tasks such as focussing attention on face regions most liable to change in the stimulus set). Consistent with this interpretation, spacing change sensitivity increases between 8 years and adulthood as much for monkey faces as for human faces, despite the face system's lack of perceptual expertise with monkeys (Mondloch et al., 2006).

7.2. Development of face-space

The literature on development of face-space is smaller than that for holistic processing. Again, however, our review concluded that the studies with the most appropriate methodology for making quantitative comparisons across age groups all favoured no developmental change (distinctiveness effect, Gilchrist & McKone, 2003; other-race effect, Pezdek et al., 2003; adaptation aftereffect, Nishimura et al., 2008). Results apparently showing quantitative increases in face-space effects with age could all be attributed to restriction of range problems in younger age groups.

The present study provides some further support for early quantitative maturity, via the results concerning own- versus other-age effects in Experiment 3. Our implicit memory results showed children's face systems' ability to encode and store a new adult (i.e., other-age) face is as good as that of adult observers, implying that the explicit memory own-age advantage in children (also Anastasi & Rhodes, 2005) does not represent a perceptual difference in face-space between 5–11 year-olds and adults, but instead represents differences in attention and/or interest that affect explicit memory task performance. Consistent with this idea, children also show no own-age advantage on a same-different sequential presentation task (Mondloch et al., 2006), a task that does not require the same strategies as long-term explicit memory.

We thus conclude that, at least with the evidence available to date, findings favour quantitative maturity of face-space at 5–8 years: specifically, there is no evidence that young children's face-space has fewer dimensions than adults', less appropriate weighting of face dimensions, or other limitations such as poorer tuning within a dimension. We note, however, that children's face-space has received relatively little attention, and so the conclusion that face-space is fully mature early cannot be drawn as strongly as can the conclusion regarding holistic processing.

7.3. Development of perceptual encoding of novel faces

So far, we have discussed basic perceptual abilities of the face system that can be applied to all faces regardless of whether they are familiar or unfamiliar. But, what about the process of making a new face familiar? Is this more difficult for children than for adults?

Carey (1981,1992), Carey et al. (1980) argued that it was. In the context of modern findings, however, the evidence originally presented for this idea is weak. Carey (1992) cited the strong age-related improvement on the Benton and Van Allen clinical test. However, this test is strongly affected by strategies unrelated to face recognition. It falsely diagnoses many adult prosopagnosics as normal (Duchaine & Nakayama, 2006), and normal adults can perform well purely by matching the eyebrows (with all internal facial features ablated, Duchaine & Weidenfeld, 2003). Thus, the age-related improvement could reflect merely developing appreciation of the eyebrow matching strategy. The other evidence cited was early findings of faster development of memory for upright than inverted faces (Carey & Diamond, 1977; Carey et al., 1980). We agree with the logic that such findings, if genuine, would demonstrate special development of encoding within the face system. The findings, however, were open to the critique of restriction of range (Fig. 1A).

Our present study has provided important new evidence. Most directly, Experiment 3 used implicit memory (repetition priming) to show that perceptual encoding of a once-seen novel face, disentangled from explicit memory strategies, was as strong in 5–6 year-olds as in adults. We also showed that when restriction of range is avoided, rates of development of explicit memory are equal for upright faces and inverted faces (Experiment 2; also see Carey, 1981 in Fig. 1C), a result which precludes special development of *face* encoding. Our results thus support the view that the ability of the face system to describe and store the appearance of new faces is quantitatively mature in early childhood.

A caveat is that we have tested encoding only with the same image used at study and test. Mondloch et al. (2003) suggested children are poor at the particular task of perceptually encoding a once-seen image of a new face in such a way that it is *generalisable across view change*. Currently, evidence for this idea is not compelling. Certainly, children are poorer than adults at cross-view recognition memory tasks (Bruce et al., 2000; Mondloch et al., 2003). The difficulty (as usual) is to tease apart any face perception contribution to this pattern from contributions of general cognitive development. Mondloch et al. (2003) attempted to do this by comparing rate of development on an identity-match-across-view-change task with that on several other face tasks. Three of the comparison tasks were much easier than the identity-match-across-view in adults, and so the results, rather than indicating late maturity specifically for cross-view generalisation, could indicate merely late maturity on difficult tasks due to children losing concentration faster than adults. The comparison of identity-match-across-view-change with identity-match-across-expression-change did not suffer from this problem, and results showed apparently slower development on the across-views task; unfortunately, however, statistics directly comparing the age trend across the two matched tasks were not presented, and also the across-expression task produced an atypically small inversion effect in adults (suggesting the possibility of unusual strategies on this stimulus set).

Overall, we conclude perceptual ability to encode novel faces is mature early in childhood when the study and test images are the same. More research is needed to see if this conclusion of early maturity also holds when different viewpoints are used at study and test, or where other image changes are made (e.g., lighting changes).

7.4. A general caveat – developmental changes in speed?

We have argued that present results converge with previous findings to favour the view that perceptual face recognition ability is mature early. Importantly, however, both the present experiments and the great majority of the articles we have cited have tested face perception under conditions where those mechanisms are operating without substantial speed stress. For example, for learning trials, typical presentation times across studies are at least 2–6 s per face (our own three experiments all used 5 s). For memory test trials, or for faces presented for naming, stimuli typically remain on the screen until response.[17]

This type of relatively unspeeded face recognition is, we suggest, of strong theoretical importance because it corresponds to the situation that occurs most commonly in natural settings. In everyday life, children (and adults) are not often called upon to identify a person's face from, say, a 150 ms exposure. Instead, a person approaches the observer in a room, or along a path, or the observer sees another child playing in the school playground. In all these circumstances, it probably does not matter very much whether the face system takes 150 ms or 500 ms or even 1000 ms to identify the face: the primary requirement is that the face is recognised *accurately*.

It should be noted, however, that neither our own results nor the previous literature rule out the possibility of late developmental change in the *speed* with which face perception mechanisms can resolve the identify of faces. Studies using event-related potentials (ERPs) show the face-selective 'N170' over posterior temporal sites peaks at 170 ms after stimulus onset in adults, but at progressively later times earlier in development (e.g., 185 ms in 10–11 year-olds, 270 ms in 4–5 year-olds; Taylor, Batty, & Itier, 2004). This implies that in young children either (a) inputs to face areas from early visual areas are slower, and/or (b) the face system itself is slower to resolve these inputs into a representation of the face. Given late developmental changes in processing speed throughout the brain, as implied by the gradual shifts of many different ERP peaks (Nelson & Monk, 2001), it would seem reasonably probable that *the face perception system itself* does becomes faster with age.

7.5. Summary of behavioural face recognition ability in the 5-years-and-up age range

In the developmental face recognition literature, it is now generally agreed that all qualitative aspects of adult-like face recognition are present in young children. The more controversial question, however, has been the age at which face perception reaches quantitative maturity.

We have argued that all methodologically valid results available to date support the view that, although there may be late ongoing speed changes, quantitative maturity of mechanisms related to the accuracy of face recognition is reached early (i.e., by 5–7 years at the latest). With respect to the various aspects of face recognition considered, we have argued the evidence for early maturity is compelling for holistic processing, reasonably strong for face-space (the caveat being there have been relatively few tests to date), and strong for encoding of novel faces (with the caveat that across-view generalisation needs further testing). Taken together, the results strongly suggest there is no development in the accuracy of the processing performed by identity-related face perception mechanisms after early childhood, and that the substantial improvements on experimental task performance after 5–7 years reflect improvements in general cognitive abilities (i.e., refuting the face-specific perceptual development theory, and supporting the general cognitive development theory).

We suggest that this conclusion from experimental studies is consistent with naturalistic observations of children's behaviour. In everyday life, children are perfectly capable of learning a large number of new faces, and recognising these people correctly, at least with natural exposure durations and when attention is motivated by social interest in the people to be learned (e.g., classmates at school or day-care). Anecdotally, children certainly can make mistakes in recognition, and they can also be distracted by paraphernalia (e.g., failing to recognise a person in a new hat). But, these mistakes could easily reflect failures of attention or social interest rather than failures of face perception per se. Also note that there are now striking demonstrations that even adults' real world face recognition can be spectacularly bad under conditions of low social interest in the person to whom one is speaking and/or in the presence of attention-attracting paraphernalia (Simons & Levin, 1998).

7.6. Complete developmental course of behaviour, and causal origins of adult expertise in face recognition

The research discussed in the present article, focussing on the 5-year-and-up age range, forms part of a broader literature tackling two important topics: first, the description of the complete developmental course of face recognition from birth through to adulthood; and, second, the investigation of the causal factors present at each stage of development and how these contribute to eventual adult ability. Our findings have implications for both these topics.

Regarding description of the full developmental course, it is important to note that although we have talked about adult levels of ability being achieved at approximately 5–7 years, this does not rule out maturity being reached earlier. We have focussed here on 5-years-and-up because 4–5 years (or later in some tasks, see Experiment 2) is approximately the youngest age at which adult experimental tasks can be adapted for children, thus allowing potential for direct quantitative comparison of children and adults on the same task. There are almost no face recognition studies in the entire age range between 9 months and 3 years. Given this lack of data, it is quite possible that facial identity perception is quantitatively mature in infancy. Or, it might not be mature until children are 4–5 years old. Thus, although we can conclude maturity is achieved 'early', with current methods we cannot tell exactly how early.

Regarding the causal mechanisms involved at each stage of development, there has been longstanding interest in the roles of *inherited genetics* and *experience with faces* in achieving the adult level of expertise in face recognition. Some role for *genetics* is clearly indicated (heritability of developmental prosopagnosia, Duchaine, Germine, & Nakayama, 2007; twin effects on size and location of face-selective cortical areas in fMRI, Polk, Park, Smith, & Park, 2007). Recent studies also argue strongly for an

---

[17] Note our Experiment 3 used quite short presentation durations during the *test* phase; but, the topic addressed by that experiment was the ability to *encode* novel faces, and encoding time in the study phase was long (5 s).

innate component present at birth, and thus independent of face experience. Importantly, innate abilities in newborn humans (Turati et al., 2006; Turati et al., 2008) or in monkeys deprived of visual face input from birth (Sugita, 2008) include the *discrimination of individual faces*, not merely the attraction of babies' attention to faces (as has been known about for some time, see Johnson, 2005).

Regarding *experience*, there are important effects in infancy. People deprived of normal patterned visual input during infancy via congenital cataracts do not show holistic processing for faces in later life (no composite effect; Le Grand, Mondloch, Maurer, & Brent, 2004). Perceptual narrowing for faces occurs across infancy: young human infants and face-input-deprived monkeys can initially discriminate individuals of *all* tested species and races, but post-birth experience with one subtype of faces (e.g., own-species, own-race) leads older infants (and adults) to lose discrimination for individuals of non-experienced subtypes (e.g., other-species or other-race; Kelly et al., 2007; Pascalis et al., 2002; Sugita 2008). And, the loss of discrimination within non-experienced subtypes co-occurs with an improvement in discriminability of, or memory for, faces of experienced subtypes (Humphreys & Johnson, 2007).[18]

A highly influential early theory then proposed that experience effects continued into adolescence, and that the primary cause of adult face recognition expertise was 10 years or more of practice in within-class discrimination (Carey, 1992; Carey et al., 1980; Diamond & Carey, 1986). However, the present evidence of quantitative maturity of the face perception system by age 5–7 years rules out any effect of greater experience with faces on development of the face perception system after early childhood.[19] Thus, the present article demonstrates that adult ability with faces is *not* based on ongoing experience extending into adolescence.

Overall, the picture emerging from current findings is consistent with a view of face recognition in which the social importance of discrimination of conspecifics – which in humans is driven primarily by information from the face – has led to the evolution of a system where many abilities are present even at birth, and quantitative maturity of ability occurs early. Experience with faces is also important for improving face recognition skills in early infancy. However, continued experience with faces as a class after early childhood does not lead to ongoing developmental improvements in the accuracy of face perception.

7.7. Earlier maturity of behaviour than of size of cortical face recognition areas

We finish by noting a striking difference between the results of behavioural studies – supporting full maturity of face perception ability by early childhood – and results from fMRI, where development in the size of face-selective cortical areas continues well into adolescence. The Fusiform Face Area (Kanwisher, McDermott, & Chun, 1997) has received the most attention, being an area known, in adults, to be involved in the coding of facial identity (Rotshtein, Henson, Treves, Driver, & Dolan, 2005), and to show repetition priming, holistic processing, and effects consistent with face-space coding (Loffler, Yourganov, Wilkinson, & Wilson, 2005; Pourtois et al., 2005; Schiltz & Rossion, 2006). In children, the FFA is present even in young children, but it increases substantially in volume between early-to-mid childhood and adulthood (5–8 year-olds Scherf et al., 2007; 7–11 year-olds Golarai et al., 2007). This late developmental increase argues that *the size of the FFA is not a direct cause or reflection of an age-group's behavioural abilities* in face recognition.

So, what does the increasing size of the FFA represent? One possibility is that larger FFAs support developmental increases in *speed* of recognition of faces, even if FFA size has no causal influence on accuracy. A second possibility is that FFA size reflects the number of individuals with whom a participant is familiar, and that average FFA size increases across development simply because adults have met, and stored the appearance of, more people than younger children. This idea would carry the implication that storing more faces in the FFA requires dedication of more face-selective neurons; presumably, these might be taken over for this purpose from object-general areas of inferotemporal cortex surrounding the FFA. A third idea is that measured FFA size might be determined by top-down processing as well as by bottom-up face perception. That is, stronger self-guidance of attention to faces in the 'just watch' procedure of Scherf et al. (2007), or stronger implementation of strategies involved in checking for a repeated face in the 1-back task of Golarai et al. (2007) could perhaps affect the number of voxels containing face-selective cells that achieve BOLD responses above statistical threshold.

7.8. Conclusion

In the present article, we have argued that modern evidence now supports a complete reversal of early theoretical opinions regarding the behavioural development of face recognition in children. The early view (e.g., Carey, 1992; Carey et al., 1980) suggested that perceptual processing of facial identity matured very late in development – well into adolescence – and that ongoing experience with faces as a class was the causal driver of this development. The review and new results we have presented here argue, in contrast, that face recognition is fully mature – quantitatively as well as qualitatively – in early childhood (and possibly earlier). This conclusion is consistent with the picture emerging from recent infant studies, where it has been shown that even newborns demonstrate face recogni-

---

[18] An interesting question concerns how flexible the system remains to re-learning ability for initially-lost face subtypes in later life. Sangrigoli, Pallier, Argenti, Ventureyra, and de Schonen (2005) found ethnic Koreans born in Korea and adopted into Caucasian families in Europe at age 3–9 years showed, as adults, a complete reversal of the usual other-race effect, suggesting early-to-mid childhood was not too late to relearn Caucasian discrimination and lose Asian discrimination. However, at a similar developmental age, Sugita (2008) found macaques (1.5–3 years) initially exposed only to human faces could not relearn to individuate macaque faces.

[19] This is not to say, of course, there are no experience effects with different *subtypes* of faces (e.g., different races) or different *individual* faces (i.e., familiar versus unfamiliar faces): experience can change face perception for particular faces even in adulthood.

tion skills that are much better than researchers might previously have imagined. A challenge for future studies is to determine exactly when, in the birth to 5 years age range, perceptual processing of facial identity reaches adult strength.

Acknowledgements

Research supported by Australian Research Council Grant No. DP0450636 to Elinor McKone. We thank Rachel Robbins for providing the dog stimuli, and Stefan Horarik for testing some of the adults in Experiments 1 and 2.

References

Aloisi, B. A., McKone, E., & Heubeck, B. G. (2004). Implicit and explicit memory performance in children with attention deficit/hyperactivity disorder. *British Journal of Development Psychology, 22*, 275–292.

Anastasi, J. S., & Rhodes, M. G. (2005). An own-age bias in face recognition for children and older adults. *Psychonomic Bulletin and Review, 12*(6), 1043–1047.

Aylward, E. H., Park, J. E., Field, K. M., Parsons, A. C., Richards, T. L., Cramer, S. C., et al (2005). Brain activation during face perception: Evidence of a developmental change. *Journal of Cognitive Neuroscience, 17*(2), 308–319.

Bernstein, M. J., Young, S. G., & Hugenberg, K. (2007). The cross-category effect: Mere social categorization is sufficient to elicit an own-group bias in face recognition. *Psychological Science, 8*, 706–712.

Betts, J., Mckay, J., Maruff, P., & Anderson, V. (2006). The development of sustained attention in children: The effect of age and task load. *Child Neuropsychology, 12*, 205–221.

Bjorklund, D. F., & Douglas, R. N. (1997). The development of memory strategies. In N. Cowan (Ed.), *The Development of Memory in Childhood* (pp. 201–246). Hove, East Sussex: Psychology Press.

Blaney, R. L., & Winograd, E. (1978). Developmental differences in children's recognition memory for faces. *Developmental Psychology, 14*(4), 441–442.

Brace, N. A., Hole, G. J., Kemp, R. I., Pike, G. E., Van Duuren, M., & Norgate, L. (2001). Developmental changes in the effect of inversion: Using a picture book to investigate face recognition. *Perception, 30*, 85–94.

Bruce, V., Campbell, R. N., Doherty-Sneddon, G., Import, A., Langton, S., McAuley, S., et al (2000). Testing face processing skills in children. *British Journal of Development Psychology, 18*, 319–333.

Bushnell, I. W. R. (2001). Mother's face recognition in newborn infants: Learning and memory. *Infant and Child Development, 10*, 67–74.

Carey, S. (1981). The development of face perception. In G. Davies, H. D. Ellis, & J. Shepherd (Eds.), *Perceiving and remembering faces* (pp. 9–38). New York: Academic Press Inc.

Carey, S. (1992). Becoming a face expert. *Philosophical Transactions of the Royal Society of London. Series B, 335*, 95–103.

Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science, 195*, 312–314.

Carey, S., & Diamond, R. (1994). Are faces perceived as configurations more by adults than by children? *Visual Cognition, 2*(3), 253–274.

Carey, S., Diamond, R., & Woods, B. (1980). Development of face recognition – A maturational component? *Developmental Psychology, 16*(4), 257–269.

Carlesimo, G. A., Vicari, S., Albertoni, A., Turriziani, P., & Caltagirone, C. (2000). Developmental dissociation between visual and auditory repetition priming: The role of input lexicons. *Cortex, 36*, 181–193.

Cermak, L. S., Talbot, N., Chandler, K., & Wolbarst, L. R. (1985). The perceptual priming phenomenon in amnesia. *Neuropsychologia, 23*(5), 615–622.

Chance, J. E., Turner, A. L., & Goldstein, A. G. (1982). Development of differential recognition for own- and other-race faces. *The Journal of Psychology, 112*, 29–37.

Chang, P. P. W., Levine, S. C., & Benson, P. J. (2002). Children's recognition of caricatures. *Developmental Psychology, 38*(6), 1038–1051.

Cohen, L. B., & Cashon, C. H. (2001). Do 7-month-old infants process independent features of facial configurations? *Infant and Child Development, 10*, 83–92.

Cohen Kadosh, K., & Johnson, M. H. (2007). Developing a cortex specialized for face perception. *Trends in Cognitive Sciences, 11*(9), 367–369.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, P. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments and Computers, 25*, 257–271.

Cooper, P. A., Geldart, S. S., Mondloch, C. J., & Maurer, D. (2006). Developmental changes in perceptions of attractiveness: A role for experience? *Developmental Science, 9*(5), 530–543.

Corenblum, B., & Meissner, C. A. (2006). Recognition of faces of ingroup and outgroup children and adults. *Journal of Experimental Child Psychology, 93*, 187–206.

de Heering, A., Houthuys, S., & Rossion, B. (2007). Holistic face processing is mature at 4 years of age: Evidence from the composite face effect. *Journal of Experimental Child Psychology, 96*, 57–70.

Diamond, R., & Carey, S. (1977). Developmental changes in the representation of faces. *Journal of Experimental Child Psychology, 23*, 1–22.

Diamond, R., & Carey, S. (1986). Why faces are and are not special: An effect of expertise. *Journal of Experimental Psychology: General, 115*(2), 107–117.

Duchaine, B. C., Germine, L., & Nakayama, K. (2007). Family resemblance. Ten family members with prosopagnosia and within-class object agnosia. *Cognitive Neuropsychology, 24*(4), 419–430.

Duchaine, B. C., & Nakayama, K. (2006). The Cambridge face memory test: Results for neurologically intact individuals and an investigation of its validity using inverted face stimuli and prosopagnosic participants. *Neuropsychologia, 44*, 576–585.

Duchaine, B. C., & Weidenfeld, A. (2003). An evaluation of two commonly used tests of unfamiliar face recognition. *Neuropsychologia, 41*, 713–720.

Ellis, H. D. (1992). The development of face processing skills. *Philosophical Transactions of the Royal Society of London. Series B, 335*, 105–111.

Ellis, H. D., Ellis, D. M., & Hosie, J. A. (1993). Priming effects in children's face recognition. *British Journal of Psychology, 84*, 101–110.

Ellis, H. D., & Flin, R. H. (1990). Encoding and storage effects in 7-year-olds' and 10-year-olds' memory for faces. *British Journal of Development Psychology, 8*, 77–92.

Faulkner, T. F., Rhodes, G., Palermo, R., Pellicano, E., & Ferguson, D. (2002). Recognizing the un-real McCoy: Priming and the modularity of face recognition. *Psychonomic Bulletin and Review, 9*(2), 327–334.

Firestone, A., Turk-Browne, N. B., & Ryan, J. D. (2006). Age-related deficits in face recognition are related to underlying changes in scanning behavior. *Aging, Neuropsychology, and Cognition*, 1–14.

Flavell, J. H. (1985). *Cognitive development* (2nd ed.). Englewood Cliffs, New Jersey: Prentice-Hall.

Flavell, J. H., & Wellman, H. M. (1977). Metamemory. In R. V. Kail & J. W. Hagen (Eds.), *Perspectives on the development of memory and cognition*. Hillsdale, New Jersey, USA: Lawrence Erlbaum Associates.

Flin, R. H. (1980). Age effects in children's memory for unfamiliar faces. *Developmental Psychology, 16*(4), 373–374.

Flin, R. H. (1985). Development of face recognition: An encoding switch? *British Journal of Psychology, 76*, 123–134.

Freire, A., & Lee, K. (2001). Face recognition in 4- to 7-year-olds: Processing of configural, featural, and paraphernalia information. *Journal of Experimental Child Psychology, 80*, 347–371.

Gilchrist, A., & McKone, E. (2003). Early maturity of face processing in children: Local and relational distinctiveness effects in 7-year-olds. *Visual Cognition, 10*(7), 769–793.

Golarai, G., Ghahremani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D. E., et al (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience, 10*(4), 512–522.

Goshen-Gottstein, Y., & Ganel, T. (2000). Repetition priming for familiar and unfamiliar faces in a sex-judgment task: Evidence for a common route for the processing of sex and identity. *Journal of Experimental Psychology: Learning, Memory and Cognition, 26*(5), 1198–1214.

Hayden, A., Bhatt, R. S., Reed, A., Corbly, C. R., & Joseph, J. E. (2007). The development of expert face processing: Are infants sensitive to normal differences in second-order relational information? *Journal of Experimental Child Psychology, 97*, 85–98.

Humphreys, K., & Johnson, M. H. (2007). The development of "face-space" in infancy. *Visual Cognition, 15*(5), 578–598.

Johnson, M. H. (2005). Subcortical face processing. *Nature Reviews Neuroscience, 6*, 766–774.

Johnston, R. A., & Ellis, H. D. (1995). Age effects in the processing of typical and distinctive faces. *The Quarterly Journal of Experimental Psychology, 48A*(2), 447–465.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109*(3), 490–501.

Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *The Journal of Neuroscience, 17*(11), 4302–4311.

Kelly, D. J., Quinn, P. C., Slater, A., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science, 18*(12), 1084–1089.

Kylliäinen, A., Braeutigam, S., Hietanen, J. K., Swithenby, S. J., & Bailey, A. J. (2006). Face and gaze processing normally developing children: A magnetoencephalographic study. *European Journal of Neuroscience, 23*, 801–810.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science, 15*(11), 762–768.

Leopold, D. A., O'Toole, A. J., Vetter, T., & Blanz, V. (2001). Prototype-referenced shape encoding revealed by high-level aftereffects. *Nature Neuroscience, 4*(1), 89–94.

Loffler, G., Yourganov, G., Wilkinson, F., & Wilson, H. R. (2005). FMRI evidence for the neural representation of faces. *Nature Neuroscience, 8*(10), 1386–1390.

Lundy, B. L., Jackson, J. W., & Haaf, R. A. (2001). Stimulus properties, attentional limitations, and young children's face recognition. *Perceptual and Motor Skills, 92*, 919–929.

Macchi Cassia, V., Picozzi, M., Kuefner, D., Bricolo, E., & Turati, C. (2009). Holistic processing for faces and cars in preschool-aged children and adults: Evidence from the composite effect. *Developmental Science, 12*(2), 236–248.

Maurer, D., Le Grand, R., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences, 6*(6), 255–260.

McKone, E. (1995). Short-term implicit memory for words and nonwords. *Journal of Experimental Psychology: Learning, Memory and Cognition, 21*(5), 1108–1126.

McKone, E. (in press). Face and object recognition: How do they differ? In V. Coltheart (Ed.), *Tutorials in visual cognition*. Hove, UK: Psychology Press.

McKone, E., Aitkin, A., & Edwards, M. (2005). Categorical and coordinate relations in faces, or Fechner's law and face space instead? *Journal of Experimental Psychology: Human Perception and Performance, 31*(6), 1181–1198.

McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology, 94*(2), 134–162.

McKone, E., Crookes, K., & Kanwisher, N. (2009). The cognitive and neural development of face recognition in humans. In M. S. Gazzaniga (Ed.). The Cognitive Neurosciences (Vol. IV). Cambridge, Massachusetts, USA: Bradford Books.

McKone, E., Kanwisher, N., & Duchaine, B. C. (2007). Can generic expertise explain special processing for faces? *Trends in Cognitive Sciences, 11*(1), 8–15.

McKone, E., & Slee, J. (1997). Explicit contamination in "implicit" memory for new association. *Memory and Cognition, 25*(3), 352–366.

Mondloch, C. J., Dobson, K. S., Parsons, J., & Maurer, D. (2004). Why 8-year-olds cannot tell the difference between Steve Martin and Paul Newman: Factors contributing to the slow development of sensitivity to the spacing of facial features. *Journal of Experimental Child Psychology, 89*, 159–181.

Mondloch, C. J., Geldart, S., Maurer, D., & Le Grand, R. (2003). Developmental changes in face processing skills. *Journal of Experimental Child Psychology, 86*, 67–84.

Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception, 31*, 553–566.

Mondloch, C. J., Maurer, D., & Ahola, S. (2006). Becoming a face expert. *Psychological Science, 17*(11), 930–934.

Mondloch, C. J., Pathman, T., Maurer, D., Le Grand, R., & de Schonen, S. (2007). The composite face effect in six-year-old children: Evidence of adult-like holistic face processing. *Visual Cognition, 15*(5), 564–577.

Mondloch, C. J., & Thomson, K. (2008). Limitations in four-year-old children's sensitivity to the spacing among facial features. *Child Development, 79*(5), 1513–1523.

Mulligan, N. W., Duke, M., & Cooper, A. W. (2007). The effects of divided attention on auditory priming. *Memory and Cognition, 35*(6), 1245–1254.

Murphy, K., McKone, E., & Slee, J. (2003). Dissociations between implicit and explicit memory in children: The role of strategic processing and the knowledge base. *Journal of Experimental Child Psychology, 84*, 124–165.

Nelson, C. A., & Monk, C. S. (2001). The use of event-related potentials in the study of cognitive development. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience*. Cambridge, Massachusetts, USA: The MIT Press.

Nishimura, M., Maurer, D., Jeffery, L., Pellicano, E., & Rhodes, G. (2008). Fitting the child's mind to the world: Adaptive norm-based coding of facial identity in 8-year-olds. *Developmental Science, 11*(4), 620–627.

Parkin, A. J., Reid, T. K., & Russo, R. (1990). On the differential nature of implicit and explicit memory. *Memory and Cognition, 18*(5), 507–514.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296*, 1321–1323.

Pascalis, O., de Haan, M., Nelson, C. A., & de Schonen, S. (1998). Long-term recognition memory for faces assessed by visual paired comparison in 3- and 6-month-old infants. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*(1), 249–260.

Pascalis, O., & de Schonen, S. (1994). Recognition memory in 3- to 4-day-old human neonates. *NeuroReport, 5*, 1721–1724.

Pascalis, O., de Schonen, S., Morton, J., Deruelle, C., & Fabre-Grenet, M. (1995). Mother's face recognition by neonates: A replication and an extension. *Infant Behavior and Development, 18*, 79–85.

Pastò, L., & Burack, J. A. (1997). A developmental study of visual attention: Issues of filtering efficiency and focus. *Cognitive Development, 12*, 523–535.

Pellicano, E., & Rhodes, G. (2003). Holistic processing of faces in preschool children and adults. *Psychological Science, 14*(6), 618–622.

Pellicano, E., Rhodes, G., & Peters, M. (2006). Are preschoolers sensitive to configural information in faces? *Developmental Science, 9*(3), 270–277.

Pezdek, K., Blandon-Gitlin, I., & Moore, C. (2003). Children's face recognition memory: More evidence for the cross-race effect. *Journal of Applied Psychology, 88*(4), 760–763.

Polk, T. A., Park, J., Smith, M. R., & Park, D. (2007). Nature versus nurture in ventral visual cortex: A functional magnetic resonance imaging study of twins. *The Journal of Neuroscience, 27*(51), 13921–13925.

Pourtois, G., Schwartz, S., Seghier, M. L., Lazeyras, F., & Vuilleumier, P. (2005). Portraits or people? Distinct representations of face identity in the human visual cortex. *Journal of Cognitive Neuroscience, 17*(7), 1043–1057.

Rhodes, G., Brake, S., & Atkinson, A. P. (1993). What's lost in inverted faces? *Cognition, 47*, 25–57.

Rhodes, G., Brennan, S., & Carey, S. (1987). Identification and ratings of caricatures: Implications for mental representations of faces. *Cognitive Psychology, 19*(4), 473–497.

Rhodes, G., Robbins, R., Jacquet, E., McKone, E., Jeffery, L., & Clifford, C. W. G. (2005). Adaptation and face perception: How aftereffects implicate norm-based coding of faces. In C. W. G. Clifford & G. Rhodes (Eds.), *Fitting the mind to the world: Adaptation and after-effects in high-level vision* (pp. 213–240). Oxford: Oxford University Press.

Rhodes, G., Sumich, A., & Byatt, G. (1999). Are average facial configurations attractive only because of their symmetry? *Psychological Science, 10*(1), 52–58.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition, 103*(1), 34–79.

Rotshtein, P., Henson, R. N. A., Treves, A., Driver, J., & Dolan, R. J. (2005). Morphing Marilyn into Maggie dissociates physical and identity face representations in the brain. *Nature Neuroscience, 8*(1), 107–113.

Sangrigoli, S., & de Schonen, S. (2004). Effect of visual experience on face processing: A developmental study of inversion and non-native effects. *Developmental Science, 7*(1), 74–87.

Sangrigoli, S., Pallier, C., Argenti, A.-M., Ventureyra, V. A. G., & de Schonen, S. (2005). Reversibility of the other-race effect in face recognition during childhood. *Psychological Science, 16*(6), 440–444.

Scapinello, K. F., & Yarmey, A. D. (1970). The role of familiarity and orientation in immediate and delayed recognition of pictorial stimuli. *Psychonomic Science, 21*(6), 329–331.

Schacter, D. L., Alpert, N. M., Savage, C. R., Rauch, S. L., & Albert, M. S. (1996). Conscious recollection and the human hippocampal formation: Evidence from positron emission tomography. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 321–325.

Schacter, D. L., Bowers, J., & Booker, J. (1989). Intention, awareness, and implicit memory: The retrieval intentionality criterion. In S. Lewandowsky, J. C. Dunn, & K. Kirsner (Eds.), *Implicit memory: Theorectical issues*. Hillsdale, NJ: Erlbaum.

Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science, 10*(4), F15–F30.

Schiltz, C., & Rossion, B. (2006). Faces are represented holistically in the human occipito-temporal cortex. *NeuroImage, 32*, 1385–1394.

Simons, D. J., & Levin, D. T. (1998). Failure to detect changes to people during real-world interaction. *Psychonomic Bulletin and Review, 5*(4), 644–649.

Skoczenski, A. M., & Norcia, A. M. (2002). Late maturation of visual hyperacuity. *Psychological Science, 13*(6), 537–541.

Slater, A., Quinn, P. C., Hayes, R., & Brown, E. (2000). The role of facial orientation in newborn infants' preference for attractive faces. *Developmental Science, 3*(2), 181–185.

Sugita, Y. (2008). Face perception in monkeys reared with no exposure to faces. *Proceedings of the National Academy of Sciences of the United States of America, 105*(1), 394–398.

Tanaka, J. W., & Farah, M. J. (1993). Parts and wholes in face recognition. *The Quarterly Journal of Experimental Psychology, 46A*(2), 225–245.

Tanaka, J. W., Kay, J. B., Grinnell, E., Stansfield, B., & Szechter, L. (1998). Face recognition in young children: When the whole is greater than the sum of its parts. *Visual Cognition, 5*(4), 479–496.

Tanaka, J. W., & Sengco, J. A. (1997). Features and their configuration in face recognition. *Memory and Cognition, 25*(5), 583–592.

Taylor, M. J., Batty, M., & Itier, R. J. (2004). The faces of development: A review of early face processing over childhood. *Journal of Cognitive Neuroscience, 16*(8), 1426–1442.

Teunisse, J.-P., & de Gelder, B. (2003). Face processing in adolescents with autistic disorder: The inversion and composite effects. *Brain and Cognition, 52*, 285–294.

Tong, F., & Nakayama, K. (1999). Robust representations for faces: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1016–1035.

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

Turati, C., Macchi Cassia, V., Simion, F., & Leo, I. (2006). Newborns' face recognition: Role of inner and outer facial features. *Child Development, 77*(2), 297–311.

Turati, C., Sangrigoli, S., Ruel, J., & de Schonen, S. (2004). Evidence of the face inversion effect in 4-month-old infants. *Infancy, 6*(2), 275–297.

Valentine, T. (1991). A unified account of the effects of distinctiveness, inversion, and race in face recognition. *The Quarterly Journal of Experimental Psychology, 43A*(2), 161–204.

Valentine, T., & Bruce, V. (1986). The effects of distinctiveness in recognising and classifying faces. *Perception, 15*, 525–535.

Want, S. C., Pascalis, O., Coleman, M., & Blades, M. (2003). Face facts: Is the development of face recognition in early and middle childhood really so special? In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood* (pp. 207–221). New York: Nova Science Publishers.

Webster, M. A., & MacLin, O. H. (1999). Figural aftereffects in the perception of faces. *Psychonomic Bulletin and Review, 6*(4), 647–653.

Wilson, R. R., Blades, M., & Pascalis, O. (2007). What do children look at in an adult face with which they are personally familiar? *British Journal of Development Psychology, 25*, 375–382.

Yin, R. K. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81*(1), 141–145.

Young, A. W., Hellawell, D., & Hay, D. C. (1987). Configurational information in face perception. *Perception, 16*, 747–759.

Young, A. W., McWeeny, K. H., Hay, D. C., & Ellis, A. W. (1986). Access to identity-specific semantic codes from familiar faces. *The Quarterly Journal of Experimental Psychology, 38A*, 271–295.

Yovel, G., & Duchaine, B. C. (2006). Specialized face perception mechanisms extract both part and spacing information: Evidence from developmental prosopagnosia. *Journal of Cognitive Neuroscience, 18*(4), 580–593.

4.4 Relevant literature published after this paper was accepted

Since this paper was accepted for publication (February 2009) three additional studies have appeared which might be taken by some readers to be relevant to the quantitative development of *holistic processing* (Macchi Cassia et al., 2009a) and *face-space* (Anzures et al., 2009; de Heering, de Liedekerke, Deboni, & Rossion, in press). Results of these papers do not reject the conclusion drawn in Crookes and McKone (2009), namely of early quantitative maturity of both holistic processing and face-space.

In Macchi Cassia et al. (2009a), holistic processing was assessed via the inversion effect for faces. Results showed that 3-year-olds demonstrated a numerically *larger* inversion effect than the adults. The authors did not perform quantitative comparison across age groups, and indeed this would have been invalid due to the fact that ceiling effects were present in the adult group. Thus, as with most previous studies in the literature, this study allows the valid conclusion of the qualitative presence of holistic processing in 3-year-olds, but does not allow comparison of its strength across age groups (and nor was it aimed at doing so).

In Anzures et al. (2009), the situation is different in that the authors themselves made claims of ongoing perceptual development. Specifically, Anzures et al. (2009) found that, to get their attractiveness-rating adaptation aftereffect procedure to work, it was necessary to use more extreme distortion (expanded/contracted) levels on the test faces for the children (±90%, ±70%, 0%) than for the adults (±60%, ±40%, 0%); this was because pilot testing showed that the 8-year-olds did not rate the more mildly distorted faces (±40%) as less attractive than the undistorted faces (0%). Anzures et al. (2009) interpret this finding as evidence that the children had a less refined face-space than adults. I argue, however, that several other interpretations are possible. Firstly, it is possible that young children can encode the physical differences in the faces within their face-space but can not, or are unwilling to, make fine-scale subjective ratings of *attractiveness*: perhaps an interest in exact degree of people's attractiveness is something that develops only after puberty; or, because the method required participants to rate *boys* faces with regard to how "pretty" they were, the task may have been perceived as a socially unacceptable by 8-year-old children ("pretty" is a term usually reserved for describing girls). Secondly, the manipulation of attractiveness (expansion or contraction via "spherizing" the faces) was not natural, and perhaps children found it more difficult than adults to understand the artificial task; thus, the fact that they did not make fine discriminations of attractiveness amongst spherized faces does not guarantee that they were not able to make fine discriminations amongst attractiveness of natural individuals (indeed, even newborn infants can determine which of two natural faces is most attractive; Slater, Quinn, Hayes, & Brown, 2000). Thirdly, it may be that the children found the 5-point rating response cognitively demanding and that, in combination with the cognitive demands of having to make their perception of attractiveness explicit, resulted in their suffering more lapses of attention on "difficult" (±40%) trials than did adults; thus, it remains possible that children might demonstrate ability to make fine-grained distinctions of attractiveness with a simpler response task (e.g., choose the most attractive of two alternatives).

In de Heering et al. (in press) the size of the own-race effect on recognition memory was assessed in Caucasian children aged 6 to 14 years. Mean performance for the group was nicely placed in the middle of the response range for the 2AFC task (68.5% averaged across Caucasian and Asian faces). No correlation was observed between the size of the own-race effect and age (in months). This finding supports the previous reports of no change in the size of the own-race bias with age when restriction of range is avoided.

A caveat was placed on the conclusions in this paper. It was argued that while behavioural performance as measured by accuracy is mature by 4-5 years, speed of processing may continue to develop. At the time of publication there were no studies which had adequately addressed this question. A recent study (Kuefner et al., in press) argues that there is no face-specific development in speed of processing between 5 and 16 years. Kuefner et al (in press) investigated ERPs for faces and cars and found no face-specific age related changes in any aspect of the response including latency. This provides further support for the early maturity of all aspects of face identity perception.

In sum, I argue that the Crookes and McKone (2009) conclusion of early quantitative maturity is not challenged by the results of these recent papers. Also note that regarding a different topic discussed briefly in Crookes and McKone (2009) – the question of whether there is an own-age bias in adults – there are also three new studies available (de Heering & Rossion, 2008; Kuefner, Macchi Cassia, Picozzi, & Bricolo, 2008; Kuefner, Macchi Cassia, Vescovo, & Picozzi, in press), which are reviewed in Chapter 5.

CHAPTER 5 – THE COMPOSITE TASK REVEALS STRONGER HOLISTIC PROCESSING IN CHILDREN THAN ADULTS FOR CHILD FACES

5.1 Context statement

There were two aims to the study in this chapter, both of which follow directly from the previous chapter. The first aim was to investigate quantitative development in the size of the *composite effect* across age. The previous chapter concluded that holistic processing was quantitatively mature early in development based on evidence from several of the standard effects (including inversion and part-whole). However, the composite effect is a core holistic processing measure, and previous developmental studies of this effect have not allowed valid quantitative comparison of its size across age groups. The present chapter provides the first test of the size of the composite effect in children versus adults where baseline performance has been matched across the age groups. Thus, this study offers the opportunity to confirm or reject the conclusion of Crookes and McKone (2009) regarding early quantitative maturity of holistic processing, and again relates to the broader aim of this thesis of testing whether extended experience into adolescence is, or is not, needed for core face processing mechanisms to reach full maturity.

The second aim was to further investigate the origins of the own-age bias on recognition memory in children (Chapter 4, Experiment 3A) with regard to the broader aim of this thesis of investigating flexibility in the mature system. The fact that experience can affect recognition memory performance for certain face types (e.g., own-race bias) has often been used as evidence of the importance of lifetime experience over innate components in the developmental face processing literature. But, as argued in Chapter 2, this logic is flawed and often fails to separate the effects of maturation, lifetime experience, and experience during a sensitive period early in life. Given the arguments for early maturity of face processing presented so far in this thesis, evidence of an own-age effect in children and adults instead suggests that the face system is *mature* but that even a mature system *retains some flexibility* such that recent exposure to a face subtype can influence face recognition. The present chapter thus further addresses whether children aged 8-13 years – that is, older than the age of maturity found in Crookes and McKone (2009) – show continuing flexibility of face recognition, in this case by extending my earlier examination of own-age effects in implicit and explicit memory to an examination of own-age effects on holistic processing.

5.2 Publication status

This chapter was accepted for publication in June 2009 and appears as:

Susilo, T., **Crookes, K.,** McKone, E. & Turner, H. (2009), The composite task reveals stronger holistic processing in children than adults for child faces. *PLoS One, 4*(7), e6460

5.3 Author contributions (agreed to by all authors 18/6/09)

5.3.1 Conceived and designed the experiment

- This paper on an own-age bias in the composite effect was a side-line finding of a project originally asking a quite different theoretical question (heritability of the strength of the composite effect, as assessed via a twin study).
- Susilo (another PhD student in McKone's lab) came up with the idea for the original twin project, and made contact and arrangements for testing with the Australian Twin Registry.
- Susilo and McKone conceived the general design of the twin experiment.
- **Crookes** helped refine the design of the experiment providing feedback on pilot versions of the task and suggesting improvements.
- **Crookes** ensured that the task was suitable for the age range of participants to be tested.
- McKone came up with the idea of this particular paper, when data revealed a larger composite effect for child faces in children than in adults. **Crookes'** review of the literature confirmed this was a novel finding.

5.3.2 Stimuli

- Stimuli for this experiment were previously used in an unpublished honours project conducted by Turner and were all created by her.
- **Crookes** suggested their use in the present experiment.
- Susilo selected the subset of the faces used in the present experiment, and resized some of the stimuli.

5.3.3 Programming and Testing

- Susilo and **Crookes** designed the program for the task, Susilo wrote the program, and **Crookes** helped solve coding problems.
- Susilo tested pilot participants.
- Susilo and **Crookes** organised the testing materials, travelled to Sydney, set up the testing booth and tested the participants (half each).

5.3.4 Data analysis

- Susilo performed all data analysis and produced all graphs and tables.
- McKone suggested some additional analyses.

5.3.5 Literature review

- Much of the theory behind this paper and the review of the literature arose from **Crookes'** previous PhD work.
- **Crookes** directed Susilo to the relevant literature and references, and provided verbal summaries of the current state of the literature.
- Susilo came up with the general structure and 'story' for the introduction.

5.3.6 Writing

- Susilo wrote the first draft, and came up with points in the discussion.
- Susilo and **Crookes** then revised the manuscript together, and came up with the second draft.
- McKone then edited and refined the paper and produced the final draft, and made some extra points in the discussion.
- Following peer review McKone came up with the main rebuttal point.
- **Crookes** came up with summarised data from previous studies, which were included in the revision and the reply to reviewers.
- Susilo wrote the first drafts of the response to reviewers and revised manuscript.
- Susilo and **Crookes** together made revisions to both documents, and came up with the second drafts.
- McKone revised both came up with the final drafts.

OPEN ACCESS Freely available online PLoS one

The Composite Task Reveals Stronger Holistic Processing in Children than Adults for Child Faces

Tirta Susilo*, Kate Crookes, Elinor McKone, Hannah Turner

Department of Psychology, Australian National University, Canberra, Australian Capital Territory, Australia

Abstract

Background: While own-age faces have been reported to be better recognized than other-age faces, the underlying cause of this phenomenon remains unclear. One potential cause is holistic face processing, a special kind of perceptual and cognitive processing reserved for perceiving upright faces. Previous studies have indeed found that adults show stronger holistic processing when looking at adult faces compared to child faces, but whether a similar own-age bias exists in children remains to be shown.

Methodology/Principal Findings: Here we used the composite face task – a standard test of holistic face processing – to investigate if, for child faces, holistic processing is stronger for children than adults. Results showed child participants (8–13 years) had a larger composite effect than adult participants (22–65 years).

Conclusions/Significance: Our finding suggests that differences in strength of holistic processing may underlie the own-age bias on recognition memory. We discuss the origin of own-age biases in terms of relative experience, face-space tuning, and social categorization.

Citation: Susilo T, Crookes K, McKone E, Turner H (2009) The Composite Task Reveals Stronger Holistic Processing in Children than Adults for Child Faces. PLoS ONE 4(7): e6460. doi:10.1371/journal.pone.0006460

Editor: Chris I. Baker, National Institute of Mental Health, United States of America

Received April 13, 2009; **Accepted** June 26, 2009; **Published** July 29, 2009

Funding: This research was supported by Australian Research Council (http://www.arc.gov.au/) grant DP0450636 to EM. TS is grateful for scholarship support from ANU Centre for Visual Sciences and overseas student fee waiver from ANU Department of Psychology. We thank the Australian Twin Registry for their generous assistance and facilitation in data collection. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: tirta.susilo@anu.edu.au

Introduction

Several studies have suggested that own-age faces are better recognised than other-age faces, a phenomenon usually termed the *other-age effect* or *own-age bias* [1–3]. As with the more established *other-race effect* – better recognition memory for own-race relative to other-race faces (for review, see [4]) – the own-age effect suggests that the sensitivity of the human visual system in recognising individual faces is related in some way to the frequency with which that type of face is encountered in the everyday environment.

Exactly what lies behind these recognition memory biases, however, is less understood. One plausible candidate is *holistic/configural processing*, a special mechanism reserved for perceiving upright faces that integrates information (including spacing between features) from across the entire face at a perceptual level [5–8]. In the other-race effect literature, it has been demonstrated that holistic processing is indeed stronger for own-race than other-race faces, at least for Caucasian participants [9,10].

Two recent studies have found an own-age bias on holistic processing in adult participants: specifically, for adults with no special recent experience with children, holistic processing was stronger for adult faces than child faces [11,12]. In children, however, previous studies have failed to find an own-age bias on holistic processing [13,14], despite other demonstrations of an own-age bias on recognition memory [1,15].

It is notable that behind the apparently conflicting results are different experimental paradigms. The studies which found the own-age bias [11,12] used Young et al's composite face task [8], whereas the studies which found no own-age bias [13,14] used Tanaka and Farah's part-whole task [7] and Tanaka and Sengco's part-in-spacing-changed-whole task [16]. Here we aimed to contribute to the question of whether an own-age bias can be found in children by using the composite face task, and comparing the size of the composite effect in children and adults for child face stimuli. It is well established that children show a composite effect with adult faces [17–19], and also with familiar child faces [17], but to our knowledge there have been no previous tests of the composite effect for children with unfamiliar child faces, and no comparisons of the size of the composite effect for child faces (familiar or unfamiliar) between children and adults.

In the present study, if children show stronger holistic processing for own-age faces, then we predict a larger composite effect for children relative to adults. We measured the strength of the composite illusion using the standard same-different procedure (see Figure 1); this is the version of the task used in one of the studies that previously demonstrated an own-age bias on holistic processing in adults [11].

Methods

Participants

The 48 participants comprised 20 children (age range 8–13 years, $M = 10$ years, 9 female) and 28 adults (age range 22–65 years, $M = 44$ years, 26 female). Participants were twins attending

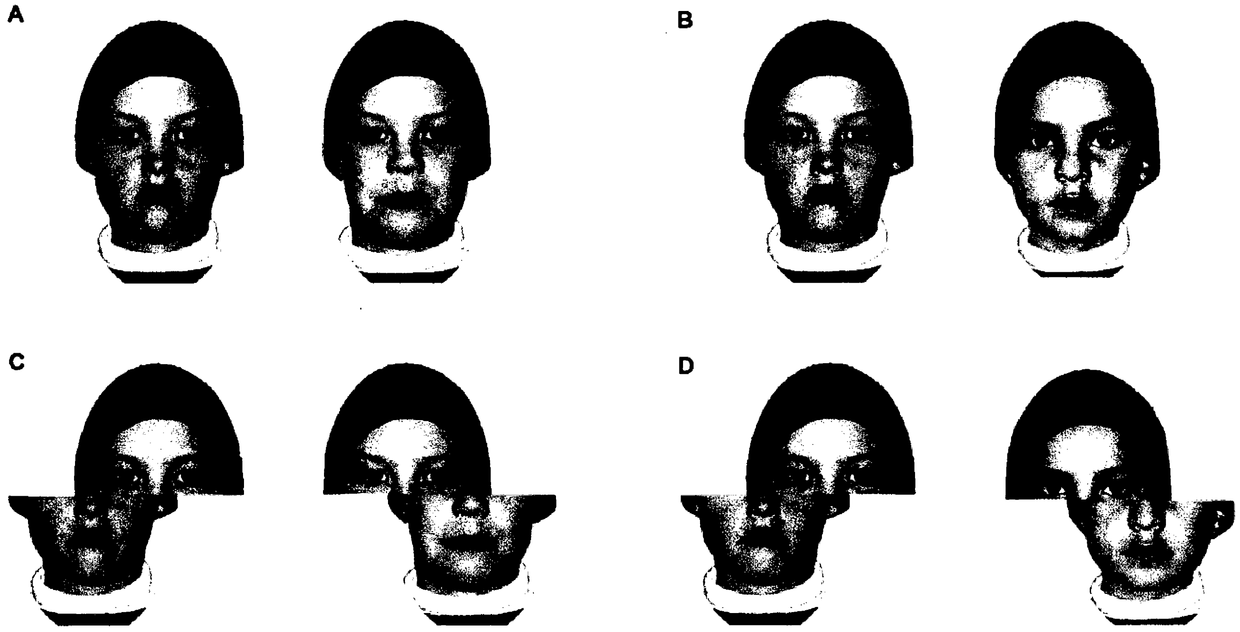


Figure 1. Examples pairs of our composite face stimuli. (A) same-aligned (SA), (B) different-aligned (DA), (C) same-misaligned (SM), and (D) different-misaligned (DM). The composite effect can be seen by comparing (A) with (C): in both cases, the two top half faces are physically identical, but, while this is easy to see in the misaligned version, it is difficult to see in the aligned version because perceptual integration of the whole face makes the top half appear different depending on which bottom half it is combined with. To tap the strength of this illusion, the composite effect is measured as the reduction in accuracy for "same" decisions in (A) as compared to (C).
doi:10.1371/journal.pone.0006460.g001

the 2009 Australian Twins Plus Festival in Sydney. (We were not interested here in twins *per se*; the present data was a serendipitous finding from a larger ongoing twin project). All were volunteers (no payment), naïve to the purpose of the study, had normal or corrected-to-normal vision, and were Caucasian (the same race as the face stimuli). Adults were a random sample of professions (i.e., as a group, they were not selected to be school teachers [11,12] or otherwise to have any specific expertise with children).

Stimuli

The original faces (i.e., from which composites were constructed) were from a database of photographs taken in Australia [20]. They were front view greyscale photographs of 48 unfamiliar Caucasian male children, with neutral expression, mostly aged 6–7 years with a few 5 year-olds. Importantly, while the specific age of the face stimuli was not matched to the age of our child participants, (a) primary school in Australia covers the age range of 5 to 12 years and so most of our child participants would see multiple 6–7 year-olds every day at school; and (b) an own-age bias on *recognition memory* for these particular faces has been previously demonstrated for children, in which the own-age advantage was as strong in older children (10–11 year-olds) as in a closely age-matched group (5–6 year-olds) [15]. A black ski-cap and white turtleneck collar were pasted onto each face to remove hair and clothing identity cues.

Figure 1 shows composite face examples. Each original face was divided horizontally below the eyes. The composite faces were created by joining the top half of one individual with the bottom half of a different individual. The top halves were always kept physically identical to the original; the size of the bottom halves was adjusted where necessary (to fit the corresponding top half). Misaligned faces were created by offsetting the top and bottom halves by half a face width. Half of the misaligned faces were offset to the left, the other half to the right. Aligned faces subtended a viewing angle of 6.3° horizontal by 9.7° vertical, and misaligned faces 8.6° horizontal by 9.7° vertical. Faces were presented against a grey background. All manipulations were done using Adobe Photoshop 5.5.

The composite faces were paired either as "same" or "different"; "same" pairs always had identical top-halves, "different" pairs always had different top-halves. The bottom halves for all pairs were always different. The result was four kinds of composite pairs: same-aligned (SA), same-misaligned (SM), different-aligned (DA), and different-misaligned (DM).

There were 30 different bottom halves and 30 different top halves. In the SA condition each top half was used once and each bottom half was used twice (because two different bottom halves were required for each pair of same top halves). The exact same composite combinations were used in the SM condition. In the DA condition each top half was shown once, 14 of the bottom halves were shown twice and two were shown once. The same composite combinations were used in the DM condition.

There were 90 composite face pairs in total, comprising 30 SA, 30 SM, 15 DA, and 15 DM pairs. The greater number of "same" pairs were intended to increase the proportion of trials relevant to the final analysis (a procedure used previously, [9,18]), because the composite score was defined in the standard way, namely as the accuracy difference between the same-aligned (SA) and same-misaligned (SM) trials [9,18,21–23]. Only "same" trials contribute to the measure of the composite effect because, while holistic processing makes a clear prediction that "same" responses should be more difficult for aligned than misaligned trials (Figure 1), it makes no prediction of the direction of the alignment effect for "different" trials (the direction will depend on the similarity of to-be-ignored bottom halves, (see [23]), with the result that analysis of "different" accuracy and d' are meaningless (for further discussion, see [24]).

Procedure

Each participant was tested using a CRT-screen iMac computer in an open function room with several other activities occurring around. They were seated at a distance of approximately 40 cm from the computer screen without any chin rest.

Participants were instructed to focus on the two top-halves of the sequentially presented pairs of faces and respond as to whether they were the same or different via a keyboard. It was emphasized that they were to ignore the bottom half of the face.

The 90 trials (30 SA, 30 SM, 15 DA, 15 DM) were displayed in random order. Each trial started with the presentation of the first face for 500 ms, followed by a blank screen for 400 ms and the second face for 500 ms. Each face appeared randomly in one of four different positions on the screen (up left, up right, down left and down right at 5° of eccentricity from the center of the screen). Following a blank screen of 400 ms, the question "Were the two top-halves same or different?" appeared until response. The next trial followed after 400 ms. Five practice trials were given.

The task was designed to measure accuracy. There were no instructions to respond quickly (and indeed we observed that some participants took their time, meaning that no analysis of reaction times was possible). We did not aim to measure reaction times because (a) it is inappropriate to measure reaction times when accuracy is set to be well below ceiling, and (b) baseline reaction times will inevitably vary substantially across ages from 8 to 65 years, affecting validity of comparison of the size of the composite effect across age [15].

Results

Results are shown in Figure 2 (also see Table 1). We analysed the 30 same-aligned and 30 same-misaligned trials only. The composite score was calculated as accuracy for misaligned trials *minus* accuracy for aligned trials.

Considering results for the full sample (Figure 2A), statistical analysis showed greater variability in composite scores for children than adults (Levene's test for equality of variances, $F = 10.32$, $p = .002$). Thus, in comparing the mean composite effect across groups, degrees of freedom were adjusted appropriately (using Welch-Satterthwaite equation via the "equal variances not assumed" output in SPSS). The composite effect was significantly larger in children (25.9%) than in adults (12.5%), $t(27.21) = 2.22$, $p < .05$, indicating stronger holistic processing for children than adults when looking at child faces.

We then conducted several analyses to confirm that this result could not be attributed to spurious confounds with other variables. First, we noted that the accuracy in the "baseline" misaligned condition was higher for adults than children, $t(46) = 3.32$, $p < .01$. Although there is no indication in Figure 2A that aligned-misaligned differences were affected by proximity to ceiling (or floor), we have argued elsewhere that much caution needs to be used when effects are compared across age groups in the presence of baseline differences [15]. Thus, we also analysed results from a *baseline-matched subset* (Figure 2B), created by removing the data of the 5 children with the lowest and 5 adults with the highest *misaligned* scores. Misaligned scores for the two groups were successfully matched (86.3% vs. 88.3%), $t < 1$, but children's mean composite score (32.3%) was still larger than adults' (10.5%), $t(19.77) = 3.31$, $p < .01$ (Levene's test for equality of variances, $F = 6.84$, $p = .013$). This analysis demonstrates that our finding of stronger holistic processing for own-age faces in children is not due to mismatched baseline performance of the two groups.

Second, it is possible that the age-group difference could be attributed to the fact that our adult sample included a very wide range of ages. If there were a reduction in holistic processing with aging (e.g., after, say, 50 years of age), or if holistic processing for child faces continued to reduce in strength the longer the time since the participant had been a child, the comparison of the composite effect in children with that in the adult group could be affected. However, Figure 2C provides a scatterplot of exact age against the composite effect score (for the full sample), and shows that there was no decline across the adult age range. Statistical analysis confirmed that, within adults, there was no correlation between age and composite score, $r(28) = .17$, $p = .398$.

Third, because our participants were twins, their performance might not have been totally independent from one another (as we have assumed above in conducting independent-samples t-tests). We therefore conducted a 2×2 ANOVA with twin pairs as a repeated measure factor and age group as a between-subject factor. The main effect of age group was again found to be significant, $F(1,22) = 37.82$, $p < .01$, confirming a larger composite effect in children than in adults.

Finally, before turning to theoretical interpretation, it is necessary to dispose of one last potential limitation in our study. This is the unequal distribution of gender across age. In the child group, 45% of participants (9 out of 20) were female, whereas in the adult group, 93% (26 out of 28) were female. This raises the possibility that the weaker holistic processing observed in adults may have something to do with being female. However, the literature suggests that it is females who have better recognition memory with faces in general [25]. More relevant to our study, females' superior recognition ability extends to child faces [26], and this sex difference is also present in children [27]. Therefore, if anything, the prediction of our study would have been stronger holistic processing for adult participants, where there was a higher proportion of females. Yet our findings were the opposite, in that it was the child participants who showed stronger holistic processing.

Discussion

Our results are novel in several ways. First, they provide the first demonstration that children show a composite effect for unfamiliar child faces. Second, they provide the first comparison of the size of the composite effect for child faces across child and adult participants, and thus provide the first evidence that the composite effect is larger in the former case. Finally, they provide the first comparison of the composite effect across participant age, for *any* age of face, that avoids problems associated with restriction of range due to ceiling effects in adults (see next section for details).

An own-age bias or a larger composite effect in children for faces of all ages?

We have shown that children have a larger composite effect than adults for child faces. Our preferred interpretation is that this arises from an own-age bias on holistic processing in child participants, and thus complements earlier demonstrations of own-age biases on holistic processing in adult participants [11,12].

However, given that we did not test an adult face set, there is an alternative possible interpretation, namely that children might show a larger composite effect that adults for *all* face ages. Previous data [18,19] do seem to show, at first glance, that children have a stronger composite effect than adults even when tested with adult faces: the size of the composite effect in de Heering et al [18] was

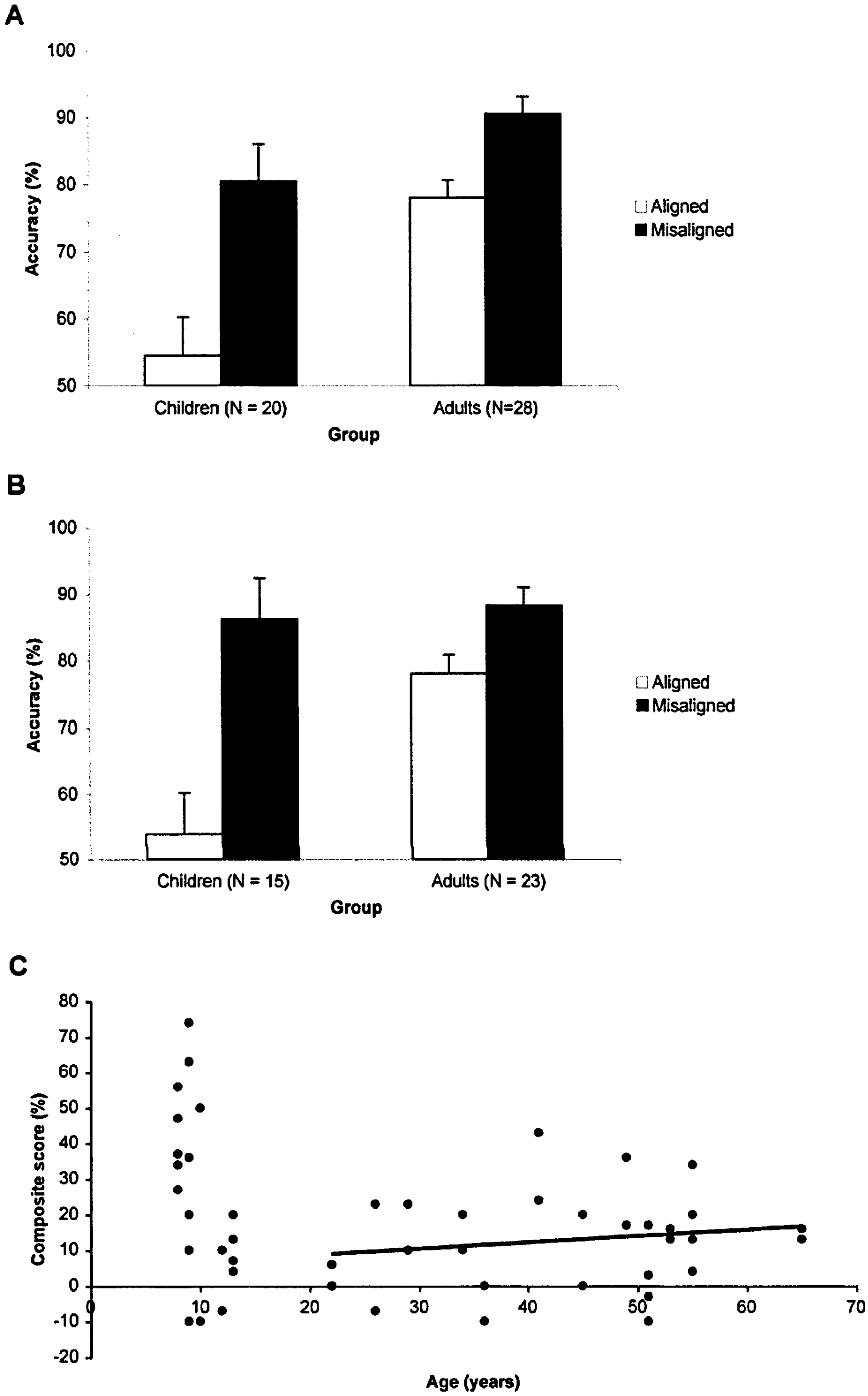


Figure 2. Results. (A) Accuracy (% correct matches) for same-aligned and same-misaligned trials in the full sample, showing a larger composite effect in children than adults. Error bars show ±1 SEM of the composite effect score, as appropriate for the within-subject comparison of aligned and misaligned. (B) The same result holds for a subset of participants for whom "baseline" performance in the control misaligned condition was matched across age groups. (C) Scatterplot of age versus composite score, with best linear fit for the adults, showing no age-related decline in holistic processing in older adults.

doi:10.1371/journal.pone.0006460.g002

Table 1. Mean accuracies for same and different trials.

Data Set	Group	N	Aligned Accuracy (%)	Misaligned Accuracy (%)	Composite Score (%) (Misaligned Accuracy - Aligned Accuracy)
Full	Children	20	54.6 (5.2)	80.5 (3)	25.9 (5.6)
	Adults	28	78.1 (2.6)	90.6 (1.5)	12.5 (2.6)
Baseline-matched	Children	15	54 (6.8)	86.3 (2)	32.3 (6.2)
	Adults	23	78.1 (2.9)	88.3 (1.5)	10.5 (2.8)

(A) Mean accuracies (% correct matches) for aligned and misaligned conditions in the full and baseline-matched datasets of the same trials. (B) Mean accuracies for aligned and misaligned conditions of the different trials. SEM in brackets.

doi:10.1371/journal.pone.0006460.t001

19% for children (aged 4–6 years) and 7% for adults; and in Macchi Cassia et al [19], with a slightly different way of creating the composites, it was 11% for children (aged 3–5 years) and 5% for adults. In both studies, however, there was a methodological issue that prevents valid comparison of the size of the composite effect across age groups. Specifically, there was a substantial difference in overall performance between age groups such that adult participants performed close to ceiling (the average of same-aligned and same-misaligned was 92% [18] and 93% [19]) while children's performance was placed nicely in the middle of the 2AFC 50–100 range (82% [18] and 77% [19]). This means that, while both studies [18,19] provide compelling and theoretically important evidence that young children show strong composite effects, the claim of a stronger composite effect in children than adults could be due simply to a restriction-of-range problem in adults. This interpretation is directly supported by two studies with adult participants [28,29], taken from the same laboratory as the de Heering et al [18] study. These studies used composite stimuli constructed in the same way as in de Heering et al [18] (i.e., with a small vertical gap between the top and bottom halves) but set task difficulty so as to avoid ceiling effects in adults (2AFC task with average of aligned and misaligned performance 86% [28] and 78% [29]). Under these circumstances, the size of the composite effect for adults was 15% [28] and 22% [29]; this is very comparable in size to that found for children in de Heering et al (19%) [18].

In addition to this evidence, there is a second reason to think that there should be no differences between the size of the composite effect between children and adults for adult faces. The composite effect is a measure of holistic processing. The disproportionate inversion effect (the amount by which the inversion-reduction in memory for faces exceeds the inversion-reduction in memory for objects) is another measure of holistic processing. For adult faces, Crookes and McKone [15] found that the disproportionate inversion effect was the same size in children and adults. Also, again using adult faces, both Crookes and McKone [15] and Carey [30] found the size of the inversion effect for faces itself was the same size in children and adults. Crucially, both studies matched baseline performance across age groups. These inversion results therefore make a strong case that holistic processing is *not* larger in children than adults for adult faces.

Taking all findings together, we believe the most probable interpretation of the present result is that it represents an own-age bias in children for children's faces. We acknowledge, however, that to date there have been no studies that allow direct valid comparison of the size of the composite effect across children and adults for adult faces, and thus it remains possible (although we believe unlikely) that future studies could demonstrate that children show larger composite effects for all face types.

Comparison with part-whole studies in children

Our composite effect results are in conflict with the two previous part-whole studies [13,14], both of which tested child faces and did not find that holistic processing was stronger in children than adults. What is the origin of this conflict? We see two possibilities.

First, it may be (again) due to the presence of baseline differences between age groups in the earlier studies, which placed scores sufficiently close to ceiling (in adults) or floor (in children) so that range to show the holistic processing effect tested might have been restricted in one or other age group. In Pellicano and Rhodes [13], the average of the two conditions compared to calculate holistic processing (part and whole) was nicely in the middle of the 2AFC accuracy scale for adults (80%), but was low enough to perhaps produce a restriction-of-range problem in children (63%). Correspondingly, children showed a nonsignificant trend towards *less* holistic processing than adults (i.e., the reverse direction to the present study). In Pellicano et al [14], there was the opposite problem of potential restriction-of-range in adults (average across whole and part-in-spacing-changed-whole conditions = 90%), but not children (average = 71%); and, correspondingly, children showed a nonsignificant trend towards *more* holistic processing than adults (i.e., the same direction as the present study). Thus, in failing to equate baselines, the methodology of [13] and [14] may have masked any own-age bias.

The second possibility is that task itself matters (part-whole [13] and part-in-spacing-changed-whole [14]) versus the composite effect (present study). That is, while the part-whole and composite effects are both widely accepted as good measures of holistic processing, there may be some poorly understood difference between them that could produce genuine differences in results for child faces between the two tasks. In the absence of part-whole studies that have equated baseline performance across age groups, however, it would premature to draw any such conclusion at this stage.

Origins of an own-age bias on holistic processing

Overall, we suggest that our results in children complement those of previous papers in adults to make a strong case that holistic processing can be influenced by own-age effects, just as it is influenced by own-race effects. This implies that differences in holistic processing for different face types may be an important variable driving corresponding differences in recognition memory for own-age as well as own-race faces.

We next consider the possible cause of an own-age bias on holistic processing. Presumably, this relates in some way to the amount of (recent) visual experience participants have with different face types: two recent studies have found that preschool teachers showed stronger holistic processing for child faces than did ordinary ("child-face-novice") adults [11,12]. (Another intriguing aspect of both studies is that while preschool teachers showed stronger holistic processing for child faces, they also showed weaker holistic processing for adult faces than the novice group. On a speculative note, this seems to indicate some kind of trade-off between the use of holistic processing for own-age and other-age faces. Perhaps holistic face processing capacity is limited such that it is automatically deployed more for the most commonly encountered or socially important face type. Our present data are silent with respect to this issue, since we did not test our child participants with adult faces. This speculation predicts that, in future studies, children with more visual experience of, or social interest toward, adult faces would show stronger holistic processing with adult faces than child faces.) Similarly, our own child participants (most of whom saw 6–7 year old faces at school every day) would have had greater recent experience with children's faces than did our adult participants (who were unselected for profession).

It remains an open question, however, as to whether the relationship of holistic processing to experience is direct or indirect. There may be a direct effect on the tuning of perceptual processing mechanisms. By analogy, dimensions of face-space are commonly argued to be tuned by recent exposure to match the "face diet" to which one has been exposed (e.g., when explaining adaptation aftereffects for faces; [31]).

Alternatively, it may be that there is no direct causal effect of experience on holistic processing, but that the relationship may arise indirectly via the correlation between experience and social categorisation, social interest, and/or attention given to difference face types. Face memory has been shown to be reduced by social outgroup categorisation [32] and, in the race field, it has been shown that strength of holistic processing can be altered merely by changing the perceived race group of an ambiguous-race face stimulus (an Asian-Caucasian morph; [33]). It may be that similar social effects contribute to other-age effects. In explaining previous findings in adults, it may be that people who choose to become preschool teachers are likely to be socially interested in children (and to not spontaneously categorise them as social outgroup members). Similarly, in our own study, the children may well have treated child faces as ingroup members more so than did the adults. Indeed, if the 8–13 year old children differed *amongst themselves* in how strongly they categorised 5–7 year old face stimuli as ingroup members, this could explain why our child group showed not only a greater mean composite score but also higher *variance* in composite scores than our adult group.

Of course, these two proposals (direct and indirect influences) are not necessarily mutually exclusive. It could be that the own-age bias on holistic processing is caused by some interaction between the amount, quality, and recency of visual experience with a face type, tuning of perceptual mechanisms, and social categorization.

Development of the "special" aspect of face recognition

Finally, our results have theoretical implications for a topic quite different than own-age bias, namely the development of the "special" aspect of face recognition across childhood. It is now widely agreed that holistic processing is qualitatively present in very young children (i.e., all the standard phenomena have been demonstrated at 4–5 years, including composite, part-whole, inversion, sensitivity to spacing between facial features [13,15,18,34]). There have been different recent views, however, about whether holistic processing remains immature until late in childhood in the sense that it is *quantitatively* weaker in children than in adults [15,35]: results of many studies do suggest this on a *prima facie* basis [35] but we have argued elsewhere [15] that the findings of increases in holistic processing effects with age are unreliable due to substantial baseline changes across age groups. Our present study joins an emerging literature arguing that holistic processing is in fact quantitatively mature earlier rather than later (for review see [15]). In fact, our findings show that it is possible for children's holistic processing to be *stronger* than adults'.

Author Contributions

Conceived and designed the experiments: TS KC EM. Performed the experiments: TS KC. Analyzed the data: TS. Wrote the paper: TS KC EM. Designed the stimuli: HT. Responsible for literature review: KC TS.

References

1. Anastasi JS, Rhodes MG (2005) An own-age bias in face recognition for children and older adults. Psychonomic Bulletin & Review 2005: 1043–1047.
2. Kuefner D, Macchi Cassia V, Picozzi M, Bricolo E (2008) Do all kids look alike? Evidence for an other-age effect in adults. Journal of Experimental Psychology: Human Perception and Performance 34: 811–817.
3. Lamont AC, Stewart-Williams S, Podd J (2005) Face recognition and aging: Effects of target age and memory load. Memory and Cognition 2005: 1017–1024.
4. Meissner CA, Brigham JC (2001) Thirty years of investigating the own-race bias in memory for faces: A meta-analytic review. Psychology, Public Policy, & Law 7: 3–35.
5. Maurer D, Le Grand R, Mondloch CJ (2002) The many faces of configural processing. Trends in Cognitive Sciences 6: 255–260.
6. McKone E, Kanwisher N, Duchaine BC (2007) Can generic expertise explain special processing for faces? Trends in Cognitive Sciences 11: 8–15.
7. Tanaka JW, Farah MJ (1993) Parts and wholes in face recognition. Quarterly Journal of Experimental Psychology A 46: 225–245.
8. Young AW, Hellawell D, Hay DC (1987) Configurational information in face perception. Perception 16: 747–759.
9. Michel C, Rossion B, Han J, Chung CS, Caldara R (2006) Holistic processing is finely tuned for faces of our own race. Psychological Science 17: 608–615.
10. Tanaka JW, Kiefer M, Bukach CM (2004) A holistic account of the own-race effect in face recognition: Evidence from a cross-cultural study. Cognition 93: B1–B9.
11. de Heering A, Rossion B (2008) Prolonged visual experience in adulthood modulates holistic face perception. PLoS ONE 3: e2317.
12. Kuefner D, Macchi Cassia V, Vescovo E, Picozzi M (in press) Natural experience acquired in adulthood enhances holistic processing of other-age faces. Visual Cognition.
13. Pellicano E, Rhodes G (2003) Holistic processing of faces in preschool children and adults. Psychological Science 14: 618–622.
14. Pellicano E, Rhodes G, Peters M (2006) Are preschoolers sensitive to configural information in faces? Developmental Science 9: 270–277.
15. Crookes K, McKone E (2009) Early maturity of face recognition: No childhood development of holistic processing, novel face-encoding, or face-space. Cognition 111: 219–247.
16. Tanaka JW, Sengco JA (1997) Features and their configuration in face recognition. Memory and Cognition 25: 583–592.
17. Carey S, Diamond R (1994) Are faces perceived as configurations more by adults than by children? Visual Cognition 1994: 253–274.
18. de Heering A, Houthuys S, Rossion B (2007) Holistic face processing is mature at 4 years of age: Evidence from the composite face effect. Journal of Experimental Child Psychology 96: 57–70.
19. Macchi Cassia V, Picozzi M, Kuefner D, Bricolo E, Turati C (2009) Holistic processing for faces and cars in preschool-aged children and adults: Evidence from the composite effect. Developmental Science 12: 236–248.
20. Gilchrist A, McKone E (2003) Early maturity of face processing in children: Local and relational distinctiveness effects in 7-year-olds. Visual Cognition 10: 769–793.
21. Goffaux V, Rossion B (2006) Faces are "spatial"- holistic face perception is supported by low spatial frequencies. Journal of Experimental Psychology: Human Perception and Performance 32: 1023–1039.
22. Le Grand R, Mondloch CJ, Maurer D, Brent HP (2004) Impairment in holistic face processing following early visual deprivation. Psychological Science 15: 762–768.
23. Robbins R, McKone E (2007) No face-like processing for objects-of-expertise in three behavioural tasks. Cognition 103: 34–79.
24. McKone E, Robbins R (2007) The evidence rejects the expertise hypothesis: Reply to Gauthier & Bukach. Cognition 103: 331–336.
25. Ellis H, Shepherd J, Bruce A (1973) The effects of age and sex upon adolescents' recognition of faces. Journal of Genetic Psychology 123: 173–174.
26. Rehnman J, Herlitz A (2007) Women remember more faces than men do. Acta Psychologica 124: 344–355.
27. Rehnman J, Herlitz A (2006) Higher face recognition ability in girls: Magnified by own-sex and own-ethnicity bias. Memory 14: 289–296.

28. Goffaux V, Rossion B (2006) Faces are "spatial"- holistic face perception is supported by low spatial frequencies. Journal of Experimental Psychology: Human Perception and Performance 32: 1023–1039.
29. Rossion B, Boremanse A (2008) Nonlinear relationship between holistic processing of individual faces and picture-plane rotation: evidence from the face composite illusion. Journal of Vision 8: 1–13.
30. Carey S (1981) The development of face perception. In: Davies G, Ellis HD, Shepherd J, eds. Perceiving and Remembering Faces. New York: Academic Press. pp 9–38.
31. Rhodes G, Robbins R, Jaquet E, McKone E, Jeffery L, et al. (2005) Adaptation and face perception - How aftereffects implicate norm-based coding of faces. In: Clifford CWG, Rhodes G, eds. Fitting the Mind to the World: Adaptation and After-Effects in High-Level Vision. Oxford: Oxford University Press. pp 213–240.
32. Bernstein MJ, Young SG, Hugenberg K (2007) The cross-category effect: Mere social categorization is sufficient to elicit an own-group bias in face recognition. Psychological Science 18: 706–712.
33. Michel C, Corneille O, Rossion B (in press) Holistic face encoding is modulated by perceived face race: Evidence from perceptual adaptation. Visual Cognition.
34. McKone E, Boyer BL (2006) Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. Journal of Experimental Child Psychology 94: 134–162.
35. Mondloch CJ, Le Grand R, Maurer D (2002) Configural face processing develops more slowly than featural face processing. Perception 31: 553–566.

5.4 Susilo, Crookes, McKone & Turner (2009) – addendum

The final published version of this paper was missing section B of Table 1. Below is the full table as originally intended.

Table 1.
Mean accuracies for same and different trials

A

Data Set	Group	N	Aligned Accuracy (%)	Misaligned Accuracy (%)	Composite Score (%) (Misaligned Accuracy - Aligned Accuracy)
Full	Children	20	54.6 (5.2)	80.5 (3)	25.9 (5.6)
	Adults	28	78.1 (2.6)	90.6 (1.5)	12.5 (2.6)
Baseline-matched	Children	15	54 (6.8)	86.3 (2)	32.3 (6.2)
	Adults	23	78.1 (2.9)	88.3 (1.5)	10.5 (2.8)

B

Group	N	Aligned Accuracy (%)	Misaligned Accuracy (%)
Children	20	79.6 (3.7)	69.4 (3.9)
Adults	28	85.9 (2.3)	71.2 (4.2)

(A) Mean accuracies (% correct matches) for aligned and misaligned conditions in the full and baseline-matched datasets of the same trials. (B) Mean accuracies for the aligned and misaligned conditions of the different trials. *SEM* in brackets.

5.5 Discussion – Own-age bias findings in this thesis

In the context of the thesis, recall that the first aim of the present chapter was to investigate quantitative development in the size of the composite effect across age. Here, results are clear. Findings were in agreement with the conclusions of Chapter 4 (Crookes & McKone, 2009), in showing that holistic processing was quantitatively mature in children (i.e., not quantitatively weaker in children than in adults).

The second aim of the chapter, with regard to the broader thesis aim of investigating flexibility in the mature system, was to further investigate own-age bias effects. To summarise the findings of the present thesis, results showed an own-age bias in children for recognition memory (Chapter 4, Experiment 3A) and strength of holistic processing (Chapter 5) but not in implicit memory (Chapter 4, Experiment 3B). These findings argue that the mature face processing system does retain some flexibility such that recent experience with a face subtype not only affects recognition but also perception. But note this flexibility is not necessarily in the face system itself.

In Chapter 4 the finding of an own-age bias for explicit memory in children was argued to be the result of attentional and/or social factors rather than direct perceptual factors as no equivalent bias was found on implicit memory. Does our finding of an own-age bias on holistic processing (a perceptual measure) contradict this interpretation? I argue not: perception itself may also be affected by these top-down influences. Several authors have argued that social categorisation of a face as an outgroup member can have the effect of *switching off* the normal perceptual individuation mechanisms that are automatically engaged for ingroup members (e.g., Bernstein, Young, & Hugenberg, 2007; Simons & Levin, 1998). Under this view, lack of holistic processing (or of other perceptual mechanisms involved in individuation) for other-group faces would not necessarily reflect an *inability* of the perceptual system to encode the physical form of the stimulus face in a normal manner, but instead merely a *lack of engagement* of that perceptual system. This effect has been shown directly in the other-race literature. Michel, Corneille and Rossion (2007) reported that the composite effect for morphed ambiguous-race faces was modulated by categorisation as own- or other-race. The fact that holistic processing for ambiguous-race faces was strong in one perceived-race condition demonstrates that the weak holistic processing for exactly the same stimuli in the other perceived-race condition cannot be due to a lack of *ability* to perceptually encode the stimulus faces; instead, it must reflect a lack of engagement of the relevant perceptual system. Thus, in the present thesis, the holistic processing and explicit/implicit memory results are compatible if it is presumed that perceiving a face as not own-age may partially switch off normal holistic face processing mechanisms (either via lack of attention, or via some effect of social outgroup categorisation).

This interpretation then poses an additional question: Why do we observe an own-age bias on the composite effect but not on implicit memory for children in overlapping age groups, when both are argued to be measures that tap face perception? This remains an open question. One possible answer is that the composite effect taps *conscious* face perception, while implicit memory taps the *unconscious* influences of perceptual encoding. It is known that conscious and unconscious perception can be dissociated, including for faces. For example, there are cases of acquired prosopagnosia in which the subject demonstrates implicit knowledge of a person's appearance without any apparent ability to access this knowledge explicitly (e.g., de Haan, Young, & Newcombe, 1987). This raises the novel idea that perhaps the social factors affecting face processing do not actually disrupt the engagement of the perceptual measures per se, but instead disrupt conscious access to the output of these mechanisms.

A final topic to which the own-age results are relevant is the question of *when in life* experience affects face recognition. Chapter 2 noted that findings that differential exposure to face subtypes (e.g., more experience with own-race face than other-race faces, or with human faces than with chimpanzee faces) influence face processing has been used to support arguments that lifetime experience with faces is the origin of adult abilities with faces (e.g., Martin-Malivel & Okada, 2007), reflecting the classic Carey and Diamond (1994) idea that *total* lifetime experience is the key factor because increased experience produces greater expertise in individuating faces. As previously discussed, a core role for total lifetime experience is rejected empirically by findings of expertise without face experience (in newborns and face-deprived monkeys) and also by the evidence of early quantitative maturity in Chapter 4 (Crookes & McKone, 2009). It is further rejected by the results of Chapter 5: while the own-age bias on holistic processing certainly argues that experience can affect face recognition, it refutes the idea that *total* lifetime experience is the relevant factor. Total lifetime experience would have predicted holistic processing could never be stronger in children than in adults, because the adult participants were once children and so have had at least as much total lifetime experience with 5-7 year-old faces as have the 8-13 year-old participants.

The results of Chapter 5 thus allow us to tease apart the effects of total lifetime experience versus recent experience. The findings clearly support the view that it is *recent* experience that modulates face processing: child participants have stronger recent exposure to 5-7 year-old faces than typical adults, corresponding to our finding of stronger holistic processing in children than in adult participants. This idea can also explain the results of two recent studies examining own-age bias effects on holistic processing in adults with different levels of experience with children (de Heering & Rossion, 2008; Kuefner et al., in press). These studies found that adults with strong recent experience with children (preschool teachers) showed stronger holistic processing for child faces, relative to adult faces, than did typical adults with no special recent experience with children.

In conclusion, our results argue that, although children's face perception system is mature early, this mature system retains flexibility such that concentrated recent exposure to a face subtype can influence the operation of this system (or perhaps conscious access to its outputs), including at a perceptual level. The exact mechanism via which experience produces this influence has not yet been established. It appears unlikely that the mechanism is direct changes to tuning of the perceptual mechanisms themselves (e.g., better ability in holistic processing, better tuning of face-space dimensions), and presumably arises through indirect effects of social or attentional factors.

CHAPTER 6 – EXPERTISE WITHOUT EXPERIENCE: 4-MONTH-OLD INFANTS INDIVIDUATE UPRIGHT HORSES

6.1 Context statement

The previous two chapters established that face perception is mature early in childhood and that adult expertise with faces is not based on ongoing experience with faces into adolescence. This finding resolves a longstanding inconsistency between the remarkable face discrimination abilities displayed by neonates and the protracted development seen on face tasks into adolescence. Instead it appears, based on evidence of remarkable early abilities, perceptual narrowing and critical/sensitive period for faces, that adult expertise for faces results from a combination of an experience-expectant innate representation and early experience with the faces of conspecifics.

This chapter turns to infancy and addresses the third main aim of this thesis: to investigate the nature of the experience-expectant component present at birth. Specifically, this chapter investigates two questions raised in Chapter 2: (1) Is the innate component which supports face discrimination specifically a *face* representation or is it broader?; and (2) How tightly tuned is the representation to conspecifics (for humans, does it include non-human primates, for example, but not all mammals)?

6.2 Publication status

This chapter has been written as a paper for submission, in a format suitable for Developmental Science. It will be submitted as:

Crookes, K. & McKone, E. Expertise without experience: 4-month-old humans individuate upright horses.

6.3 Author contributions

6.3.1 Literature review

- **Crookes** was responsible for the literature review, including literature searches, reading papers, understanding methods and results, summarising findings, and noting methodological issues.

6.3.2 Conceived and designed the experiment

- All experiments were conceived and designed by **Crookes** in conjunction with McKone.

6.3.3 Designed and built baby lab

- **Crookes** researched and designed the baby lab and oversaw construction
- **Crookes** was responsible for procuring appropriate software and equipment

6.3.4 Programming and Testing

- **Crookes** programmed all the tasks and created the stimuli
- **Crookes** arranged all the infant testing including ethics clearance from the health department and the university, establishing contact and liaising with paediatricians, nurses and department of health officials to advertise the study
- **Crookes** collected all the infant and adult data

6.3.5 Data analysis

- **Crookes** was responsible for deciding what statistical analysis would be performed.
- McKone suggested additional analyses.
- **Crookes** performed all the data analysis.

6.3.6 Theory development

- **Crookes** and McKone worked together to develop the arguments and theories presented

6.3.7 Writing

- **Crookes** wrote the paper and produced all the tables and figures
- McKone then edited and refined the paper

6.4 Abstract

Face individuation undergoes perceptual narrowing across infancy, arguing for a broadly tuned innate representation. Previous studies have shown this representation encompasses monkey as well as human faces, but it has implicitly been assumed that it is of a *face*. Here, we consider the possibility that it is even broader. We tested individual level discrimination of whole animals (bay thoroughbred horses, shown in side view), in 4-month-olds (before any narrowing for faces has been observed). Horses and human faces were equated for visual similarity as demonstrated by matched performance in adults for the inverted orientation. Results then showed that infants could discriminate upright horses at least as well as upright faces, despite adults showing the expected pattern of poor discrimination of upright horses relative to upright faces. Infants did not discriminate inverted horse stimuli. Our findings imply innate individuation is broader than a primate face, encompassing at least other mammal heads (in profile view), and perhaps full bodies of all animals.

6.5 Introduction

Accurate face recognition early in life is socially important and has the potential to confer an evolutionary advantage. Correspondingly, there has long been speculation that there may be some component to face recognition skill that is present at birth.

Early studies showed that newborn infants track a face-like pattern of blobs further than an inverted or scrambled pattern, indicating that faces are special very early in life, and that face preference is unlikely to be explained by experience only (Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). One influential early theory arguing for an innate representation was proposed by Morton and Johnson (1991), who argued that infants are born with a face-specific subcortical system which orients attention to faces (Conspec), with individual level discrimination then developing later (around 3 months) and performed by a second system (Conlern). Others have argued that the infant preference for faces might arise not from a specific face bias, but rather from a number of non-specific biases in the infant visual system (e.g., preference for stimuli with more elements in the upper half of the visual field) which coincidentally occur in faces (for review see Simion, Macchi Cassia, Turati, & Valenza, 2003). In this way, there would be no innate "face" component, but rather a preference for looking at stimuli which share certain characteristics most commonly found in faces.

More recently, however, three lines of evidence have emerged which argue strongly that an "experience expectant" innate[2] capacity, first proposed by Nelson (Nelson, 2001), is capable of much more than simple orienting to faces. Human neonates can discriminate their mother from other similar looking females at less than 5 days old (Bushnell, 2001; Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995), although there is some evidence that this maybe reliant on prenatal experience with their mother's voice (Sai, 2005). At 1-3 days old, neonates can also discriminate previously unfamiliar female faces without hair: that is, following habituation to one individual infants will look longer at a "new" identity face compared to the "old" habituated face (Turati, Macchi Cassia, Simion, & Leo, 2006). Turati et al. (2006) further found that infants can perform this discrimination when the faces are upright but not inverted, in a pattern similar to the standard "inversion effect" in adults (i.e., more accurate recognition of upright than upside-down faces; Yin, 1969). At the same age, infants can even recognise a previously unfamiliar individual across a view change. Turati, Bulf and Simion (2008) found that, for example, infants habituated to a three-quarter profile view of a face, then tested with front view stimuli will look longer at a "new" face than the "old" face identity. However, this generalisation across views had limits, in that infants could only perform the discrimination from front to three-quarter view (and vice versa), but not from three-quarter view to profile.

These studies demonstrate advanced face processing skills in human neonates, which include *individual-level discrimination*, not merely orienting. Further evidence that early face discrimination ability does not require experience comes from a study of monkeys raised without face input from birth. Sugita (2008) found that 6-24 month-old face-deprived monkeys, upon first exposure to faces, demonstrated not only a preference for photographs of faces over other novel objects, but were also able to make fine discriminations between very similar individual faces (e.g., differing only in the spacing between the eyes and between eyes and mouth).

A second source of evidence that innate contributions to face recognition are more complex than simply an orienting device comes from the effects of lack of face experience during a critical or sensitive period in infancy. Critical/sensitive periods are

---

[2] Throughout this article, the term "innate" should be read as shorthand for "experience-expectant innate": we make no claims that face processing is fully mature at birth and in fact argue for the importance of early experience.

found where, in the absence of expected appropriate input, an inborn neural system is taken over for another purpose (see Sengpiel, 2007 for review). Infants born with dense bilateral cataracts preventing all pattern visual input until the cataracts were removed at approximately 2-19 months of age show deficits later in life, even with more than 9 years of post-operative experience with faces, in both holistic face processing (e.g., composite effect, Le Grand, Mondloch, Maurer, & Brent, 2004; spacing sensitivity, Le Grand, Mondloch, Maurer, & Brent, 2001) and cross-view face recognition (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002).

Final evidence for advanced innate face recognition abilities comes from findings supporting an inborn ability to discriminate individuals not only of one's own species of primate, but individuals of another species which the infant has had no prior experience. *Perceptual narrowing* refers to the situation in which an initially broadly tuned inborn system becomes more specific when experience is limited to a subset of a stimulus class. For instance, in the language domain, infants are born with the ability to discriminate all phonemes from all languages. By 6-12 months of age, phoneme discrimination is limited to those present in the language(s) to which the infant has been exposed (Kuhl, Tsao, & Liu, 2003).

In the face domain, evidence argues that the representation supporting face individuation starts out broadly tuned – encompassing nonhuman primate faces and faces of all human races – and becomes own-species and own-race specific with experience. Six-month-old human infants demonstrate individual level discrimination of both human faces and monkey faces, but 9-month-olds and adults show discrimination ability limited to human faces (Pascalis, de Haan, & Nelson, 2002). Narrowing is not observed if the infants received experience with monkey faces between 6 and 9 months (Pascalis et al., 2005), and this is dependent on the quality of experience: individual level naming experience maintains discrimination ability whereas categorisation as "monkey" or simple exposure still results in narrowing (Scott & Monesson, 2009). Similarly, the face-deprived monkeys of Sugita (2008) could initially perform discrimination of both monkey and human faces but following 1 month of exposure to a single face type (either monkey or human) discrimination had become limited to the species experienced. In the case of the monkeys exposed to human faces, discrimination of monkey faces was not relearned despite later receiving 11 months of experience sharing a cage with other monkeys.

Narrowing for race-of-face has also been observed in human infants. Kelly et al. (2007) found that 3-month-old Caucasian infants with little or no experience with Asian or African faces could discriminate faces from all three races across a view change. At 6-months the ability to discriminate African faces had been lost, and by 9-months infants could only discriminate Caucasian faces.

Taken together all these studies demonstrate that, for upright but not inverted faces, babies demonstrate expertise without experience in individual-level discrimination. Results argue that infants are born with a representation that starts out broadly tuned, supporting discrimination of other-primate-species and other-race faces at 3-6 months. The representation then narrows with experience, to be human face and own-race specific by 9 months.

Throughout these previous studies it has been presumed that the innate representation, while broadly tuned at birth, is specifically a *face* representation. It is possible, however, that the innate representation is in fact broader that is an innate individuation ability. In the present study, we investigate the possibility that whole animal bodies are a candidate for inclusion in an innate individual-level identification system.

There are at least two reasons to consider whole animals. First, a study using the change-blindness procedure of Rensink, O'Regan & Clark (1997), in adults, found that participants were less blind to changes in a natural scene where these changes involved an animal (e.g., addition of a lion to a savannah scene), than other types of objects (e.g., trees, vehicles, buildings; New, Cosmides, & Tooby, 2007). Thus, although typical adults have poor ability to *individuate* animals (e.g., dogs of a given breed, Diamond & Carey, 1986; Robbins & McKone, 2007), it seems that animals retain some special status in terms of *attracting attention.* Second, in infants, there is evidence of at least some type of innate whole-animal representation. Specifically, Simion, Regolin & Bulf (2008) demonstrated that human newborns (1-5 days old) prefer upright biological motion (point light motion) of walking *chickens* to inverted or scrambled chicken motion. An open question is whether this innate animal representation can support individual level discrimination.

There are a number of previous studies of infants viewing photographs of individual animals of a given species. None, however, have addressed the question of whether infants can tell apart the identity of those individual animals. Previous studies of whole animal recognition have focussed on categorisation at a species level (e.g., showing that 3-4 month-olds can deduce the categories 'cat' versus 'dog'; Quinn & Eimas, 1996, 1998). Where within class discrimination has been tested (e.g., Siamese cat 1 vs. Siamese cat 2), stance has varied substantially between the images (e.g., sitting vs. standing), meaning that results could reflect discrimination of pose rather than identity (6-month-olds; Quinn, 2004).

The aim of the present study was to investigate the breadth of the innate representation driving adult face-specificity for individuation. Identity discrimination within a class of whole animal bodies was tested at an age (4 months) before any narrowing for faces has been observed, to examine whether the representation is restricted to faces-only (but broad enough to include primate faces) or includes whole animals.

Our animal category was bay thoroughbred horses, photographed in side view. These were selected because a large range of high quality colour photographs is available from sire websites, all of which present the horse in a highly standard stance, thus minimising low-level image differences between individual exemplars. Our task was a particularly demanding (in the infant context) discrimination task, requiring the recognition of *three* different horse identities: infants habituated to an alternating sequence of two different horses, after which we tested whether the infant could discriminate a third new horse (i.e., looked longer at the new horse than at a randomly-chosen one of the two old horses). This procedure has previously been used with faces, where it has been shown that 7-month-olds can discriminate the identity of the three different faces (Cohen & Cashon, 2001).

6.6 Experiment 1 – disproportionate inversion effect for faces versus horses in adults

Our infant experiments measured both discrimination of horses and discrimination of faces. To ensure any difference in discrimination performance for upright horses and upright faces was not due to differences between stimulus sets in physical similarity (i.e., the face set being intrinsically more discriminable than the horse set, or vice versa), we first ran an adult experiment demonstrating matched performance for face and horse sets in the *inverted* orientation.

A standard finding in adults is that, while all objects with a natural upright are individuated slightly better upright than upside-down, this upright advantage is much larger for faces than for other object classes (e.g., Yin, 1969) including whole animal bodies (dogs, Diamond & Carey, 1986; Robbins & McKone, 2007). This finding is attributed to the special holistic/configural processing that has been shown to operate for upright faces, but not for inverted faces, or for objects in either orientation (e.g., Robbins & McKone, 2007; Tanaka & Farah, 1993; Young, Hellawell, & Hay, 1987). Our rationale for matching our horse and face sets for inverted recognition accuracy was therefore to assess perceptual similarity of the two stimulus sets while avoiding the effects of special processing mechanisms that would differ between the two stimulus classes.

If our stimuli are shown in Experiment 1 to produce matched performance for inverted faces and inverted horses in adults, then we will be able to argue that any finding of good (or poor) discrimination of horses in our infant experiments is not an artefact of stimulus selection. In addition, in the context of matched inverted performance, if we show the expected result that adults discriminate the upright horses more poorly that the upright faces, this will mean that a finding of good upright horse discrimination in infants would indicate perceptual narrowing by adulthood.

6.6.1 Method

6.6.1.1 Participants

Participants were 20 adults (mean age 22.05 years; 8 males) from the Australian National University community. All were Caucasian (the same race as the face stimuli), and were paid $5 for the 30 min experiment.

6.6.1.2 Design

The task was designed to logically match the task the infants would be performing, except for the use of a direct recognition memory task rather than looking time to assess discrimination. Participants were presented with 2 faces (or horses) sequentially, followed by a third face (or horse). They were asked to respond if the third face (horse) was “old” (one of the previous two) or “new” (not one of the previous two). Stimulus class (faces, horses) and orientation (upright, inverted) were varied within-subjects. Participants completed one block of upright and one block of inverted trials with order counterbalanced across participants. Within each block face and horse trials were intermixed. The same stimuli were used upright and inverted. Dependent measures were Hits, False Alarms, and a corrected recognition memory score (% hits - % false alarms).

6.6.1.3 Materials

Stimuli were colour photographs of 12 faces and 12 horses presented against a uniform grey background (see Figure 1). Faces were front view photographs of Caucasian females with neutral expressions and no glasses or make-up, from the Australian National University face database. Faces were cropped at the neck and retained ears and cheek and chin shape. The same grey headband was pasted on each face to remove hair cues to identity. Distinguishing features such as birthmarks, blemishes and earrings were removed. Faces were sized 20cm vertical (top of headband to bottom of the visible neck) by 14.4-16.5cm (average 15.2cm) horizontal (ear to ear), corresponding to 22.6° to 17.3° at the viewing distance of 50cm.

Horses were side view photographs of bay thoroughbred stallions pictured in the same stance. Photographs were from www.stallions.com.au, an online sire database. Horses were cropped to exclude background. Extraneous identifying features such as brands were removed. Where grass obscured the hoofs, new hoofs were pasted on. All horses were wearing a bridle. Horses were 20cm horizontal (nose to tail) by 14.5-16.7cm (average 15.6) vertical (tip of ears to hoofs), corresponding to 22.6° by 17.7°.

Inverted stimuli were created by rotating the photographs 180°. Adobe Photoshop 7.0 was used for all manipulations.

Stimuli were organised into sets of three (see Figure 1). There were 4 triplets of faces (A, B, C & D) and 4 triplets of horses of similar exact shades of bay (A, B, C & D). The final items included in the stimulus set, and the combinations these items into specific triplets, were the result of extensive pilot testing to match discrimination performance for faces and horses inverted.

Figure 1. (1) Face and (2) horse triplets A-D.

6.6.1.4 Procedure

Stimuli were presented on a CRT screen eMac computer using Psyscope X software (Cohen, MacWhinney, Flatt, & Provost, 1993; http://psy.ck.sissa.it/). Participants were tested individually in a quiet room. During a practice block (16 trials) using brightly coloured cartoon dinosaurs as stimuli, feedback on incorrect responses was provided.

Each trial began with a black fixation cross in the centre of the screen for 1000ms. The first stimulus was then presented for 400ms, followed by 800ms of blank screen and the second stimulus for 400ms. A red fixation cross then appeared in the centre of the screen for 1000ms followed by the third stimulus which was presented until response. Participants were instructed to respond as to whether the third stimulus of each trial was “old” (in the first two stimuli) or “new” via keyboard buttons. There was no feedback during experimental trials.

A 1 minute break followed the first block. Participants then completed the remaining block (e.g., inverted if upright was presented first).

In each block there were 96 trials (48 face and 48 horse trials, intermixed and in different random order for each subject). The third stimulus was “old” on 50% of trials. There were 12 trials for each triplet shown in Figure 1. Each individual face or horse was presented four times as the first stimulus of the trial, four times as the second stimulus and four times as the third stimulus (twice as “new” and twice as “old”).

6.6.2 Results

The aim in creating the stimuli was to match performance for the inverted condition across stimulus class. Given the nature of the task, this required matching hits, false alarms and corrected recognition scores. This was achieved (Table 1). Performance for inverted faces and inverted horses did not differ on all three measures: hits $t(19) = 1.08, p > .2$; false alarms $t < 1$; corrected recognition $t < 1$.

Table 1. Results of Experiment 1: Adult data showing discrimination (recognition memory for the third item in the triplet) for the face and horse stimulus sets.

		% old to old item (hits)	% old to new item (false alarms)	Corrected recognition (hits – false alarms)
Inverted Horses	*M*	76.7	22.9	53.8
	SEM	2.3	2.5	2.9
Inverted Faces	*M*	79.8	24.2	55.6
	SEM	2.9	3.5	3.7
Upright Horses	*M*	78.5	19.4	59.2
	SEM	2.7	3.1	3.8
Upright Faces	*M*	85.4	13.1	72.3
	SEM	2.8	2.3	4.0

Turning to the *upright* orientation, as expected adults then showed significantly poorer discriminability of upright horses than of upright faces (Figure 2), $t(19) = 3.11, p = .006$. The advantage to upright over inverted was significant for faces, $t(19) = 3.79, p = .001$, but not for horses, $t(19) = 1.67, p >.1$. A significant interaction between stimulus class and orientation, $F(1,19) = 5.15, p < .04$, confirmed the upright advantage (upright *minus* inverted) was significantly larger for faces (16.7%) than horses (5.4%).

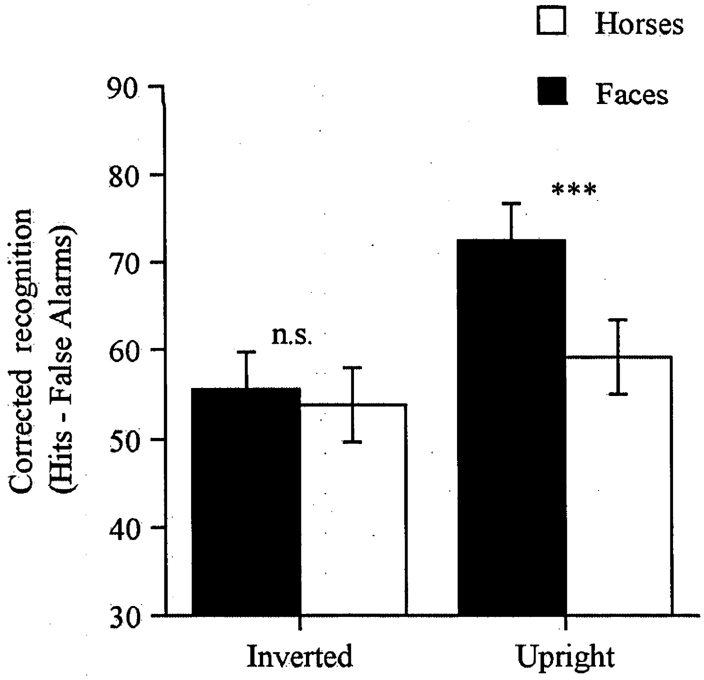


Figure 2. Results of Experiment 1, showing discrimination of faces and horses in adults. Error bars are as appropriate for the within-subjects comparison of faces and horses (i.e., ±1 *SEM* of the face *minus* horse difference scores). *** $p = .006$

6.6.3 Discussion

Experiment 1 confirmed that the inverted faces and horses produced matched performance in adults. This evidence of matched physical similarity indicates that our stimuli are suitable for investigating discrimination ability in the upright orientation in infants. Moreover, because adults showed the expected pattern of poor discrimination of horses compared to faces in the upright orientation, evidence of face-level discrimination ability for upright horses in infants would imply that perceptual narrowing has occurred in adults.

6.7 Experiments 2-4: Identity discrimination of faces and horses in 4-month-olds

The aim of the following set of three experiments was to investigate the breadth of the innate representation underlying adult upright face specialisation demonstrated in Experiment 1. The ability of 4-month-olds to perform individual level discrimination of upright horses (Experiment 2), upright faces (Experiment 3) and inverted horses (Experiment 4) was assessed. The 4-month age group was selected because this age is before any perceptual narrowing has occurred in previous studies. If the innate representation supporting discrimination is specific to primate faces, we would expect discrimination of the face stimuli only. However, if the innate representation is more broadly tuned, we would expect discrimination of both upright faces and upright horses but not inverted horses.

6.7.1 Method

6.7.1.1 Participants

Infants aged 3.5 months – 4.5 months, from the Canberra, Australia region were recruited through advertisements in newspapers, on radio, at maternity wards, at maternal and child health clinics, and through word of mouth. All infants were full term and Caucasian (i.e., both parents were Caucasian), the same race as the face stimuli. Parents reported that no infant had any identified visual problems. Parents received $12 reimbursement.

Each infant was tested on up to two Experiments, where feasible (i.e., if after completing the first, they were still attentive for the second). For a total of 22 infants, the Experiments used were (a) horses upright (Experiment 2) and (b) faces upright

(Experiment 3), conducted in counterbalanced order across infants. For a total of 17 infants, the Experiments used were (a) horses inverted (Experiment 4) and (b) faces upright (Experiment 3), conducted in counterbalanced order.

For the *horses upright experiment* (Experiment 2), 22 infants began testing (mean age = 122 days, range = 110-133 days; 16 male). For the discrimination test, 16 infants remained in the sample (mean age = 121 days, range 110-130 days; 11 male) following exclusion for crying (2) or failure to habituate (4).

For the *faces upright experiment* (Experiment 3), 39 infants began testing (mean age = 124 days, range = 110-138 days; 25 male). For the discrimination test, 19 infants remained (mean age = 122 days, range 115-133 days; 16 male) following exclusion for crying (6) or failure to habituate (14).

For the *horses inverted experiment* (Experiment 4), 17 infants began testing (mean age = 126 days, range = 117-138 days; 11 male). For the discrimination test, 6 infants remained (mean age = 127 days, range 121-134 days; 3 male) following exclusion for crying (2) or failure to habituate (9).

6.7.1.2 Design

An infant controlled habituation procedure was used. Infants were presented with one stimulus at a time. During the habituation phase, the stimulus alternated in identity between two stimulus items of a triplet. At test, infants saw an "old" habituated item and a "new" item (see Figure 3). Looking time to each stimulus item was recorded. Discrimination was indicated by dishabituation (longer looking time) for the new compared to old item at test.

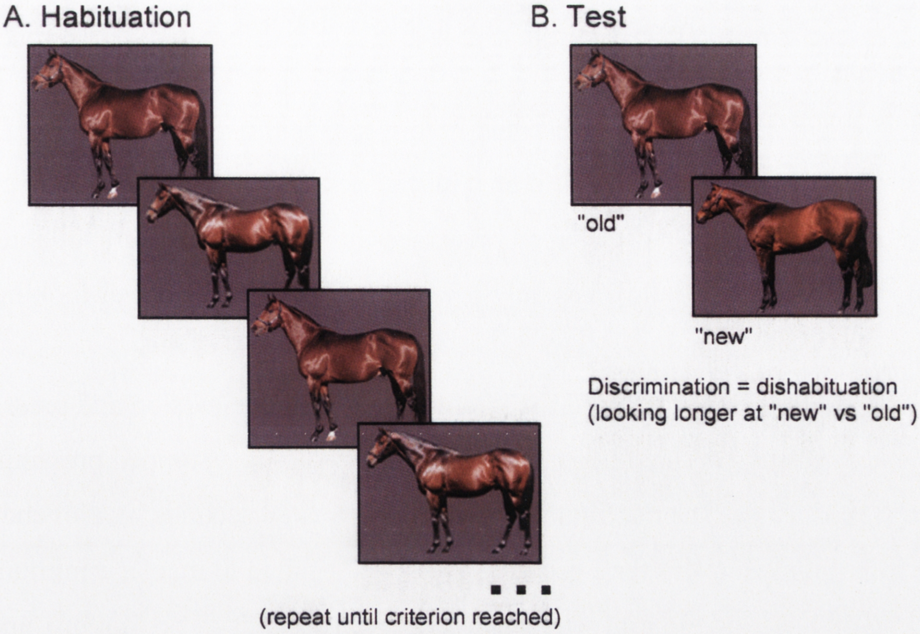


Figure 3. Procedure for Experiment 2 (upright horses in infants), showing (A) habituation trials and (B) discrimination test trials.

6.7.1.3 Stimuli

The stimulus items and organisation into "triplets" were the same as in Experiment 1 (see Figure 1). An Experiment presented an infant with one of the triplets (e.g., an upright horse triplet in Experiment 2). The triplet used (A, B, C or D), and which items were used as habituation items versus the novel test item within the triplet, were counterbalanced across participants. The viewing distance was approximately 50 cm, making stimulus visual angles as given for Experiment 1.

6.7.1.4 Procedure

Stimuli were presented on a Compaq P1220 22-inch CRT monitor using Habit X 1.0 (Cohen, Atkinson, & Chaput, 2004) software running on a MacBook. A Sony DSR-PDX10P Digital Camcorder was positioned above the centre of the monitor to allow a view of the infant's eyes on a television in front of the experimenter.

Infants were tested in a quiet, darkened room. The experimenter, the equipment, and the room were screened off from the infant by placing the infant and parent inside a cubicle with black walls and roof. The cubicle was open to the room behind the parent's seat, and had cutout openings at the front for the monitor and video camera. Infants were positioned comfortably on their parent's lap. The parent was seated on a height adjustable chair. The parent wore an eye mask throughout the experiment to prevent their own response to the stimuli affecting the infant's response. The experimenter could not see the stimuli being presented, and was blind as to which stimulus was being presented at any given time and to when the habituation phase was completed and the test trials began.

An "attention getter" was presented before each stimulus. This consisted of an expanding and contracting green circle on a black background presented at the centre of the screen, accompanied by a bell sound presented through two speakers mounted on top of the monitor. The stimulus was only presented when the infant was looking at the screen.

The experimenter monitored the infant's eyes on the television and pressed a key on the keyboard when the infant looked at the stimulus and stopped pressing when the infant looked away. The maximum trial duration was 20 seconds. A trial ended when the infant looked away for 1 second. If the infant failed to meet a minimum looking time of 1 second the trial was aborted after 10 seconds of no looking, and rerun. During the habituation phase, the two habituation stimuli were alternated. For the computer-controlled presentation, the infant was considered to have habituated when the mean looking time of 4 consecutive trials dropped to 50% of the mean of the looking time for the first 4 trials. The maximum number of habituation trials was 16. Following the habituation phase two test trials (one "old" habituated stimulus, one "new") were presented. Order of old and new was counterbalanced across participants.

Prior to analysis, a more detailed examination of habituation patterns was conducted. Thomas and Gilmore (2004) have shown that the standard 50%-of-initial-looking-time criterion can sometimes lead to erroneous decisions regarding whether or not the infant has habituated: this includes both false positives, where the habituation criterion has apparently been reached by chance (i.e., further repetition of an old stimulus in the discrimination test phase produces much longer looking times than at the end of the habituation phase); and false negatives, where infants show consistently decreasing looking times that eventually flatten out at a low value but low internal variability means that the final value never reaches 50% of the first four trials. We therefore visually examined the full habituation curve for each infant individually. Based on the agreement of two judges, who had no information available as to the recorded looking time for the *new* test trial, we reversed the classification of the standard 50% criterion in 7 cases (10.3% of all cases), 3 false positives, and 4 false negatives.

The procedure for each Experiment was identical, except for the nature of the stimulus class (upright horses, inverted horses, or upright faces).

6.7.2 Results

The results in Figure 4A demonstrate that infants discriminated individual horse identity in the upright orientation. Importantly, discrimination was at least as strong for upright horses as it was for upright faces. At test, infants dishabituated to the "new" horse; that is, they looked significantly longer at the "new" compared to the "old" horse, $t(15) = 2.73, p = .015$. Dishabituation for upright faces was marginally significant, $t(18) = 2.02, p = .058$.

We also examined the proportion of infants who habituated, taking the presence of habituation as at least partially reflective of stimulus encoding ability (Colombo & Mitchell, 2009). Results further support the idea that encoding of upright horse identity was at least as good as encoding of upright face identity. As shown in Figure 4B, 80% of non-crying infants reached the habituation criterion for upright horses, a larger proportion than the 57% who reached habituation criterion for faces.

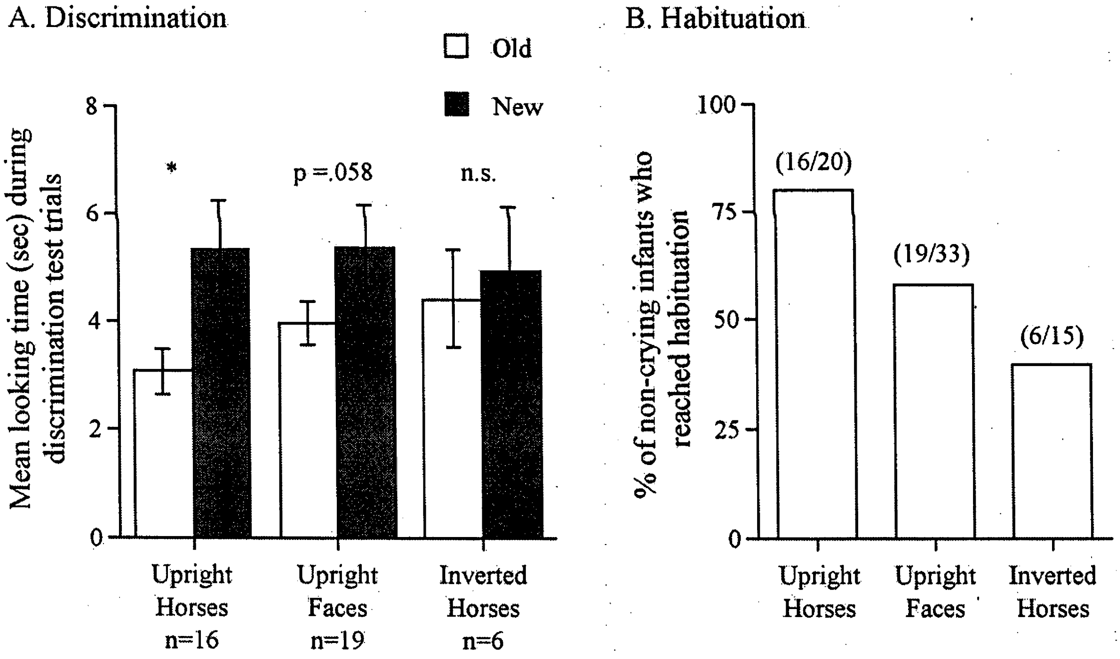


Figure 4. Results of Experiments 2-4 in four-month-old infants. A. Mean looking time during discrimination test trials. Error bars are ±1 *SEM*. B. Percentage of non-crying infants who reached habituation for each stimulus type. * $p < .05$

Turning to the *inverted* orientation, there was no evidence that infants individuated inverted horses. In test trials, there was no suggestion of any difference in looking times to old and new stimuli: Figure 4A, $t(5) < 1$. Further, the small sample size (n=6) for the discrimination task is a reflection of the difficulty encountered in habituating infants to inverted horses: only 40% of non-crying infants reached the habituation criterion. Both the discrimination and the habituation findings thus argue that 4-month-olds did not encode the identity of inverted horses.

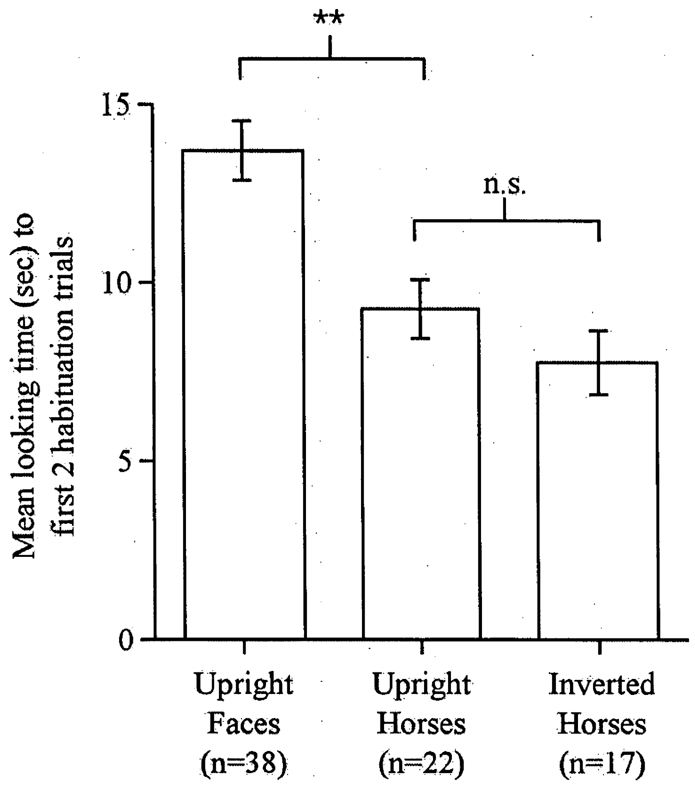


Figure 5. Mean looking time to the first two habituation trials. Sample includes all infants who completed the first two habituation trials for the given condition. Error bars are ±1 *SEM.* ** $p = .01$

One final observation was that, despite infants discriminating upright horses at least as well as upright faces, 4-month-olds found faces as a class more interesting than horses. Figure 5 plots looking times for the first two habituation trials (that is, to the first presentation of each habituation stimulus). Results show that infants looked longer at upright faces than upright horses. Statistical evaluation of this difference was complicated by the fact that there was partial overlap in samples between infants tested in the upright face and upright horse experiments (all 22 infants in the upright horse experiment were also tested in the face experiment, but the face experiment included a further 16 infants who were not tested on upright horses), meaning that neither standard independent-samples nor dependent-samples t-tests were appropriate. To deal with this issue, we conducted an independent samples t-test by randomly assigning half of the infants who completed both tasks to inclusion in only one experiment (i.e., we ignored their data from the other experiment), and repeated this procedure for 20 different random allocations. Results showed a significant difference in initial looking time to faces and horses (across the 20 iterations, mean $t(27.25) = 3.19$, mean $p = .01$), reflecting a preference for upright faces over upright horses. Finally, we compared preference across the two horse experiments; looking times to upright versus inverted horses did not differ significantly, $t(37) = 1.21$, $p > .2$, (Figure 5).

6.7.3 Discussion

The primary results of Experiments 2-4 were that 4-month-olds successfully discriminated upright horses at the individual level. Indeed, they were able to discriminate and remember identity information for *three* horses (a more demanding test than the more usual two-item discrimination tasks). This discrimination ability was at least as good as that for faces; if anything, the trend was for *better* horse discrimination than face discrimination. Horse discrimination ability was also apparently limited to the upright orientation: there was no evidence of discrimination of the horse stimuli when these were shown inverted.

A secondary observation was that there was evidence that infants did recognise the social importance of faces, finding them more interesting than horses. Consistent with a social interest interpretation of the looking-time data, the experimenter observed that many infants smiled or laughed at the faces. This behaviour was not observed for the horses in either orientation.

6.8 General Discussion

The finding of Experiment 2, that infants can discriminate individual horses, is the first demonstration of individuation beyond primate faces in young infants. Moreover, the pattern of results observed for infants differed from that seen for adults in Experiment 1, although comparison is made difficult by the unavoidable differences in procedure between the age groups. Infants demonstrated discrimination of upright horses that was at least as good as their discrimination of upright faces, in contrast to the pattern in adults in which faces were discriminated significantly better than horses. Infants also demonstrated discrimination ability only for upright horses and not inverted horses, in contrast to the adult pattern in which horse discrimination was equally poor for both orientations. These results argue that there exists a broadly tuned representation supporting upright horse discrimination in infancy, and that perceptual narrowing occurs such that good discrimination is retained only for human faces in adults.

At what age does this narrowing occur? From the present study, we cannot say. However, we note that the previous studies of perceptual narrowing for face types (those of other primates, or other human races) find narrowing has occurred by 9 months of age, making it plausible that the same age would apply to animal individuation. Certainly, we have good reason to think that the adult pattern of animal discrimination is attained by 7 years of age at the very latest. Using side views of Labrador dogs, equated to human faces for physical similarity using inverted orientation performance, normal adults show the same pattern observed in the present study – that is, good discrimination only of upright faces (Robbins & McKone, 2007; see Diamond & Carey, 1986, for similar findings). Using the same stimulus sets, we have previously reported that 7-year-olds show the same pattern (Crookes & McKone, 2009).

We now discuss three possible critiques of our results. First, is it problematic that infants' discrimination of faces was not quite statistically significant? We argue not. The previous studies demonstrating face discrimination in our age group (e.g., Kelly et al., 2007; Pascalis, de Haan, Nelson, & de Schonen, 1998) have used the standard procedure in which infants are required to discriminate only two identities (i.e., habituate to one item, one new item at test). Here, in contrast, we used a more difficult procedure, requiring discrimination of three different faces. Although it has been shown that the 3-item task demonstrates significant face discrimination in older infants (7-month-olds, Cohen & Cashon, 2001), it has never before been tested in infants aged 4 months. Thus, our results are not in direct contrast to any previous findings. Also, of course, it seems quite likely that a larger sample size in the present study would show face discrimination to be properly significant. But the core point is that, even if lack of discrimination of faces was the true result for 4-month-olds in the 3-item task, this is not fatal to our conclusion about *horses*: discrimination of three horses was clearly significant in our study.

Second, could it be that our infants' successful discrimination of horses relied merely on some easy local cue, such as a difference in exact shade of bay, or the presence of a small high-contrast white sock above the hoof? Again, we argue not. The crucial point is that these cues are available in the inverted orientation just as much as in the upright orientation, and yet infants demonstrated discrimination only of upright horses. More generally, our 3-item task was designed to minimise the influence of any single local cues (e.g., if a new item differed from one of the old items in presence of a sock, it did not differ from the other old item in this way), and the inverted results for adults also argue that local cues were no easier to use in the horse stimulus set than in the face stimulus set.

Third, it could be that infants are less sensitive to information in the bottom-half of the visual field. Both faces and horses have more information in their top-halves. Thus if infants are more sensitive to information in the top-half than the bottom-half of the visual field this may account for the inversion effect seen for horses. However infants were not limited in the time allowed to explore the stimulus (up to 20 seconds) and they were able to move their heads and eyes to concentrate on a region of interest or importance.

We thus conclude that our results reflect innately-driven expertise in upright horse individuation. The evidence that the discrimination ability must be innately-driven is that 4-month-old infants typically have no experience with horses. It is extremely unlikely that our results could reflect development of expertise through post-birth exposure to horses. No parents were horse owners or enthusiasts, and infants were recruited in a city rather than from country areas. Infants' exposure to horses prior to the experimental testing is therefore likely to have been limited to between zero and one schematic horses in storybooks and between zero and one real horse (e.g., one mother commented "he saw his first horse yesterday"). Moreover, any exposure to horses would almost certainly have been at the basic level of categorisation as a horse (e.g., "Look, there's a horse"), rather than involving the individual level labelling which has been shown to be critical for the maintenance of discrimination ability for non-human primate faces in older infants (Scott & Monesson, 2009). Finally, even if infants had seen one or two horses, it is undoubtedly the case that by the age of 4 months they would have had dramatically more experience with faces than with horses; yet, discrimination ability with horses was as least as good as for faces. The primary theoretical question in the present article was how broad is the broadly tuned innate representation that supports individuation. Previous studies have shown it is as least as broad as a primate face: that is, before narrowing takes place, humans can discriminate both human faces and monkey faces (Pascalis et al., 2002), and monkeys can discriminate both monkey faces and human faces (Sugita, 2008). The major theoretical implication of the present study is that the innate representation is broader than that of a primate face, and extends at least to other mammals.

This is a novel finding. It is consistent with evidence that human infants show attractiveness preference within non-primate faces (front-view faces of tigers and domestic cats in 3-4 month-olds; Quinn, Kelly, Lee, Pascalis, & Slater, 2008). However, our finding goes beyond this in arguing that human infants have *full individuation* ability for non-primates. That is, it is unlikely that our infants based their discrimination solely on attractiveness of the individual horses. All stimuli were successful racehorses that had been selectively bred to show the same physical traits. Also, horses within each Set in Figure 1 do not appear to differ noticeably in attractiveness (except possibly in coat shine, a cue also available in the inverted orientation, where it was not used by infants). Finally, even if there were small attractiveness differences between the horses, our 3-item procedure means that, although the new horse in a trial might differ in attractiveness from *one* of the old horses, it was very unlikely to differ noticeably in attractiveness from the *mean* of *both* old horses (and even if it did, we note that Quinn et al. found novelty preference only in one direction of attractiveness change: infants showed novelty preference for an attractive tiger face following familiarisation with an unattractive one, but not vice versa).

Having concluded that the representation supporting individuation is broader than a *primate face*, can we conclude that it is even broader again and represents non-primate *whole bodies*? This is one possible interpretation of our present findings. A whole-animal conclusion would be consistent with the evidence that newborns have body-motion representation for upright chickens (Simion et al., 2008), but would go beyond these findings to argue that an innate body representation is able to support *individual-level* discrimination, not merely recognition of the presence of upright body structure.

The alternative interpretation is that, given that our horse stimuli all included *heads*, the discrimination ability we have observed is based not on the information contained in the body, but rather the information in the profile view of the horses' faces. This possibility is also potentially consistent with a number of previous findings. In previous studies using whole-animal stimuli (i.e., bodies-plus-heads), tracking of eye movements has shown that infants oversample the face: that is, although they look at the body approximately 50% of the time (suggesting they may well gain some useful information from this region), they spend 50% of the time looking at the head despite this making up only 18% of the total animal image size (6-7 month-olds, Quinn, Doran, Reiss, & Hoffman, 2009). The plausibility of humans having an innate representation of faces that covers all mammals is also suggested by findings that, like humans and other primates, even sheep show face-selective neurons (Kendrick & Baldwin, 1987) and human-like behavioural patterns for faces (e.g., an upright advantage for faces and not for buckets, Kendrick, Atkins, Hinton, Heavens, & Keverne, 1996). These results suggest that face representations are very old in evolutionary terms. (Although of course they do not rule out the possibility of evolutionarily-old *body* representations as well.)

Two other observations, however, tend to argue against the face as the likely source of the infants' discrimination. First, our horse heads were *profile views*. Adults find profiles much more difficult to discriminate than front or three-quarter views (e.g., McKone, 2008). In infants, we could locate only one study testing discrimination of face profiles (i.e., where all images were profile view). Fagan (1979) found 5-month-olds showed chance performance in discrimination of profiles (while successfully discriminating 3/4 view faces), even though these were highly dissimilar men with hair. Even by 7 months, discrimination of profiles was found only for highly dissimilar faces-and-hair, and not for similar faces-and-hair. Further evidence of weak representation of profiles is that newborns fail to generalise identity across view change from or to a profile view (despite being able to generalise identity information between 3/4 and front views; Turati et al., 2008).

Second, our horse heads were *small*. Typically, infant discrimination studies using human faces present the faces at sizes of 20-25° of vertical visual angle, corresponding to a real human head viewed at distances at which a infant would typically see its parents' faces. The smallest size we are aware of in 3-4 month-olds is 14° (Kelly et al., 2007). In contrast, our present stimuli presented horse heads at approximately 5.6° vertical (including the peaked ears) by 4.0° horizontal. Thus, if our present results reflect head discrimination, this would imply that young infants should also show good discrimination of *small* human faces in *profile* view.

Overall, our results are consistent with an innate representation of either face or body structure. However, the face interpretation would seem viable only if it can be shown in future studies that young infants can discriminate human faces in profile view. Note that our present study did not attempt to tease apart face and body contributions to horse discrimination by testing a headless body condition. The reason for this is that removing the head creates a bizarre image; thus, failure to discriminate the body in a headless-body condition would not, to our minds, show that infants had not been not using body information for our normal-format whole horse images. Indeed, even adults show an upright advantage in individuation of human bodies only when the whole is present (i.e., bodies with heads but not without heads; Minnebusch, Suchan, & Daum, 2009; also see Yovel, Pelc, & Lubetzky, in press, for a similar result involving body pose).

Might the innate representation be even broader than animals? Might researchers eventually find that young infants can discrimination any real object class (e.g., cars, houses) at the individual level? Our finding that infants could not discriminate inverted horses argues against this. If the innate discrimination ability were infinitely broad, then we should have found discrimination of inverted horses, but there was no evidence of this. Instead, the results reported here support the idea that the innate representation is limited to certain structural forms. Our findings are consistent with many other infant studies – involving human faces, monkey faces, feline faces, and chicken bodies – in showing innate ability to represent only the upright versions of biological stimuli. These findings suggest innate representation of object structure is most likely restricted to circumstances where the processes of evolution have had the opportunity to "learn" the structure of a very general class (e.g., terrestrial vertebrate bodies) in the upright orientation. This applies to faces, and to bodies, but not to cars.

A final theoretical question is whether we can be sure that the innate representation that supports *horse* individuation is the same one that eventually narrows to only support own-species own-race *face* individuation in older infants and adults. Until now, we have been talking about *the* innate representation, as if there is only one. A single innate representation is perhaps the most parsimonious explanation. However, we cannot rule out an alternative idea, namely that there exist *two* separate innate representations: one of faces, and one of bodies. Each of these would be initially tuned to a wide variety of animals, and each would eventually narrow down with lack of individuation experience. For the innate face representation, this narrowing process would result in good individuation remaining only for own-species own-race faces. For bodies, it would drop out altogether for individuation. In either single- or double-representation scenarios, however, some vestige of the innate representation of whole animals may remain in the form of an attentional bias towards animals in adults (New et al., 2007).

6.9 Conclusion

Our study showed that 4-month-old infants can individuate a set of three very similar horses, when upright but not inverted. This indicates expertise without experience in horse individuation. This discrimination could plausibly rely on the whole body shape or, somewhat less plausibly, on the profile face region alone. We conclude that innate representation/s capable of supporting individuation of upright biological stimuli are extremely broad in form, encompassing at least all mammals.

6.10 References

Bushnell, I. W. R. (2001). Mother's face recognition in newborn infants: Learning and memory. *Infant and Child Development, 10*, 67-74.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, P. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments and Computers, 25*, 257-271.

Cohen, L. B., Atkinson, D. J., & Chaput, H. H. (2004). Habit X: A new program for obtaining and organizing data in infant perception and cognition studies (Version 1.0). Austin: University of Texas.

Cohen, L. B., & Cashon, C. H. (2001). Do 7-month-old infants process independent features of facial configurations? *Infant and Child Development, 10*, 83-92.

Colombo, J., & Mitchell, D. W. (2009). Infant visual habituation. *Neurobiology of Learning and Memory, 92*, 225-234.

Crookes, K., & McKone, E. (2009). Early maturity of face recognition: No childhood development of holistic processing, novel face encoding, or face-space. *Cognition, 111*(2), 219-247.

Diamond, R., & Carey, S. (1986). Why faces are and are not special: An effect of expertise. *Journal of Experimental Psychology: General, 115*(2), 107-117.

Fagan, J. F. (1979). The origins of facial pattern recognition. In M. H. Bornstein & W. Keesan (Eds.), *Psychological Development from Infancy to Intention.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Geldart, S., Mondloch, C. J., Maurer, D., de Schonen, S., & Brent, H. P. (2002). The effect of early visual deprivation on the development of face processing. *Developmental Science, 5*(4), 490-501.

Goren, C. C., Sarty, M., & Wu, P. Y. K. (1975). Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics, 56*(4), 544-549.

Johnson, M. H., Dziurawiec, S., Ellis, H. D., & Morton, J. (1991). Newborns' preferential tracking of faces and its subsequent decline. *Cognition, 40*(1-2), 1-19.

Kelly, D. J., Quinn, P. C., Slater, A., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science, 18*(12), 1084-1089.

Kendrick, K. M., Atkins, K., Hinton, M. R., Heavens, P., & Keverne, B. (1996). Are faces special for sheep? Evidence from facial and object discrimination learning tests showing effects of inversion and social familiarity. *Behavioural Processes, 38*(1), 19-35.

Kendrick, K. M., & Baldwin, B. A. (1987). Cells in temporal cortex of conscious sheep can respond preferentially to the sight of faces. *Science, 236*, 448-450.

Kuhl, P. K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences of the United States of America, 100*, 9096-9101.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2001). Early visual experience and face processing. *Nature, 410*, 890.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science, 15*(11), 762-768.

McKone, E. (2008). Configural processing and face viewpoint. *Journal of Experimental Psychology: Human Perception and Performance, 34*(2), 310-327.

Minnebusch, D. A., Suchan, B., & Daum, I. (2009). Losing your head: Behavioral and electrophysiological effects of body inversion. *Journal of Cognitive Neuroscience, 21*(5), 865-874.

Morton, J., & Johnson, M. H. (1991). CONSPEC and CONLERN: A two-process theory of infant face recognition. *Psychological Review, 98*(2), 164-181.

Nelson, C. A. (2001). The development and neural bases of face recognition. *Infant and Child Development, 10*, 3-18.

New, J., Cosmides, L., & Tooby, J. (2007). Category-specific attention for animals reflects ancestral priorities, not expertise. *Proceedings of the National Academy of Sciences of the United States of America, 104*(42), 16598-16603.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296*, 1321-1323.

Pascalis, O., de Haan, M., Nelson, C. A., & de Schonen, S. (1998). Long-term recognition memory for faces assessed by visual paired comparison in 3- and 6-month-old infants. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*(1), 249-260.

Pascalis, O., de Schonen, S., Morton, J., Deruelle, C., & Fabre-Grenet, M. (1995). Mother's face recognition by neonates: A replication and an extension. *Infant Behavior and Development, 18*, 79-85.

Pascalis, O., Scott, L. S., Kelly, D. J., Shannon, R. W., Nicholson, E., Coleman, M., et al. (2005). Plasticity of face processing in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 102*(14), 5297-5300.

Quinn, P. C. (2004). Development of subordinate-level categorization in 3- to 7-month-old infants. *Child Development, 75*(3), 886-899.

Quinn, P. C., Doran, M. M., Reiss, J. E., & Hoffman, J. E. (2009). Time course of visual attention in infant categorization of cats versus dogs: Evidence for a head bias as revealed through eye tracking. *Child Development, 20*(1), 151-161.

Quinn, P. C., & Eimas, P. D. (1996). Perceptual cues that permit categorical differentiation of animal species by infants. *Journal of Experimental Child Psychology, 63*, 189-211.

Quinn, P. C., & Eimas, P. D. (1998). Evidence for a global categorical representation of humans by young infants. *Journal of Experimental Child Psychology, 69*, 151-174.

Quinn, P. C., Kelly, D. J., Lee, K., Pascalis, O., & Slater, A. (2008). Preference for attractive faces in human infants extends beyond conspecifics. *Developmental Science, 11*(1), 76-83.

Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science, 8*(5), 368-373.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition, 103*(1), 34-79.

Sai, F. Z. (2005). The role of the mother's voice in developing mother's face preference: Evidence for intermodal perception at birth. *Infant and Child Development, 14*, 29-50.

Scott, L. S., & Monesson, A. (2009). The origin of biases in face perception. *Psychological Science, 20*(6), 676-680.

Sengpiel, F. (2007). The critical period. *Current Biology, 17*(17), R742-743.

Simion, F., Macchi Cassia, V., Turati, C., & Valenza, E. (2003). Non-specific perceptual biases at the origins of face processing. In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood: Current perspectives* (pp. 13-25). New York: Nova Science Publisher, Inc.

Simion, F., Regolin, L., & Bulf, H. (2008). A predisposition for biological motion in the newborn baby. *Proceedings of the National Academy of Sciences of the United States of America, 105*(2), 809-813.

Sugita, Y. (2008). Face perception in monkeys reared with no exposure to faces. *Proceedings of the National Academy of Sciences of the United States of America, 105*(1), 394-398.

Tanaka, J. W., & Farah, M. J. (1993). Parts and wholes in face recognition. *The Quarterly Journal of Experimental Psychology, 46A*(2), 225-245.

Thomas, H., & Gilmore, R. O. (2004). Habituation assessment in infancy. *Psychological Methods, 9*(1), 70-92.

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

Turati, C., Macchi Cassia, V., Simion, F., & Leo, I. (2006). Newborns' face recognition: Role of inner and outer facial features. *Child Development, 77*(2), 297-311.

Yin, R. K. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81*(1), 141-145.

Young, A. W., Hellawell, D., & Hay, D. C. (1987). Configurational information in face perception. *Perception, 16*, 747-759.

Yovel, G., Pelc, T., & Lubetzky, I. (in press). It's all in your head: Why is the body inversion effect abolished for headless bodies? *Journal of Experimental Psychology: Human Perception and Performance.*

CHAPTER 7 – PILOT STUDIES

7.1 Introduction

A number of pilot experiments and additional data that would normally have been reported in a conventional thesis have been omitted from the final papers presented in the previous chapters, due to constraints of the journal format. In total, these represent a substantial amount of work, including testing 112 participants (82 adults and 30 children). The aims, methods and results of these studies are summarised in the present chapter.

I have reported only the ways in which the methods for the pilot experiments differ from those of the final experiments reported in the previous chapters. In all other respects they are identical.

7.2 Pilot studies for Chapter 4 – Experiment 1

7.2.1 Matching memory performance for upright faces and dogs

The aim in developing the stimuli for this experiment was to match memory performance for upright faces and upright dogs. On tests of recognition memory, similarity between items affects performance such that memory performance is better for more-different items than more-similar items. I started with the stimuli used by Robbins and McKone (2007), which were originally matched for memory performance in the *inverted* orientation. Due to the special processing mechanisms available for upright faces, these stimuli then, as expected, did not produce matched performance when presented upright (i.e., the faces were remembered much more accurately than dogs). As stated in Chapter 4 (p. 228 of the paper) to match performance in the upright condition, the physical similarity of the faces was increased across each block and the similarity of the dogs was decreased both across each block and within each pair.

Two different versions of the stimuli were pilot tested in adults. As shown in Table 7.1 neither produced the desired matching of memory performance across object class, but both served as steps along the way to eventually achieving this aim. Pilot Study 1 included male and female faces from two different databases. The pairing of individual stimuli was as in Robbins and McKone (2007). The dogs were re-paired to maximise the physically dissimilarity (as judged by me) across blocks and within pairs. Pilot Study 2 included only male faces from a single database (all photos taken under the same lighting conditions, University of Ljubljana CVL and CV, PTER, Velenje database, http://lrv.fri.uni-lj.si/facedb.html); the dogs were as in Pilot Study 1. The final stimuli used in Experiment 1 included the same faces as Pilot Study 2, but the dogs included a few new stimuli and different combinations across the blocks and within pairs.

Table 7.1.
Adult pilot studies for Experiment 1 Crookes & McKone (2009) – matching memory performance for faces and dogs.

		% correct: 2AFC recognition memory	
	N	faces	dogs
Pilot study 1.	4	92.5	85.0
Pilot study 2	6	85.0	80.0

7.3 Pilot studies for Chapter 4 – Experiment 2

7.3.1 Matching memory performance for inverted faces (and dogs) across age groups

The design of this experiment required comparing the size of inversion effects on memory between 6-7 year-olds and adults, which required matching baseline performance (in this case *inverted*) across the two age groups. The aim in adapting Robbins and McKone's (2007) inversion task for children was to adjust the procedure to match the children's memory performance for inverted stimuli to that of the Robbins and McKone adults. This required making the task easier for children, which was attempted by reducing the learning set size from 15 to 5 (i.e., 3 blocks of 5 learning items, instead of 1 block of 15 learning items).

The procedure for Pilot Study 3 was the same as the experiment described in the chapter with two exceptions: it did not include the encoding question (i.e., children were simply told to look carefully at the face/dog because they would be asked to remember it later on; they were not asked to rate "how nice this person/dog is"); and it included a 30 s study-test delay (instead of minimal study-test delay). As shown in Table 7.2 performance on this task was well below that of the adults, especially for the dog stimuli.

Pilot Study 4 also had no encoding question but, to make the task easier, the study-test delay was minimised (approx 15 s). The children's performance was again poor compared to adults (see Table 7.2). In the final version of the task an encoding question ("how nice is this person/dog?") was included, the study-test delay minimised, and only 7-year-olds were tested; this produced well matched performance across both stimulus type and age group (see Chapter 4).

Table 7.2.
Child pilot studies for Experiment 2 Crookes & McKone (2009) – matching memory performance for inverted faces and dogs to adults from Robbins & McKone (2007)[3].

			% correct: 2AFC recognition memory	
	Age	N	Inverted faces	Inverted dogs
Robbins & McKone (2007)	Adults	22	63.3	66.3
Pilot Study 3	6-7 yrs	6	61.1	43.3
Pilot Study 4	6-7 yrs	12	55.6	58.3

7.3.2 Additional age group

The final Crookes and McKone (2009) article only included data from 7-year-olds and adults. A group of 6-year-olds was also tested on the final task. They were excluded from the paper as they performed close to floor for the dogs (Table 7.3): the average of the upright and inverted dog conditions was 59.2%. This meets our criterion for potential restriction of range (average of the two conditions tested ≤ 63%; caption Fig 1, p. 223). In fact the average of all four conditions was only 63.9. This poor performance suggests 6-year-olds were too young to cope with the memory demands of the task.

Table 7.3.
Results for younger age group age group not included in Experiment 2 Crookes & McKone (2009).

		% correct: 2AFC recognition memory (& *SEM*)			
	N	Upright faces	Inverted faces	Upright dogs	Inverted dogs
6 y.o.	12	70.55 (3.97)	66.67 (4.34)	64.44 (4.73)	53.89 (1.73)

7.4 Pilot studies for Chapter 4 – Experiment 3A

7.4.1 Designing an appropriate explicit memory task

The aim in Experiment 3A was to match the procedure for the explicit memory task as closely as possible to that for the implicit memory task. In practice, however,

---

[3] Pilot participants also completed the upright conditions for both faces and dogs. Results are not reported due to lack of matching for inverted stimuli.

some changes were necessary. Firstly, as noted in the procedure for Experiment 3A, the study phase included an explicit encoding instruction which was not present in the implicit task. This was required to keep the encoding conditions the same across the two face-age blocks: that is, having completed the first block, participants may have learnt to use encoding strategies on the subsequent block, and this would change the explicit memory task from incidental learning on the first face-age tested to intentional learning on the second face-age tested.

Secondly, pilot testing with adults revealed changes also needed to be made to the test phase to avoid floor effects on conscious recollection (explicit memory). Pilot Study 5 included 60 faces at test, comprised of 15 studied and 15 unstudied normal format faces plus 30 unstudied distorted format faces (i.e., the same faces that appeared in the test phase of the implicit memory task), and faces were presented for 200ms. As shown in Table 7.4 accuracy, as measured by corrected recognition, was very poor. Participants also reported being confused by the presence of the distorted faces and, as shown in Table 7.4, incorrectly answered "old" for more than half the distorted faces. In an effort to make the task clearer, the distorted faces were removed from the test phase for Pilot Study 6 (making the task much more similar to any standard explicit memory face tasks in the literature), but the limited presentation was retained. Again performance was poor (see Table 7.4). The final task included only the normal format faces presented until response.

Table 7.4
Adult pilot studies for Crookes and McKone (2009) Experiment 3A. Mean percent "old" responses.

	N	Studied normal (hits)	Unstudied normal (false alarms)	Corrected recognition (hits – false alarms)	Unstudied distorted
Pilot Study 5	3	75.56	37.78	37.78	51.11
Pilot Study 6	12	68.89	34.44	34.44	-

7.5 Pilot studies for Chapter 4 – Experiment 3B

7.5.1 Matching unstudied performance across age groups

Experiment 3B is an extension of my Honours project (Crookes & McKone, 2004). In that study, the aim of matching across age groups on unstudied normal accuracy was not achieved – adult accuracy was well below that of the child groups (see Table 7.5). Performance levels were adjusted across the groups by, at test, changing the "spherize" level of the distorted faces and the presentation duration. In my PhD research, the first change to the adult experiment was to shorten the presentation duration from 300 ms to 200 ms. The aim was to get a relatively pure measure of face processing and shortening the presentation duration helped this by minimising the possibility of participants using "non-face" strategies to solve the task (e.g., focusing on a single photographic feature rather than the face as a whole). The task was then made easier by increasing the "spherize" level. In my Honours project a level of ± 25% was used. Pilot Study 7 used ± 30% which, as shown in Table 7.5, was still too difficult. Pilot study 8 used ± 40% which was too easy (see Table 7.5). The level used in the final task was ± 35%.

Table 7.5
Adult pilot studies for Crookes and McKone (2009) Experiment 3B – matching baseline unstudied performance to child groups. Mean percent "normal" responses.

	Age group	N	Distortion	Presentation duration	Unstudied normal	Unstudied distorted
Crookes & McKone (2009)	5-6 yrs	32	± 70%	1000 ms	65.3	10.4
Crookes & McKone (2009)	10-11 yrs	32	± 50%	500 ms	70.9	15.6
Crookes & McKone (2004)[a]	Adults	24	± 25%	300 ms	59.0	32.5
Pilot Study 7	Adults	5	± 30%	200 ms	64.7	32.0
Pilot Study 8	Adults	4	± 40%	200 ms	76.7	27.1

[a] Data previously included and examined as part of my Honours thesis. It is therefore not eligible for examination here but is included for comparison to the present pilot studies.

As noted in Chapter 4 it was not possible to simultaneously match child and adult participants on both unstudied normal and unstudied distorted performance (Table 7.5). Children were biased to respond "distorted", and this could not be replicated in adults despite changes to both presentation duration and distortion level.

7.6 Pilot studies for Chapter 6

7.6.1 Matching faces and horses for discriminability when inverted in adults

The aim in producing the stimuli for this task was to match discriminability of the faces and horses in the inverted orientation, such that any advantage for faces over horses when presented upright could be attributed to the special processing of upright faces. Given the design of the task, this meant matching both "hits" and "false alarms". The pilot studies were run using the same procedure as the final adult task but with inverted stimuli only. Three different versions of the stimuli were pilot tested (Pilot Studies 9-11). As shown in Table 7.6, the horse stimuli in Pilot Study 9 produced a higher false alarm rate than did the face stimuli. The particular horse triplets producing this effect were identified, and a different combination of horse stimuli was used in Pilot Study 10. Again the false alarm rate was higher for horses than faces. A third combination of horse stimuli was used in Pilot Study 11, and this produced nicely matched performance for faces and horses in both hits and false alarms. The stimuli from Pilot Study 11 were those used in the final task.

I had some concern that using the same stimuli for habituation and test was not ideal and that using different images might provide stronger evidence of individual level encoding. Thus, given that we were unable to obtain multiple images of the individual horses, Pilot Study 12 used the same combination of stimuli as Pilot Study 11 but with brightness and contrast altered versions of the study images at test. As shown in Table 7.6 this increased the false alarm rate for horses but not faces and this manipulation was abandoned.

Table 7.6.
Adult pilot studies for Crookes and McKone (in preparation) – matching accuracy for inverted faces and inverted horses. Mean percent "present" responses.

		Faces		Horses	
	N	Present (hits)	Absent (false alarms)	Present (hits)	Absent (false alarms)
Pilot Study 9	11	71.59	25.00	72.73	34.09
Pilot Study 10	16	75.00	22.92	72.92	28.39
Pilot Study 11	12	69.10	24.65	73.26	22.57
Pilot Study 12	9	71.76	23.15	68.52	36.57

CHAPTER 8 – GENERAL DISCUSSION

This chapter serves as the General Discussion for the thesis. As each empirical chapter was written as a standalone paper each contained a detailed discussion of its own. This chapter will not repeat those discussions but rather summarise the findings of the thesis as a whole, and place them back within the broader context of the literature. This chapter begins with a summary of the novel empirical finding in this thesis. This is followed by a discussion contrasting historical ideas about the developmental course of behavioural face recognition with a more current model based on the findings of this thesis and other recent discoveries. I then conclude with a number of important open questions and directions for future research.

8.1 Summary of the new empirical findings

The new empirical findings from this thesis fall into three categories reflecting the general aims set out in Chapter 1. Ordering these now by stage of development, these involve: (1) the breadth of innate discrimination ability in infancy; (2) the childhood development and age of maturity of face-specific processing mechanisms; and (3) retained flexibility in the mature perceptual system as reflected in the own-age bias on face recognition in older children.

Beginning with infancy, Chapter 6 investigated the breadth of the experience-expectant innate discrimination ability which has been previously shown to extend beyond human faces to include non-human primate faces. Here we found that 4-month-olds could discriminate upright side-view photographs of whole horses, at least as well as upright human faces, but did not discriminate inverted horses. This pattern contrasts with that in adults who, as expected, showed much better discrimination of upright faces than upright horses. These findings argue that innate individuation ability is initially very broadly tuned, including at least profile views of other mammal heads, and possibly whole bodies of mammals or indeed all animals.

Turning next to childhood, the core finding was that all behavioural aspects of face perception (except possibly speed) reached full quantitative maturity in early childhood, specifically by 5-7 years of age. My research on this topic placed particular emphasis on theoretical and methodological improvements over most previous studies. Theoretically, these improvements included separating face-specific development from development in general cognitive factors which affect task performance. Methodologically, we were also careful to avoid differences in proximity to floor or ceiling across age groups, such that no group's performance would be affected by restrictions in range. This approach allowed for fair quantitative comparisons across age groups. New empirical results then found no evidence of face-specific development across childhood. First, recognition memory for faces and Labrador dogs improved at the same rate across childhood and into adulthood (5 years+ Chapter 4, Experiment 1), arguing for development of task-general rather than face-specific factors. Second, holistic processing was as strong in children as in adults, as illustrated by the disproportionate inversion effect for faces versus dogs (7-year-olds; Chapter 4, Experiment 2) and also by the composite effect for faces (8-13 years; Chapter 5). Third, a lack of own-age bias on implicit memory suggested no change in perceptual representations in face-space with age (Chapter 4, Experiment 3). And finally, no development was observed for implicit memory between 5-6 years, 10-11 years and adults (Chapter 4, Experiment 3), arguing that ability to perceptually encode a novel face does not change with age; instead, the observed strong development on explicit memory must reflect improvement in other cognitive processes (e.g., deliberate memory strategies, ability to concentrate upon instruction). Together with the comprehensive literature review in Chapter 4, these experimental findings argue that there is no evidence that young children are poorer than adults in any of the core face perception abilities: holistic processing; face-space; and ability to perceptually encode novel faces from a single exposure.

Turning finally to the mature face recognition system (i.e., 5-7 years of age and older), our own-age bias results argued that the engagement of the mature face processing system retains some flexibility to recent experience. This is consistent with findings of previous studies in adults, but goes beyond them. Specifically, it was argued that recent concentrated experience with a face subtype not only affects recognition but also perception (or perhaps merely conscious access to the outputs of perception), and also that these effects reflected attentional or social interest factors switching face mechanisms on and off, rather than deriving from structural changes within those mechanisms such as better tuning within face-space. The results supporting these conclusions were that the own-age bias in children (5-13 years) was observed for explicit memory (Chapter 4, Experiment 3) and holistic processing (composite effect, Chapter 5), but not for implicit memory (Chapter 4, Experiment 3).

8.2 The developmental course of face recognition: An about-face

The standard understanding of the developmental course of face recognition, and thus the causal origins of adult expertise with faces, has changed dramatically in the last 10-15 years. Here I outline the historic understanding ("Then"), and then detail a more current version based on the findings of this thesis and other recent literature ("Now").

8.2.1 Then (1970s to early 2000s)

It has long been known that faces are special to babies, even from the moment of birth (e.g., Goren, Sarty & Wu, 1975). The influential Conspec/Conlern theory (Morton & Johnson, 1991) argued that young infants preferentially orient to faces over other objects/patterns from birth, and that face discrimination ability emerges at approximately 3 months. Despite this early ability, the standard view was that development in face-specific perception was ongoing across childhood and did not reach maturity until early-mid adolescence (Carey, Diamond, & Woods, 1980). Up until the mid-1990s, an extreme version of this late maturity view was dominant, namely the *encoding switch hypothesis* (Carey & Diamond, 1977), which proposed that core face recognition phenomena were not even *qualitatively* present in children until 10 years of age (i.e., that children shifted from a reliance on part-based coding to holistic coding at age 10 years). From the mid-1990s on, new evidence that many aspects of face processing (e.g., part-whole, composite effect, distinctiveness effects) were qualitatively present at younger ages (e.g., 6-year-olds; Carey & Diamond, 1994; Johnston & Ellis, 1995; Tanaka, Kay, Grinnell, Stansfield, & Szechter, 1998) forced a modification of the late maturity view, with theoreticians proposing only late *quantitative* maturity of a *subset* of aspects of face perception (e.g., sensitivity to spacing between features; Mondloch, Le Grand, & Maurer, 2002).

With regard to the causal mechanism driving adult face expertise there was some conflict between researchers studying infants and those studying older children. In the infant literature, an innate orienting system (Conspec) was argued to provide the drive for the development of discrimination ability (Conlern) in older infants (approximately 3 months; Morton & Johnson, 1991). However, in the childhood literature, extended lifetime experience with faces was argued to drive the development of face-specific mechanisms (Carey & Diamond, 1994). This latter view was taken as consistent with claimed evidence that, with enough experience making within class discriminations (e.g., 10 years), other object classes (e.g., dogs) could become "special" and processed like faces (Diamond & Carey, 1986; but see Robbins & McKone, 2007, and McKone, Kanwisher, & Duchaine, 2007). Thus while there was evidence of face discrimination in infancy it was argued that this face discrimination ability did not mature until early adolescence, and that the driver for this maturity was extended lifetime experience: that is, 10 years or more of *practice*.

8.2.2 Now (2009)

The past decade has produced much new research relevant to understanding the developmental course of face perception and the causal origins of adult expertise with faces. The findings of this thesis allow a degree of reconciliation between the somewhat separate literatures on infant development and child development.

With regard to abilities with faces, we now know that newborns are capable of much more than simple orientation towards faces, and can in fact perform orientation-specific *individuation.* In the first few days of life (and, in the case of Sugita's monkeys, upon first exposure to faces) infants display prodigious face recognition abilities (Turati et al., 2008; Turati, Macchi Cassia, Simion, & Leo, 2006). In fact, infant discrimination abilities are broader than those of adults, extending beyond human faces to include monkey faces (6 months; Pascalis, de Haan, & Nelson, 2002; Scott & Monesson, 2009) and heads/bodies of other mammals (4 months, Chapter 6). It is only infant exposure to a limited subtype of faces that *limits* this discrimination ability in older infants and adults to the exposed species and race of face (Kelly et al., 2007; Pascalis et al., 2002; Scott & Monesson, 2009). Further evidence of the importance of exposure in infancy is the evidence of a critical/sensitive period for at least some aspects of face perception: without pattern visual input in the first few months of life, holistic processing, sensitivity to spacing between features, and across view recognition fail to develop in patients born with dense bilateral cataracts (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002; Le Grand, Mondloch, Maurer, & Brent, 2001, 2003).

Together, these findings argue that infants have remarkable face (and possibly body) recognition skills that are *present at birth*, and require *no prior experience* (e.g., as for monkey faces or horses). These innate skills are also *experience-expectant* in the sense that they show both perceptual narrowing and some form of sensitive/critical period.

Regarding older babies and toddlers, little is known. The toddler age group is notoriously difficult to test – they will not sit still for habituation studies, and do not have the verbal or general intellectual skills to complete adult-like tasks – and correspondingly there exist essentially no studies of face perception from the ages of 10 months to 3 years. Also note that there is almost no evidence available regarding the question of whether infants, in addition to showing *loss* of ability for non-experienced face types, simultaneously show any *improvement* in perceptual discrimination of experienced subtypes (see Section 8.4.4: Open Questions). Finally, current data do not allow quantitative comparison of levels of performance across infants and adults: that is, we cannot know whether infants' discrimination ability with faces, as revealed by novelty preference in looking times, is *as good as*, *poorer than*, (or even *better* than), adults' ability, as measured via old-new recognition memory.

The question of the age at which adult-like levels of face perceptual skill is first achieved (i.e., quantitative maturity) has thus been addressed only in children aged approximately 4 years and older. Here, my own research (together with that of Gilchrist & McKone, 2003; McKone & Boyer, 2006; Pellicano & Rhodes, 2003; Pellicano, Rhodes, & Peters, 2006) has been instrumental in making the case that ongoing late development seen on face recognition tasks is not driven by improvement in face perception but rather by general cognitive development, and that functional perceptual maturity of face recognition is established by 5-7 years at the latest. That is, all standard face effects are quantitatively mature by 5-7 years (see Chapter 4). These results clearly argue that extended lifetime experience (e.g., 10+ years of practice) is *not* the origin of adult expertise in face recognition.

In conclusion, the modern findings support almost a complete reversal of the early view of the developmental course of face recognition. The data no longer support a view in which the only face representation present at birth is a mere orienting device, and good discrimination of upright (but not inverted) faces takes many years of practice to achieve. Rather, it appears that adult expertise for faces results from a combination of: (a) a broadly tuned experience-expectant innate component which narrows with experience in early infancy; and (b) face-specific perceptual mechanisms that require at most 5 or so years of face experience to become fully mature (and possibly much less). Also note that, despite this early maturity the system retains some degree of flexibility such that recent concentrated experience with a face subtype in both children and adults can affect both recognition and holistic processing (e.g., Chapter4, Experiment 3A; Chapter 5; Anastasi & Rhodes, 2005; de Heering & Rossion, 2008; Harrison & Hole, 2009; Kuefner et al., in press).

8.3 Implications for other literatures

This thesis has focused on the development of behavioural face perception and recognition in typically-developing children. However, the findings here have implications for a number of other literatures, which I outline briefly here.

8.3.1 Developmental neuropsychology and developmental neuroimaging

There has been much recent interest in the developmental course of face-specific neural responses in typical children (e.g., with fMRI, Golarai et al., 2007), and also in behavioural processes in developmental disorders that produce atypical face recognition such as Autism Spectrum Disorder (ASD; e.g., Pellicano, Jeffery, Burr, & Rhodes, 2007) and Developmental Prosopagnosia (DP; e.g., Schmalzl, Palermo, Green, Brunsdon, & Coltheart, 2008). The most general point here is that, the fields of cognitive development, developmental neuropsychology and developmental neuroimaging, inform each other. Understanding the pattern of behavioural development in typical children is important in understanding the pattern of neural development and atypical development.

With respect to these types of research, a first implication of the present thesis derives from the conclusion that quantitative maturity of functional face recognition is reached early in typical development. This means that if researchers in developmental fMRI, or autism, or developmental prosopagnosia, start out by accepting the traditional view of very late quantitative maturity (or even the older view of late qualitative maturity), then the theoretical conclusions reached may well be invalid. For example, in the developmental neuroimaging literature the observed increase with age across childhood in the size of the FFA has been interpreted as being straightforwardly *consistent* with the behavioural findings: that is, both are claimed to show late maturity of face perception mechanisms (e.g., Aylward et al., 2005; Cohen Kadosh & Johnson, 2007). It is only in the light of the new conclusion that behaviourally face perception is mature early, that it becomes apparent that there is a *prima facie* conflict between the behavioural and fMRI findings which may be theoretically complex to resolve (see Section 8.4.7: Open Questions).

A second implication of the present findings concerns the large role of general cognitive factors on face task performance in children. This is of relevance, for example, to understanding the course of face processing in Autism Spectrum Disorder. ASD is a syndrome which has been argued to include a face recognition deficit (see

Golarai, Grill-Spector, & Reiss, 2006; Jemel, Mottron & Dawson, 2006, for review) but is characterised by a range of behavioural, social and communicative impairments (DSM IV, American Psychiatric Association, 1994). Thus, in order to conclude that there is a problem with *face* perception – for example, in a given age group of children with ASD – tasks must be carefully designed to tap the face system specifically. This might require, for example, testing of non-face objects, carefully matched to the faces on the variables discussed in Chapter 4, on the same tasks as the faces, to test for the possibility that poor performance for faces reflects a deficit in general cognitive or visual capacity.

8.3.2 Object expertise (and implications for face disorders)

The findings of this thesis also have implications for a major theory in object recognition – the "expertise hypothesis" (Diamond & Carey, 1986). This theory holds that any object class that shares a first-order configuration can become processed like faces if enough experience is gained (e.g., 10 years) in making within class discriminations. Here, I concluded based on both infant and child studies that face expertise is *not* the result of extended experience with faces, a conclusion in agreement with recent findings that objects of expertise are not processed like faces (e.g., no composite effect, small part-whole effect; for review see McKone et al., 2007 and McKone & Robbins, in press; although see Rossion & Curran, in press, for alternative view). This is not to say that expertise in subordinate or individual level discrimination cannot be gained with other objects (e.g., car experts are undoubtedly better at recognising cars than novices) it is just that they never become processed like faces. In this way faces are special to the visual system and face and object processing mechanisms are separate (for review see McKone & Robbins, in press; although see Gauthier, Skudlarski, Gore, & Anderson, 2000, for alternative view).

The conclusion of separate mechanisms supporting object and face expertise also allows speculation regarding *face* processing in certain disorders. In particular, it raises the question of whether a person could ever become an expert in individual-level discrimination of faces not through the usual innate-with-early-maturity *face* system mechanisms, but instead through the generic many-years-of-practice mechanism available within object systems. Cataract patients do not receive appropriate input to visual cortex in a critical period, and fail to develop key aspects of face perception, but, anecdotally, do not fail to recognise faces. In contrast, developmental prosopagnosics have a lifelong deficit in face recognition, despite having every opportunity to receive normal face input. What could explain these patterns? One speculative idea is that the performance of cataract patients might rely on treating faces like objects. That is, due to lack of appropriate early input, cataract patients lose their innate face system and cannot regain this system later in life; however, in the context of being born with a typical brain, object recognition systems are able to take over and perform the task of face recognition (i.e., cataract patients become object experts for faces). In developmental prosopagnosia, in contrast, the situation is different. DPs receive appropriate visual input, but are presumably born with an atypical brain. At least in adult studies, these brain abnormalities are not generally so gross as to result in a total lack of a face-selective brain regions (e.g., most possess an FFA, Avidan, Hasson, Malach, & Behrmann, 2005), but instead result in failure of normal operation of regions (e.g., failure of FFA to perform individual-level discrimination, Williams, Berberovic, & Mattingley, 2007) and/or weak white matter connections between regions (Thomas et al., 2008). Therefore, one possibility is that the appropriate early visual input of faces in DPs activates the innate face recognition system sufficiently well to prevent the critical-period loss that occurs in cataract patients; however, this faulty face recognition circuitry then continues to "grab" faces and to thus switch off generic object processing systems, preventing DPs from learning recognition ability via generic object mechanism.

8.4 Open questions

In the context of the modern understanding of the development of face recognition, I now describe what I consider some of the most important open questions in the field as a whole. These are ordered by stage of development. Most topics require only fairly brief discussion, although a final section on retained post-narrowing plasticity in children and adults is longer.

8.4.1 <u>The innate representation supporting discrimination: How broad is it and how much is shared across species?</u>

This thesis has concluded that humans are born with a representation of the structure of upright biological forms which supports individual-level discrimination within a broad range of species. Many questions remain regarding the breadth and evolutionary history of this representation.

Firstly, we are currently unable to say whether the innate representation is of whole animal bodies or just animal heads. As noted in Chapter 6, this question could be addressed indirectly via further tests of whether young infants can discriminate human faces in profile view: a conclusion that neonates or 3-month-olds cannot discriminate human profiles would argue that the discrimination of whole horses in side-view (Chapter 6) did not derive from the head; in contrast, a finding that infants can discriminate human profiles would keep a "head" interpretation of the horse findings alive. The question could also perhaps be tested more directly. For example, one could test 4-month-old's discrimination of different horse bodies where the identity of the head is kept constant: having habituated to one head-body combination, dishabituation to the habituated-head combined with a different-body would indicate that body discrimination is possible.

Secondly, we currently cannot say what range of species is covered by the innate representation. The results of Chapter 6 show that it is at least as broad as mammals, but we do not know whether it might be even broader than this. Perhaps it is limited to mammals? Or, perhaps terrestrial vertebrates are supported but not invertebrates? The chicken motion study of Simion, Regolin & Bulf (2008) suggests it may include birds, so it is possible that it extends further back in evolutionary past than humans' shared ancestor with other mammals. More generally, it would be interesting to know the evolutionary history of this representation. Is the same representation shared across all species? Perhaps the representation has evolved as a generic mechanism for conspecific recognition in any species.

8.4.2 Are the innate orienting system and the innate discrimination system one and the same?

There is clear evidence that infants have an innate *orienting preference* for faces (e.g., newborns track faces further than other objects or patterns; Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). Equally clearly, infants have an innate *discrimination* ability which supports individuation of faces (Turati et al., 2008; Turati et al., 2006). An open question is whether these two innate abilities are supported by one common mechanism or two separate ones. Johnson (2005) has argued that face orienting has a subcortical origin; for example, in humans, the finding that neonates track faces in the temporal but not nasal visual field (Simion, Valenza, Umilta, & Dalla Barba, 1998) suggests a subcortical origin. Currently, there is no evidence regarding whether the innate discrimination ability has subcortical or cortical origin, although it could be noted that detailed discrimination is the type of ability usually associated with cortical rather than subcortical visual processing in humans. If the innate discrimination is cortical while the innate orienting is subcortical, then this would indicate two separate mechanisms.

8.4.3 Do infants show all the same qualitative face effects as adults?

An open question is whether young infants perform *all* aspects of face processing in qualitatively the same manner as adults. As mentioned earlier, comparison between infants and adults is difficult even qualitatively. To date, it has been demonstrated that infants show some adult-like face effects (e.g., inversion effects, attractiveness effects). However, other basic qualitative effects remain untested. Particularly, there is a need for infant studies to test two standard holistic processing effects, namely the composite effect and the part whole effect. There is also a need to test standard effects associated with the concept of face-space, including distinctiveness effects (if these can be distinguished from attractiveness effects) and adaptation aftereffects for faces (based on figural distortions, identity distortions, gender morphs, race morphs, etc).

8.4.4 Are all the effects of experience in infancy destructive?

This thesis has highlighted the destructive effects of experience in infancy, that is, the loss of initial discrimination ability with selective exposure to faces of a single species and specific race. It is important to note that in the language domain, loss of nonexperienced phonemes is associated with improved phoneme discrimination for the experienced language (Kuhl et al., 2006). Thus, it may be that infants' ability to discriminate own-species and own-race faces improves with experience in the narrowing period.

Currently there is no solid evidence to support this. Humphreys and Johnson (2007) found that 7-month-olds required smaller physical differences between faces than 4-month-olds to demonstrate a novelty preference, and argued that this showed that the older infants were capable of making finer discriminations between faces. However, their post-habituation test task was a somewhat unusual one in that it required the infant to hold the habituated face in memory across 1-5 test trials (i.e., across up to 4 intervening faces). It is thus possible that, rather than reflecting improved perceptual discrimination with age, it may be that it was either face memory or general memory that improved in the older infants. Thus, there is a need for experiments to test whether older infants make finer face discriminations than younger infants with a standard two-stimulus dishabituation test.

8.4.5 What is the nature of the critical period for faces?

The evidence from cataract patients that lack of pattern visual input from birth leads to deficits in some aspects of face perception argues for a critical period. However many questions remain about the exact nature of the critical period. Here I stress that much of this research cannot ethically be conducted on humans but may be possible in nonhuman primates.

Firstly, a key aspect of the definition of a critical period is that deprivation will only lead to loss of function if it occurs in a specific time window (Sengpiel, 2007). For example, if the critical period is birth to 2 months of age, then the same amount of deprivation (2 months' duration) beginning at 6 months of age will not produce a deficit. While it has been demonstrated that lack of pattern visual input between birth and 2-19 months produces a deficit in some aspects of face perception (Geldart et al., 2002; Le Grand et al., 2001; Le Grand, Mondloch, Maurer, & Brent, 2004) it is not known whether the same amount of deprivation beginning later in infancy would produce the same deficit.

Secondly, further research is required into the type of visual input necessary for typical development of face systems. Cataract patients, deprived of all pattern vision, show deficits relative to controls on spacing change detection (as well as on the composite effect and cross-view generalisation). In apparent contrast, the Sugita (2008) monkeys, who received normal visual input except for being deprived of faces, successfully performed spacing change detection task (note holistic processing and cross-view generalisation were not tested). It would thus be of value to know whether, as adults, Sugita's face-deprived monkeys perform *as accurately* on the spacing change task as control monkeys with no visual deprivation. More generally, it currently remains unclear why deprivation of *all* visual input produces damage to the face system (or at least some aspects of it), while deprivation of only *face* visual input apparently leaves the face system intact.

8.4.6 What is the age of quantitative maturity of face-specific perceptual mechanisms?

I have argued (Chapters 4 and 5) that, functionally, behavioural face-specific perceptual mechanisms are mature by 5-7 years at the latest. Save for a few exceptions (e.g., aspects of adaptation aftereffects typically associated with face-space, generalisation of identity recognition across viewpoint) which have yet to be adequately tested, all key face effects have been found to be quantitatively mature by this age. The question that remains is then: At what age *younger* than 5-7 years do these effects reach maturity?

I have noted that 4-5 years is approximately the youngest age for which standard adult tasks can be made suitable for children, and thus this is the youngest age for which there is the potential for direct quantitative comparison with older children and adults. Below this age, with the techniques currently available, even qualitative comparison is difficult and quantitative comparison impossible. The present thesis thus leaves open the possibility that face identity perception might be functionally mature much earlier than 5-7 years of age, perhaps even in the first year of life. The exact age cannot yet be determined. That is, we do not know if face recognition is functionally mature once perceptual narrowing has occurred (9 months) or whether, like language, it continues to show important ongoing development until post-toddler ages.

Also, again I highlight the caveat raised in the discussion to Chapter 4 that here I have been discussing maturity of behavioural aspects as measured by performance *accuracy*. In that chapter the possibility that the *speed* of face-specific processing shows late maturity, increasing later into childhood and/or into adolescence was raised. An electrophysiological study comparing the timing of processing of faces and an appropriate comparison stimulus class (meeting the criteria set out in Chapter 4) stood out as a potentially fruitful method for testing this possibility. Such a study was recently reported comparing ERP responses to faces and cars across the 5 to 16 years age range. Kuefner, de Heering, Jacques, Palmero-Soler & Rossion (in press) found that none of the previously reported age-related changes in the electrophysiological response, including latency, were face specific. This argues for no special development of face-specific mechanisms beyond 5 years in speed of processing.

8.4.7 Why does neural processing of faces show late maturity?

Developmental neuroimaging of face perception is a burgeoning field with at least six studies (Aylward et al., 2005; Golarai et al., 2007; Passarotti et al., 2003; Passarotti, Smith, DeLano, & Huang, 2007; Scherf, Behrmann, Humphreys, & Luna, 2007) and one review paper (Cohen Kadosh & Johnson, 2007) published since 2003. As previously reviewed (Chapter 3) evidence shows there is substantial quantitative change in the face-selective neural response in the FFA continuing into adolescence. In these papers there is a tendency to interpret the findings of late developmental change in the neural representation of faces as supporting the supposed behavioural evidence that face-processing skills mature late in development.

However, in the light of the findings of Chapter 4 and 5, a new question arises: If, as argued in this thesis, behavioural face processing is functionally mature very early in life, what is the cause (and/or effect) of the late neural changes observed? Three possible suggestions for the increase in the size of the FFA with age were proposed in the discussion of Chapter 4. These were: (1) the perceptual function of increased FFA size is to improve *speed* of processing (although the recent findings of Kuefner et al., in press, would argue against an increase in the speed of processing); (2) the FFA acts as a storehouse of faces, and so the more faces a participant has seen during the course of their lifetime the bigger it is; and (3) increase in size of FFA reflects greater top-down activation and thus, rather than FFA size providing a pure measure of perceptual processing, it would be, like behaviour, influenced by other cognitive processes. Presently, any of these alternatives remain possible, and the general question of resolving the apparent conflict between the behavioural and FFA findings remains open.

8.4.8 Are children's face processing systems more flexible than adults?

In the domain of language, an early period of perceptual narrowing is followed by some ability to regain "narrowed-out" languages, but importantly this flexibility is greater during early childhood, as compared to adolescence and particularly adulthood. For example, an English-only-speaking child who moves to France as a 5-year-old will easily learn French with a perfect accent and perfect grammar. In contrast, an English-only-speaking adult who moves to France will never develop a perfect accent, and will often have ongoing difficulties with some aspects of grammar, even after 20 years of living in the new country.

An important question is whether face processing is similar to language processing in this respect. One influential finding has led to speculation that the face processing systems of children may be more flexible than those of adults. Sangrigoli, Pallier, Argenti, Ventureyra & de Schonen (2005) investigated the own-race bias in Korean children adopted to majority Caucasian countries in Western Europe between the ages of 3 and 9 years. When tested as adults the adoptees demonstrated the Caucasian pattern of race effects (i.e., better recognition of Caucasian than Asian faces), whereas Korean adults visiting France, as expected, were more accurate with Asian faces. This led to the conclusion that the face system is more flexible in childhood such that childhood experience can reverse the other-race effect.

Recently de Heering et al. (in press) attempted to replicate and improve upon this study with a similar group of adoptees, this time tested as children. De Heering et al. (in press) did not observe a full reversal of the own-race effect. Adoptees were just as accurate for Asian as Caucasian faces whereas Caucasian children did demonstrate an own-race bias (for a stimulus set previously demonstrated to produce an own-race effect in both Asian and Caucasian adults). There were many methodological differences between the two studies (i.e., delayed matched to sample vs. recognition memory; small set of faces vs. larger set; small sample size vs. larger sample size) which caution against reading too much into the differences in the results.

Both studies argue that the own-race effect, which is first observed at 6 months of age (Kelly et al., 2007), can be modulated by childhood experience. However, interpretation in terms other than greater plasticity or flexibility in childhood is possible.

In these two studies, it remains possible that it was not the *timing* of the experience that was important (i.e., experience in childhood as opposed to adulthood), but rather the total amount of experience. The children of the de Heering et al. (in press) study differed from the adults of the Sangrigoli et al. (2005) study in the length of time spent in Caucasian surroundings (5-14 years vs. mean of 23 years). It is therefore possible that a full reversal was not observed in de Heering et al. (in press) because less total experience had been gained with Caucasian faces. Consistent with this interpretation, de Heering and Rossion (2008) found a significant correlation between number of years experience as a preschool teacher and the strength of the composite effect for child relative to adult faces; indeed, it was only after approximately 8-10 years of experience that preschool teachers showed a larger composite effect for child than adult faces.

Importantly, in both the Sangrigoli et al. (2005) and the de Heering et al. (in press) study the Asian adoptee group – whose experience with Caucasians faces had begun as *children* – was never compared to a group of Asian adults who had equivalent length of experience with Caucasian faces but whose experience began as *adults*. Logically, this type of comparison is required to know whether flexibility with other-race faces (i.e., the ability to relearn a face type that was "narrowed out" during infancy) is greater in children than in adults.

Is there any other data available which can cast light on these issues? One finding is in fact strikingly different from both the Sangrigoli et al. (2005) and the de Heering et al. (in press) results, in reporting *no* retained plasticity even during *childhood*. This is Sugita's (2008) monkey study. Recall that Sugita found macaque monkeys (*Macaca fuscata*) could initially perform discrimination of both macaque and human faces. For monkeys exposed for 1 month only to human faces, discrimination then became limited to human faces. The crucial findings in the present context are then that (a) these human-exposed monkeys failed to relearn the ability to discriminate macaque faces despite subsequently receiving 11 months of experience sharing a cage with other macaques, and (b) the exposure to macaque faces began at 7-25 months of age, well before *Macaca fuscata* reach adulthood at 4 years (female) or 5 years (male; Wolfe, 1978). This suggests that flexibility is impossible after the initial narrowing period. Caveats, however, are that it is difficult to convert age-in-months to stage of development across humans and monkeys (because monkeys mature faster than humans), and it is also then difficult to know whether 11 months of experience in an immature monkey should be "enough" experience (i.e., it is hard to know how to convert this to any particular length of experience in an immature human). It is possible that Sugita's monkeys could have relearned macaque faces with greater duration of experience. Another possibility is that the difference between the Sugita results and the Asian-adoptee studies arises from the fact that the former tested relearning of a narrowed-out *species* (i.e., very different in appearance from the experienced faces), while the latter tested only a narrowed-out *race* (i.e., less different in appearance from the experienced faces). Thus, it is possible that the degree of plasticity for relearning post-infancy is related to how physically different the stimulus faces are from the types of faces to which the subject was exposed during infancy.

One final finding is also of relevance to retained flexibility. Macchi Cassia et al. (2009a) demonstrated an ability for adults to *reactive childhood experience* (note I mean *childhood* experience here, not *infant* experience). They found that 3-year-olds with younger siblings (who had therefore been exposed to infant faces) demonstrated inversion effects for both adult and infant faces, whereas 3-year-old children without younger siblings showed inversion effects only for adult faces. Interestingly, adults with recent infant face experience (first time mothers) showed inversion effects for infant faces, but only if they also had had younger siblings when they themselves were children (i.e., they had received both early childhood and adult experience with infant faces). Further, young women who had had younger siblings, but who were not mothers (i.e., they had received only early childhood experience with infant faces) did not show inversion effects for infant faces. This study argues that experience with a face subtype in early childhood can lie dormant until reactivated by further experience in adulthood.

The Macchi Cassia et al. (2009a) findings have implications for the interpretation of several other studies. First, Sangrigoli et al. (2005) found that Asian-adoptees-to-Europe were poorer at Asian faces than were Asian participants raised in Asia; the Macchi Cassia et al. (2009a) findings then suggest that this decrement for Asian faces could be easily reversed in the adoptees by a short time spent living in Asia. Second, regarding own-*age* effects, the Macchi Cassia et al. (2009a) findings suggest the fact that all typical adults were exposed to child faces as children (i.e., at school), may be an important factor in the flexibility observed in recent preschool teacher studies. These studies have found that preschool teachers show better recognition memory and holistic processing for child faces, as compared to adults without concentrated recent exposure to children (de Heering & Rossion, 2008; Harrison & Hole, 2009; Kuefner et al., 2008; Kuefner et al., in press). Rather than reflecting the effects of recent exposure during *adulthood*, these findings may reflect the combined influences of exposure to child faces during *both* childhood and adulthood.

In summary, the topic of plasticity for face types, and the extent to which plasticity differs between experience obtained in childhood and experience gained in adulthood, is of strong theoretical interest and is ripe for further investigation. It would be valuable, for example, to know the answers to any of the following questions: Can human children (e.g., 5-year-olds) relearn to discriminate the faces of other-*species*, in addition to their ability to relearn other-race faces? Is this same relearnability possible or impossible in human adults? Is relearnability, in either children or adults, related to the degree of physical difference between the infancy-experienced face type (e.g., Asian humans, in Asian observers) and the stimulus face type (e.g., Caucasian human faces vs. chimpanzee faces vs. macaque faces, vs. horse faces)? In addressing these questions, training studies may be of some value, given the inherent difficulties of matching amount of "relearning" experience in naturalistic settings.

8.5 Conclusion

The broad aim of this thesis was to contribute to the active debate in the literature which centres on the relative roles of an inborn capacity present at birth, experience with faces, and the timing of that experience, in producing adult face recognition abilities. The major conclusion from the thesis is that *all* face-specific perception mechanisms are mature by 5-7 years (and perhaps much earlier), and that development is not driven by ongoing experience with faces into adolescence but rather by the combination of (a) an experience-expectant innate component, (b) early experience in the first year of life, and (c) possible further effects of experience up to preschool ages. This thesis has also confirmed that the mature face system retains flexibility, but has suggested that this may be limited by factors such as a necessity to have had previous experience with a face type during childhood, if it was not available during infancy.

REFERENCES

(lists those papers cited in Chapter 1, 7 & 8, and the context statements)

Anastasi, J. S., & Rhodes, M. G. (2005). An own-age bias in face recognition for children and older adults. *Psychonomic Bulletin and Review, 12*(6), 1043-1047.

Anzures, G., Mondloch, C. J., & Lackner, C. (2009). Face adaptation and attractiveness aftereffects in 8-year-olds and adults. *Child Development, 80*(1), 178-191.

Avidan, G., Hasson, U., Malach, R., & Behrmann, M. (2005). Detailed exploration of face-related processing in congenital prosopagnosia: 2. Functional neuroimaging findings. *Journal of Cognitive Neuroscience, 17*(7), 1150-1167.

Aylward, E. H., Park, J. E., Field, K. M., Parsons, A. C., Richards, T. L., Cramer, S. C., et al. (2005). Brain activation during face perception: Evidence of a developmental change. *Journal of Cognitive Neuroscience, 17*(2), 308-319.

Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience, 8*(6), 551-565.

Bernstein, M. J., Young, S. G., & Hugenberg, K. (2007). The cross-category effect: Mere social categorization is sufficient to elicit an own-group bias in face recognition. *Psychological Science, 8*, 706-712.

Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science, 195*, 312-314.

Carey, S., & Diamond, R. (1994). Are faces perceived as configurations more by adults than by children? *Visual Cognition, 2/3*, 253-274.

Carey, S., Diamond, R., & Woods, B. (1980). Development of face recognition - A maturational component? *Developmental Psychology, 16*(4), 257-269.

Cohen Kadosh, K., & Johnson, M. H. (2007). Developing a cortex specialized for face perception. *Trends in Cognitive Sciences, 11*(9), 367-369.

Crookes, K., & McKone, E. (2004). Childhood development of implicit memory for unfamiliar faces [Unpublished Honours thesis]: The Australian National University.

de Haan, E., Young, A. W., & Newcombe, F. (1987). Face recognition without awareness. *Cognitive Neuropsychology, 4*(4), 385-415.

de Heering, A., de Liedekerke, C., Deboni, M., & Rossion, B. (in press). The role of experience during childhood in shaping the other-race effect. *Developmental Science.*

de Heering, A., & Rossion, B. (2008). Prolonged visual experience in adulthood modulates holistic face perception. *PLoS One, 3*(5), e2317.

Diamond, R., & Carey, S. (1986). Why faces are and are not special: An effect of expertise. *Journal of Experimental Psychology: General, 115*(2), 107-117.

Duchaine, B. C., Germine, L., & Nakayama, K. (2007). Family resemblance: Ten family members with prosopagnosia and within-class object agnosia. *Cognitive Neuropsychology, 24*(4), 419-430.

Gauthier, I., Skudlarski, P., Gore, J. C., & Anderson, A. W. (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nature Neuroscience, 3*(2), 191-197.

Geldart, S., Mondloch, C. J., Maurer, D., de Schonen, S., & Brent, H. P. (2002). The effect of early visual deprivation on the development of face processing. *Developmental Science, 5*(4), 490-501.

Gilchrist, A., & McKone, E. (2003). Early maturity of face processing in children: Local and relational distinctiveness effects in 7-year-olds. *Visual Cognition, 10*(7), 769-793.

Golarai, G., Ghahremani, D., G, Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D. E., et al. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience, 10*(4), 512-522.

Golarai, G., Grill-Spector, K., & Reiss, A. L. (2006). Autism and the development of face processing. *Clinical Neuroscience Research, 6*, 145-160.

Goren, C. C., Sarty, M., & Wu, P. Y. K. (1975). Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics, 56*(4), 544-549.

Haig, N. D. (1984). The effect of feature displacement on face recognition. *Perception, 13*(5), 505-512.

Harrison, V., & Hole, G. J. (2009). Evidence for a contact-based explanation of the own-age bias in face recognition. *Psychonomic Bulletin and Review, 16*(2), 264-269.

Humphreys, K., & Johnson, M. H. (2007). The development of "face-space" in infancy. *Visual Cognition, 15*(5), 578-598.

Jacques, C., D'Arripe, O., & Rossion, B. (2007). The time course of the inversion effect during individual face discrimination. *Journal of Vision, 7*(8), 3.

Jemel, B., Mottron, L., & Dawson, M. (2006). Impaired face processing in Autism: Fact or artifact? *Journal of Autism and Developmental Disorders, 36*(1), 91-106.

Johnson, M. H. (2005). Subcortical face processing. *Nature Reviews Neuroscience, 6*, 766-774.

Johnson, M. H., Dziurawiec, S., Ellis, H. D., & Morton, J. (1991). Newborns' preferential tracking of faces and its subsequent decline. *Cognition, 40*(1-2), 1-19.

Johnston, R. A., & Ellis, H. D. (1995). Age effects in the processing of typical and distinctive faces. *The Quarterly Journal of Experimental Psychology, 48A*(2), 447-465.

Kelly, D. J., Quinn, P. C., Slater, A., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science, 18*(12), 1084-1089.

Kuefner, D., de Heering, A., Jacques, C., Palmero-Soler, E., & Rossion, B. (in press). Early visually evoked electrophysiological responses over the human brain (P1, N170) show stable patterns of face-sensitivity from 4 years to adulthood. *Frontiers in Human Neuroscience.*

Kuefner, D., Macchi Cassia, V., Picozzi, M., & Bricolo, E. (2008). Do all kids look alike? Evidence for an other-age effect in adults. *Journal of Experimental Psychology: Human Perception and Performance, 34*(4), 811-817.

Kuefner, D., Macchi Cassia, V., Vescovo, E., & Picozzi, M. (in press). Natural experience acquired in adulthood enhances holistic processing of other-age faces. *Visual Cognition.*

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritanim, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science, 9*(2), F13-F21.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2001). Early visual experience and face processing. *Nature, 410*, 890.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2003). Expert face processing requires visual input to the right hemisphere during infancy. *Nature Neuroscience, 6*(10), 1108-1112.

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science, 15*(11), 762-768.

Leopold, D. A., O'Toole, A. J., Vetter, T., & Blanz, V. (2001). Prototype-referenced shape encoding revealed by high-level aftereffects. *Nature Neuroscience, 4*(1), 89-94.

Macchi Cassia, V., Kuefner, D., Picozzi, M., & Vescovo, E. (2009a). Early experience predicts later plasticity for face processing: Evidence for the reactivation of dormant effects. *Psychological Science*.

Macchi Cassia, V., Picozzi, M., Kuefner, D., Bricolo, E., & Turati, C. (2009b). Holistic processing for faces and cars in preschool-aged children and adults: Evidence from the composite effect. *Developmental Science, 12*(2), 236-248.

Martin-Malivel, J., & Okada, K. (2007). Human and chimpanzee face recognition in chimpanzees: Role of exposure and impact on categorical perception. *Behavioral Neuroscience, 121*, 1145-1155.

McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology, 94*(2), 134-162.

McKone, E., Kanwisher, N., & Duchaine, B. C. (2007). Can generic expertise explain special processing for faces? *Trends in Cognitive Sciences, 11*(1), 8-15.

McKone, E., & Robbins, R. (in press). Are faces special? In A. J. Calder, G. Rhodes, J. V. Haxby & M. H. Johnson (Eds.), *The Handbook of Face Perception*: Oxford University Press.

Michel, C., Corneille, O., & Rossion, B. (2007). Race categorization modulates holistic face encoding. *Cognitive Science, 31*, 911-924.

Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception, 31*, 553-566.

Morton, J., & Johnson, M. H. (1991). CONSPEC and CONLERN: A two-process theory of infant face recognition. *Psychological Review, 98*(2), 164-181.

Nishimura, M., Maurer, D., Jeffery, L., Pellicano, E., & Rhodes, G. (2008). Fitting the child's mind to the world: adaptive norm-based coding of facial identity in 8-year-olds. *Developmental Science, 11*(4), 620-627.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296*, 1321-1323.

Passarotti, A. M., Paul, B. M., Bussiere, J. R., Buxton, R. B., Wong, E. C., & Stiles, J. (2003). The development of face and location processing: an fMRI study. *Developmental Science, 6*(1), 100-117.

Passarotti, A. M., Smith, J., DeLano, M., & Huang, J. (2007). Developmental differences in the neural bases of the face inversion effect show progressive tuning of face-selective regions to the upright orientation. *NeuroImage, 34*, 1708-1722.

Pellicano, E., Jeffery, L., Burr, D., & Rhodes, G. (2007). Abnormal adaptive face-coding mechanisms in children with autism spectrum disorder. *Current Biology, 17*(7), 1508-1542.

Pellicano, E., & Rhodes, G. (2003). Holistic processing of faces in preschool children and adults. *Psychological Science, 14*(6), 618-622.

Pellicano, E., Rhodes, G., & Peters, M. (2006). Are preschoolers sensitive to configural information in faces? *Developmental Science, 9*(3), 270-277.

Pelphrey, K. A., Lopez, J., & Morris, J. P. (2009). Developmental continuity and change in responses to social and nonsocial categories in human extrastriate visual cortes. *Frontiers in Human Neuroscience, 3*(0), doi:10.3389/neuro.3309.3025.2009.

Polk, T. A., Park, J., Smith, M. R., & Park, D. (2007). Nature versus nurture in ventral visual cortex: A functional magnetic resonance imaging study of twins. *The Journal of Neuroscience, 27*(51), 13921-13925.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition, 103*(1), 34-79.

Rossion, B., & Curran, T. (in press). Visual expertise with pictures of cars correlates with RT magnitude of the car inversion effect. *Perception.*

Rossion, B., Delvenne, J.-F., Debatisse, D., Goffaux, V., Bruyer, R., Crommelinck, M., et al. (1999). Spatio-temporal localization of the face inversion effect: an event-related potentials study. *Biological Psychology, 50*, 173-189.

Sangrigoli, S., & de Schonen, S. (2004). Effect of visual experience on face processing: a developmental study of inversion and non-native effects. *Developmental Science, 7*(1), 74-87.

Sangrigoli, S., Pallier, C., Argenti, A.-M., Ventureyra, V. A. G., & de Schonen, S. (2005). Reversibility of the other-race effect in face recognition during childhood. *Psychological Science, 16*(6), 440-444.

Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science, 10*(4), F15-F30.

Schmalzl, L., Palermo, R., & Coltheart, M. (2008). Cognitive heterogeneity in genetically based prosopagnosia: A family study. *Journal of Neuropsychology, 2*(1), 99-117.

Schmalzl, L., Palermo, R., Green, M., Brunsdon, R., & Coltheart, M. (2008). Training of familiar face recognition and visual scan paths for faces in a child with congenital prosopagnosia. *Cognitive Neuropsychology, 25*(5), 704-729.

Scott, L. S., & Monesson, A. (2009). The origin of biases in face perception. *Psychological Science, 20*(6), 676-680.

Sengpiel, F. (2007). The critical period. *Current Biology, 17*(17), R742-743.

Simion, F., Regolin, L., & Bulf, H. (2008). A predisposition for biological motion in the newborn baby. *Proceedings of the National Academy of Sciences of the United States of America, 105*(2), 809-813.

Simion, F., Valenza, E., Umilta, C., & Dalla Barba, B. (1998). Preferential orienting to faces in newborns: A temporal-nasal asymmetry. *Journal of Experimental Psychology: Human Perception and Performance, 24*(5), 1399-1405.

Simons, D., J, & Levin, D. T. (1998). Failure to detect changes to people during real-world interaction. *Psychonomic Bulletin and Review, 5*(4), 644-649.

Slater, A., Quinn, P. C., Hayes, R., & Brown, E. (2000). The role of facial orientation in newborn infants' preference for attractive faces. *Developmental Science, 3*(2), 181-185.

Sugita, Y. (2008). Face perception in monkeys reared with no exposure to faces. *Proceedings of the National Academy of Sciences of the United States of America, 105*(1), 394-398.

Tanaka, J. W., Kay, J. B., Grinnell, E., Stansfield, B., & Szechter, L. (1998). Face recognition in young children: When the whole is greater than the sum of its parts. *Visual Cognition, 5*(4), 479-496.

Thomas, C., Avidan, G., Humphreys, K., Jung, K.-j., Gao, F., & Behrmann, M. (2008). Reduced structural connectivity in ventral cortex in congenital prosopagnosia. *Nature Neuroscience, 12*, 29-31.

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

Turati, C., Macchi Cassia, V., Simion, F., & Leo, I. (2006). Newborns' face recognition: Role of inner and outer facial features. *Child Development, 77*(2), 297-311.

Williams, M. A., Berberovic, N., & Mattingley, J. B. (2007). Abnormal fMRI adaptation to unfamiliar faces in a case of developmental prosopamnesia. *Current Biology, 17*, 1259-1264.

Wolfe, L. (1978). Age and sexual behavior of Japanese Macaques. *Archives of Sexual Behavior, 7*(1), 55-68.