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

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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

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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-

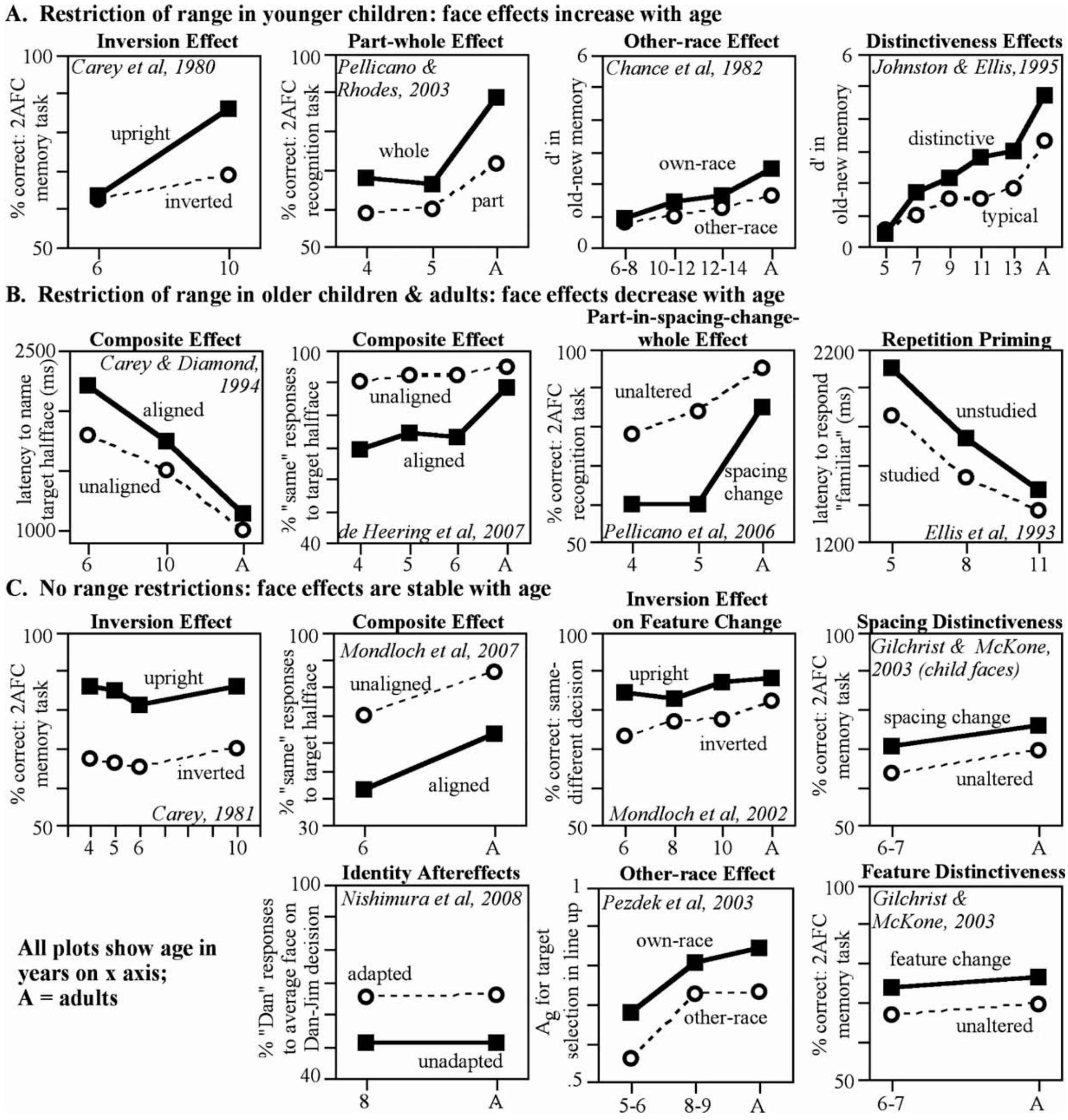

Fig. 1. Results of previous studies tracking across age the size of face effects related to holistic processing (inversion, composite, part-whole, spacing), face-space (distinctiveness, other-race, identity aftereffect), and face encoding (repetition priming). (A) Representative sample of a large number 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

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[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

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[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

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[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

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

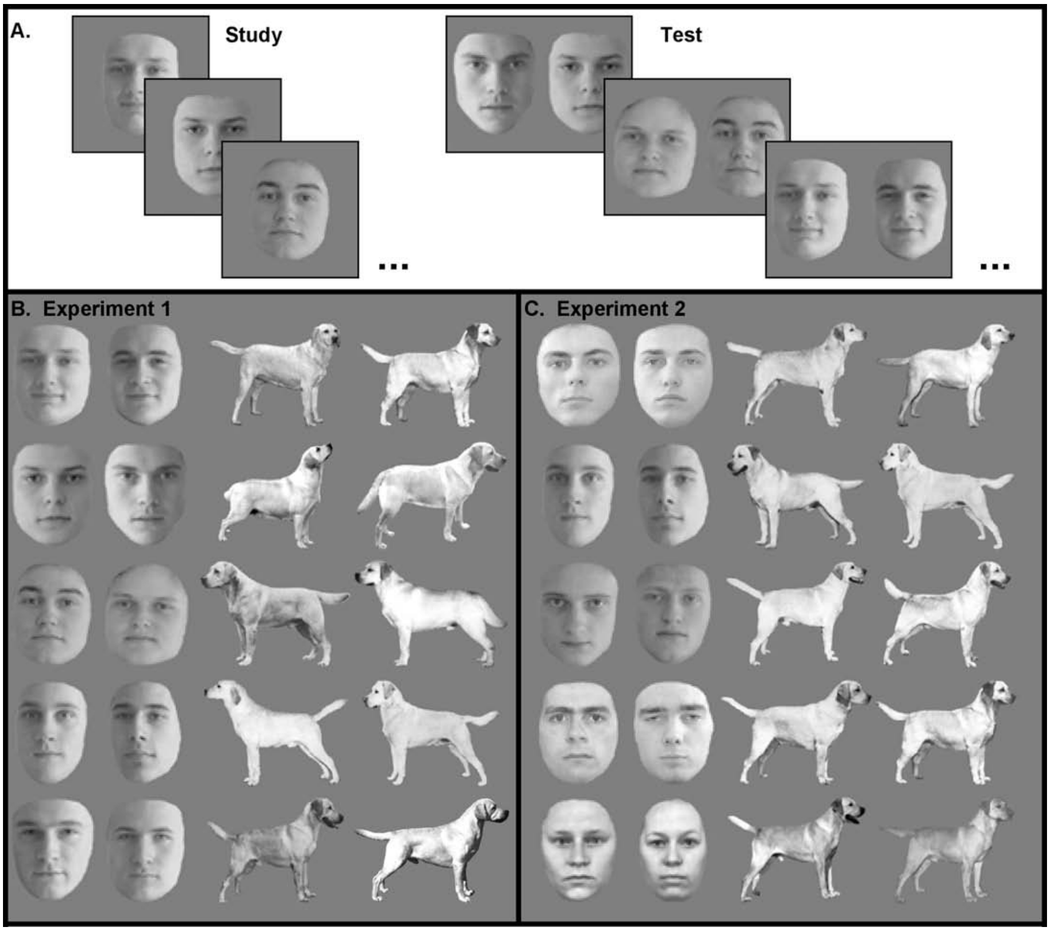

Fig. 2. (A) Procedure for Experiments 1 and 2. In a given block, participants learned 5 faces (or dogs), and later did a recognition memory test on 5 pairs (each showing one old and one new item). (B) Stimulus pairs from a sample block in Experiment 1, where *upright* memory performance was matched across 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

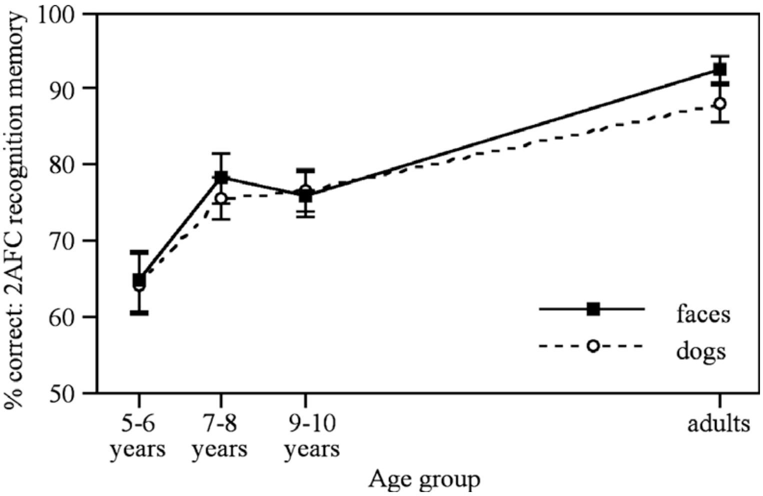

Fig. 3. Experiment 1: recognition memory results for faces versus dogs, showing no difference in rate of development with age. Error bars show ±1 *SEM*.

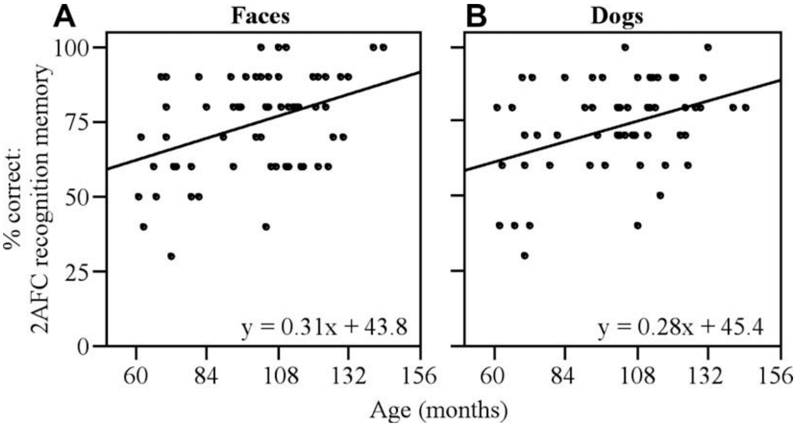

Fig. 4. Experiment 1: recognition memory plotted against exact age in months for child participants. The formula given on each plot is for the line of best fit.

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

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[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.

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[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

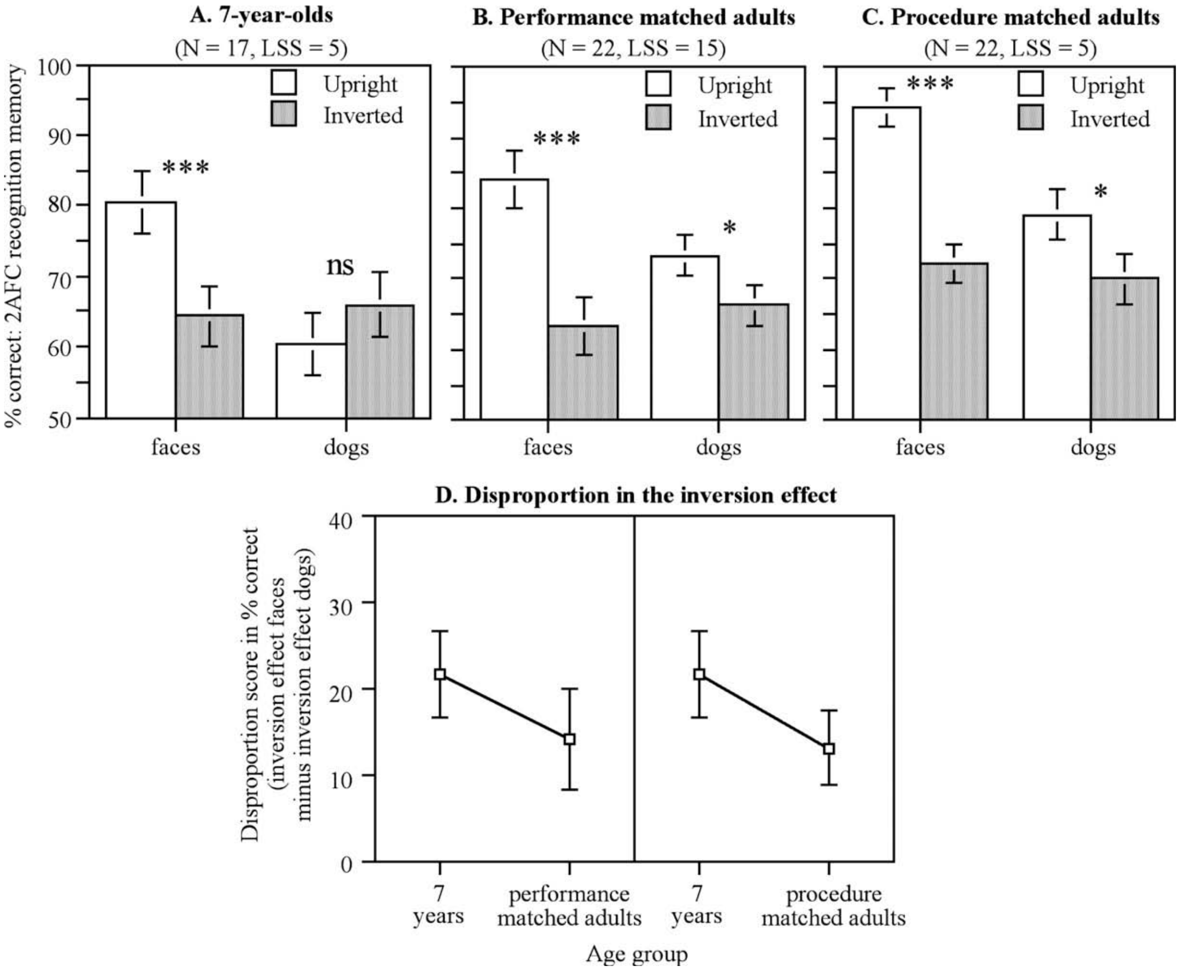

Fig. 5. Experiment 2: (A–C) seven-year-olds show the adult-like pattern of a much larger inversion effect for faces than objects (dogs); moreover, (D) the amount by which the inversion effect is larger for faces than dogs (disproportion measure) does not increase with age. Data for ‘performance-matched 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-

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[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, $t < 1$.

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[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.

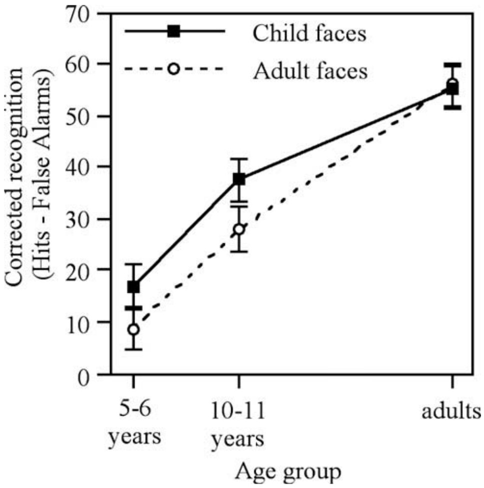

Fig. 6. Experiment 3A: explicit memory results expressed as corrected recognition scores (% "old" responses for studied normal faces *minus* % "old" responses for unstudied normal faces). Findings show (a) the expected developmental increase in explicit memory for both child and adult faces and (b) better 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-

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[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.

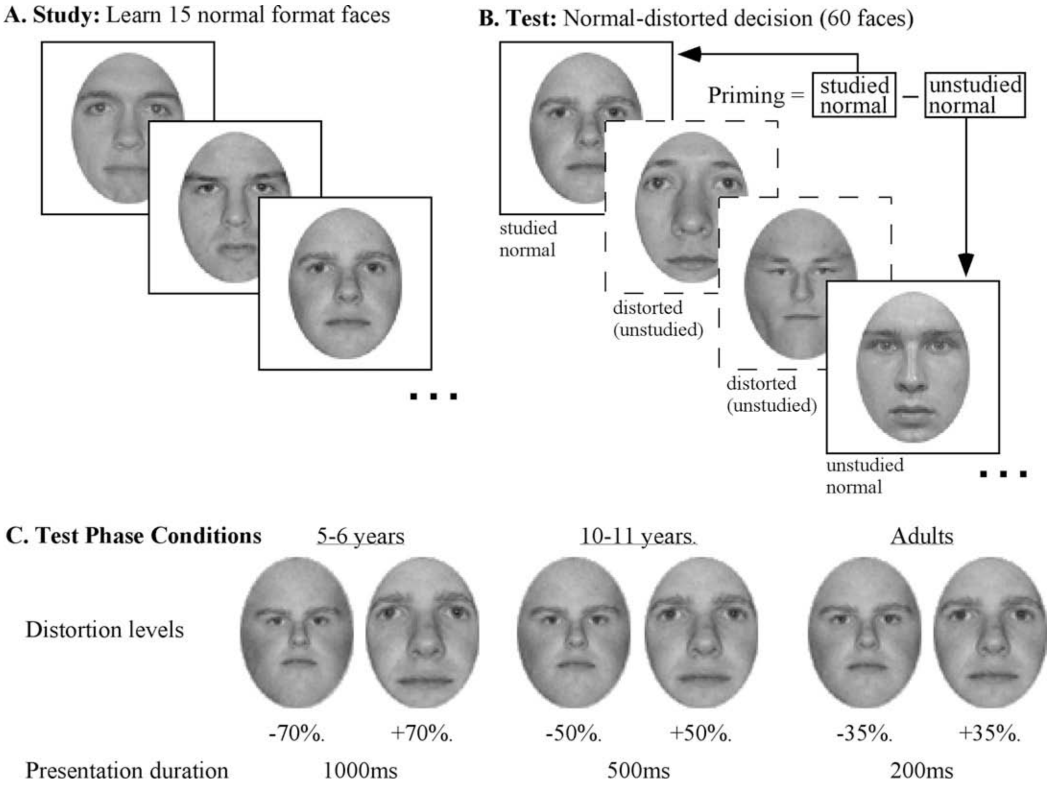

Fig. 7. Experiment 3B: procedure for the implicit memory task. (A) Participants learned 15 normal-format faces at study (the same as for the explicit memory task). (B) At test, repetition priming was assessed for normal-format faces in normal-distorted decision. (C) At test, baseline performance for 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-

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[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

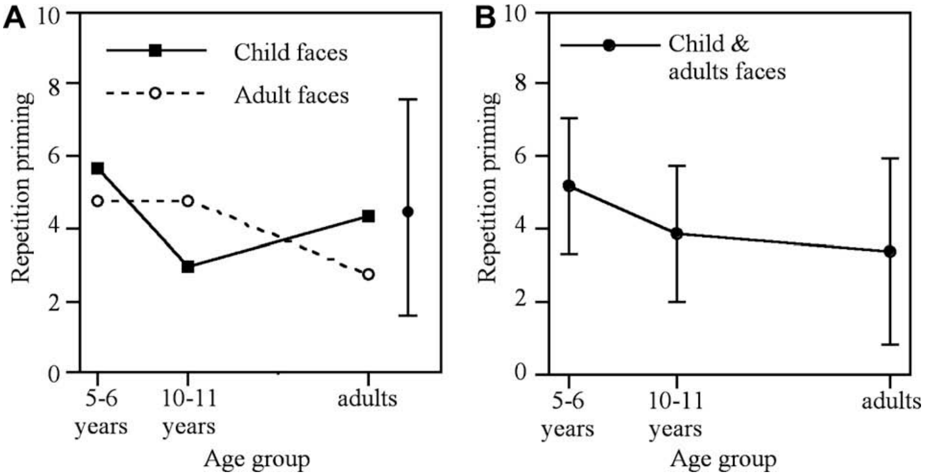

Fig. 8. Experiment 3B: implicit memory results expressed as priming scores (% "normal" responses to studied normal faces *minus* % "normal" responses to unstudied normal faces) for: (A) each face-age stimulus set separately and, (B) collapsed across the two face-age sets. Note the lack of increase in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

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[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.

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[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

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[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-

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[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.

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