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Developmental changes in the processing of hierarchical shapes continue into adolescence

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Abstract

The present study was designed to trace the normal development of local and global processing of hierarchical visual forms. We presented pairs of hierarchical shapes to children and adults and asked them to indicate whether the two shapes were the same or different at either the global or the local level. In Experiments 1 (6-year-olds, 10-year-olds, adults) and 2 (10-year-olds, 14-year-olds, adults), we presented stimuli centrally. All age groups responded faster on global trials than local trials (global precedence effect), but the bias was stronger in children and diminished to the adult level between 10 and 14 years of age. In Experiment 3 (10-year-olds, 14-year-olds, adults), we presented stimuli in the left or right visual field so that they were transmitted first to the contralateral hemisphere. All age groups responded faster on local trials when stimuli were presented in the right visual field (left hemisphere); reaction times on global trials were independent of visual field. The results of Experiment 3 suggest that by 10 years of age the hemispheres have adultlike specialization for the processing of hierarchical shapes, at least when attention is directed to the global versus local level. Nevertheless, their greater bias in Experiments 1 and 2 suggests that 10-year-olds are less able than adults to modulate attention to the output from local versus global channels–perhaps because they are less able to ignore distractors and perhaps because the cerebral hemispheres are less able to engage in parallel processing.

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Visual scenes have many levels of organization, including individual elements and the global organization of those elements. A table setting, for example, can be described at the global level as an arrangement of place-settings, serving dishes, and candles. At a more local level one can describe the arrangement of elements (e.g., glass, plate, utensils) associated with each place setting, and still more locally one can describe the details (e.g., pattern) on each piece of silverware. A long-standing debate in psychology has centered on the extent to which processing such scenes begins with identifying the local elements (e.g., a fork) or the complex whole. Object recognition appears to depend on the perception and recognition of primitive features, such as a curved edge or diagonal line (e.g., Biederman, 1987; Treisman & Gelade, 1980); however, our subjective experience is that we perceive first that a table is prepared for dining and only later analyze the objects comprising the table setting. That the whole may be recognized before its parts has been demonstrated with hierarchical alphabetical letters—larger letters (e.g., H) comprised of smaller letters that are either congruent (e.g., small Hs) or incongruent (e.g., small As) with the larger letter. When sensory factors (e.g., discriminability) are controlled for, normal adults detect targets at the global level of hierarchical stimuli more rapidly than they detect targets at the local level. Furthermore, this global advantage is enhanced when the local and global levels are incongruent (e.g., Blanca, Zalabardo, Garcia-Criado, & Stiles, 1994; Martin, 1979a; Navon, 1977), presumably because processing the global level interferes with processing the local level, but the reverse is not true (see Robertson & Lamb, 1991 for a review). This pattern of responses has been labelled global precedence. It can be explained by global information accumulating faster than local information (Hübner, 1997; Shedden & Reid, 2001)—a difference that makes global information more salient, especially in the earliest stages of processing.

Although even 3- and 4-month-old infants show global precedence effects (Colombo, Mitchell, Coldren, & Freeseman, 1991; Frick, Colombo, & Allen, 2000; Ghim & Eimas, 1988; Quinn, Burke, & Rush, 1993), children do not always show adultlike sensitivity to global versus local levels of visual stimuli. Under unlimited viewing conditions, the extent to which children show an adultlike pattern varies with task difficulty. For example, when presented with hierarchical forms and asked to judge which of two stimuli most resembles a target, both adults and children base their judgments on the global level (Dukette & Stiles, 1996). Similarly, when asked to copy (Dukette & Stiles, 2001) or describe (Elkind, Koegler, & Go, 1964) hierarchical forms, children as young as 4 years of age are competent at reproducing/describing both the local and global levels. However when these tasks are made more difficult by reducing the number of elements comprising the global form (Dukette & Stiles, 1996), by asking children to draw hierarchical forms from memory (Dukette & Stiles, 2001), or by making the hierarchical forms more complex (Prather & Bacon, 1986) children's biases shift toward the local level more readily than adults'.

The above studies demonstrate that the local level of hierarchical stimuli may dominate children's similarity judgements, replications, and descriptions of hierarchical stimuli. However, studies with infants indicate the need to distinguish between *sensitivity* to local versus global forms and the subsequent *dominance* of local versus global processing. Three- and 4-month-old infants demonstrate global precedence: they require a shorter familiarization time to discriminate a familiar hierarchical pattern from a pattern that is novel only at the global level than they do to discriminate it from a pattern that is novel only at the local level (Colombo et al., 1991; Frick et al., 2000) and this is true both for short lookers and longlookers, although the latter require longer familiarization times for both types of processing. (Infants are classified as short and longlookers based on their peak fixation during a pretest.) These results suggest that infants are more *sensitive* to the global level of visual stimuli. Despite processing the global level faster than the local level, Colombo, Freeseman, Coldren, and Frick (1995) report that long-looking infants *attend preferentially* to the local level of hierarchical stimuli: following a longer familiarization period they look longer at a hierarchical form that is novel only at the local level than at a hierarchical form that is novel only at the global level. Thus global precedence during the initial phase of processing can coexist with local dominance after additional processing. This pattern during infancy is consistent with evidence that global precedence in adults can only be demonstrated under short presentation times (see also Robertson & Lamb, 1991; Shedden & Reid, 2001).

In none of the previous studies of hierarchical processing were children tested with the short exposure times known to facilitate global precedence in adults (Kinchla & Wolfe, 1979; Martin, 1979a), and so the relative speed with which children process the global versus local level of complex stimuli remains unknown. That was the purpose of Experiment 1. In a directed attention task, participants saw two hierarchical forms presented sequentially for a brief duration and were asked to indicate whether the two forms were the same or different on the basis of either the smaller, individual elements (ignoring global shape) or the global shape (ignoring individual elements). We used hierarchical geometric shapes, rather than alphabetical letters, to avoid disadvantaging younger children who are just learning the alphabet. We predicted that under these conditions, children may be relatively more sensitive to the global form than to the local elements. In Experiment 1, we tested 6-year-olds, 10-year-olds, and adults. Because 10-year-olds made more errors than adults when asked to attend to the local level, we tested older children and adults in Experiment 2. In Experiment 3, we used a lateralized version of this task to determine the extent to which differences between children and adults on the central version of the task were related to differences in hemispheric specialization.

Experiment 1

The purpose of Experiment 1 was to test children and adults with hierarchical shapes and a short presentation time that favors global processing in adults (Kinchla & Wolfe, 1979; Martin, 1979a). Participants saw two stimuli in rapid succession and signalled whether they were the same or different at the local (blocks 2 and 3) or global (blocks 1 and 4) level. Based on pilot testing, we chose a presentation time of 150 ms because it yielded strong effects in adults but appeared to be long enough for 6-year-olds to encode the stimuli accurately in at least one condition.

Method

Participants

The participants were three groups of 24 subjects: 6-year-olds (± 3 months), 10-year-olds (± 3 months), and adults (18–28 years). Half of the subjects in each group were males. Children were recruited from names on file of mothers who had volunteered them at birth for later study. Adults were undergraduate students participating for five dollar payment or for points in a psychology course at McMaster University. None of the participants had a history of eye problems, and all met our criteria on a visual screening exam. Specifically, adults and 10-year-olds had Snellen acuity of at least 20/20 in each eye without optical correction, and 6-year-olds had visual acuity of at least 20/25 on the Goodlight Crowding test. In addition, all subjects had worse acuity with a +3 diopter lens (to rule out farsightedness of greater than 3 diopters), fusion at near on the Worth Four dot test, and stereoacuity of at least 40 arc s on the Titmus test. In addition, all subjects reported being right-handed. An additional 16 subjects were tested, but excluded from the final analysis: 12 failed visual screening (three 6-year-olds, four 10-year-olds, and five adults), three (6-year-olds) failed a face screening task designed to give them practice with the computerized procedure, and in one case the equipment failed (one 6-year-old).

Stimuli and apparatus

The stimuli were hierarchical figures, each consisting of a larger geometric shape (circle or square) produced by the arrangement of smaller black shapes (circles or squares) (see Fig. 1). Each global shape was 56.5 mm by 56.5 mm (3.24 visual degrees when viewed from 100 cm), the individual elements were 7.3 mm (.42 visual degrees) wide/high, and the spaces between them ranged between 5.1 mm (.29 visual degrees) and 8.5 mm (.49 visual degrees) wide-sizes which are within the ideal range for eliciting global precedence in adults (Kinchla & Wolfe, 1979).

Between trials, a central fixation cross appeared (.69° high by. 69° wide; stroke width = .29 visual deg). Stimuli were presented on a monochrome Radius 21-GS monitor. The experiment was controlled by Cedrus Superlab software and a Macintosh LC 475 computer. A joystick, held by the subject to make responses, was connected to the computer via a keyboard. The keyboard was placed in front of the tester, who used it to initiate each trial.

Procedure

Following an explanation of the procedure, the subject or, for children, a parent signed a consent form. In addition, each 10-year-old read a description of the study and provided assent. There were four blocks of eight trials. The experimenter initiated each trial only when the subject was fixating the central fixation cross. During

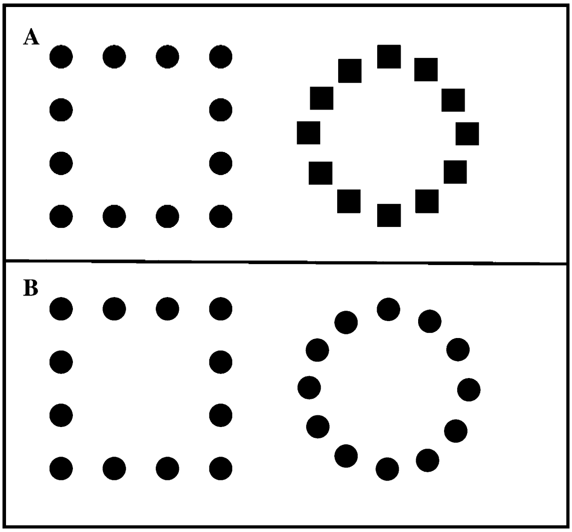

Fig. 1. Samples of stimuli presented on congruent trials (A) and incongruent trials (B). The correct response to the pair of stimuli presented in (A) is "different" on both local and global trials. The correct response to the pair of stimuli presented in (B) is "same" on local trials, but "different" on global trials.

each trial, two hierarchical figures appeared sequentially in the center of the screen for 150 ms, separated by an interstimulus interval of 50 ms. In Blocks 1 and 4, subjects were asked to decide whether the figures in each pair were the same or different on the basis of the global shape, and to ignore the local elements. In Blocks 2 and 3, subjects were asked to decide whether the figures in each pair were the same or different on the basis of the local elements, and to ignore the global shape. Within each block, there were four congruent trials—trials in which the figures were the same (two trials) or different (two trials) at both the attended and the ignored level. Within each block, there were four incongruent trials—trials in which the figures were the same at the attended level, but different at the ignored level (two trials), or different at the attended level, but the same at the ignored level (two trials). Fig. 1 gives examples of a congruent trial (Panel A) and an incongruent trial (Panel B). Instructions and four practice trials were given prior to Blocks 1, 2, and 4 (i.e., whenever the to-be-attended level changed).

Prior to the hierarchical shapes task, subjects took part in experiments on face processing, the last half of which, like Experiment 1, required same/different responses about sequential targets (Geldart, 2000). One anonymous reviewer was concerned that participating in experiments on face processing may have affected the results on our hierarchical shapes task because of the 'configural' nature of face processing. For three reasons, we do not believe that this participation had an effect. First, some of the face perception tasks directed the participants' attention towards local cues, e.g., "Are the eyes the same or different"; hence we had encouraged featural processing on some tasks. Second, to the extent that face processing is configural in nature, one can never completely eliminate the confound—after all, participants were interacting with an experimenter throughout testing and, presumably, engaged in configural processing of his/her face. Third, the 10-year-olds and adults in Experiment 2 did not take part in any other task before the hierarchical shapes task; nonetheless the pattern of results for those age groups is similar across Experiments 1 and 2.

Data analysis

Analyses were restricted to the eight incongruent trials per condition because they are the trials that provide a measure of interference from the irrelevant dimension as indexed by increased errors or increased reaction time. It was necessary to include congruent trials in the testing protocol to ensure that participants could not determine the correct responses at one level (e.g., local) based on the realization that it was always the opposite of the correct response at the other level (i.e., global). We excluded congruent trials from the analysis because correct responses can be based on either the to-be-attended level or the to-be-ignored level.

We conducted ANOVAs on proportion correct on incongruent trials and on median reaction time on correct trials with one within-subjects factor (level of processing) and one between-subjects factor (age). Interactions between age and level of processing were followed by analyses of simple effects and Dunnett's t tests comparing each group of children to adults. For the ANOVA on reaction times, we included only 10-year-olds and adults because 6-year-olds performed at chance levels on local trials. Because we anticipated that large, and uninteresting, age differences in reaction times might mask an interaction between age and level of processing, we standardized reaction time scores to eliminate any main effect of age. For each age group, we calculated the mean and standard deviation of median reaction times across both conditions (i.e., each subject contributed two values—the median reaction time for correct global trials and the median reaction time for correct local trials). We then transformed each subject's median reaction time in each condition to a z-score; negative z-scores indicate a reaction time that is faster than the mean, and positive z-scores indicate a reaction time that is slower than the mean for that age group. The resulting difference between age groups was zero, but age differences in performance on local versus global trials would be revealed by an interaction between age and level of processing (see Shore et al., 2001).

Results

Fig. 2 shows the mean raw scores for proportion correct and reaction times of correct responses for each age group. The ANOVA for proportion correct revealed main effects of age, $F(2,69) = 42.72$, $p < .0001$, and level of processing, $F(1,69) = 54.99$, $p < .0001$, and a significant age × level of processing interaction, $F(2,69) = 11.29$, $p < .0001$. Analysis of simple effects revealed a significant effect of age on both local, $F(2,69) = 35.76$, $p < .001$, and global, $F(2,69) = 20.06$, $p < .001$, trials. On local trials, both 6-year-olds and 10-year-olds were significantly less accurate than adults (Dunnet's, ps $< .05$); on global trials, 6-year-olds were significantly less accurate than adults, $p < .05$, but 10-year-olds did not differ from adults. Furthermore, while adults

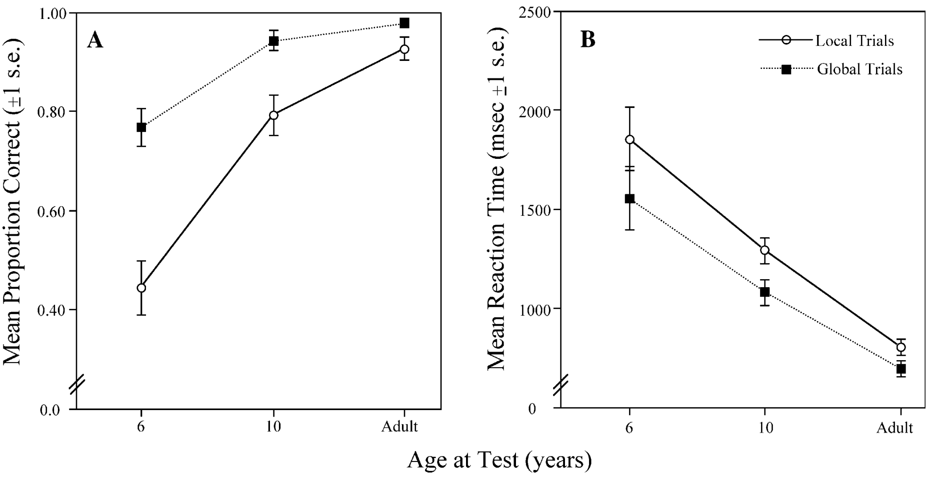

Fig. 2. Mean proportion correct (±1 *SE*; A) and mean reaction times (±1 *SE*; B) of the raw scores for 6-year-olds, 10-year-olds, and adults on incongruent trials in Experiment 1. Reaction times are based on correct trials only. Open circles represent the results for local trials and filled squares represent the results for global trials. (*Note*. Analyses of reaction times were based on standardized scores of 10-year-olds and adults, not the raw data shown here.)

made a similar number of errors on local and global trials, 6-year-olds, $F(1,69) = 62.49$, $p < .001$, and 10-year-olds, $F(1,69) = 13.49$, $p < .001$, made significantly more errors on local trials than they did on global trials (see Fig. 2).

The ANOVA on standardized reaction times revealed a main effect of level of processing, $F(1,46) = 19.42$, $p < .0001$, but no age × level of processing interaction, $p > .1$. Both adults and 10-year-olds responded faster on global trials than on local trials. Although not analyzed statistically, 6-year-olds showed a similar pattern (see Fig. 2).

Discussion

As in previous studies using short exposure times (Blanca et al., 1994; Martin, 1979a; Navon, 1977), adults were more sensitive to the global level of organization than to the local level, as evidenced by faster reaction times. Under these conditions, 6- and 10-year-old children showed an even stronger global bias: they were not only slower on local trials than they were on global trials, but also made significantly more errors on local trials, unlike adults whose accuracy did not differ. These results are in contrast to those from previous studies that did not use short exposure times (Dukette & Stiles, 1996; Dukette & Stiles, 2001; Prather & Bacon, 1986); under unlimited viewing conditions children are more biased than adults towards the local level of hierarchical stimuli.

Robertson and Lamb (1991) suggest that faster processing of the global level is caused by both perceptual and attentional mechanisms that operate well beyond the sensory level. The overall global advantage may be a *perceptual effect*, caused by the relative speed with which two neural mechanisms operate. One mechanism is associated with the right hemisphere and favours lower spatial frequencies (i.e., the global level); the other mechanism is associated with the left hemisphere and favours higher spatial frequencies (i.e., the local level). Visual half-field studies with normal adults (e.g., Blanca et al., 1994; Hellige, 1996; Ivry & Robertson, 1998; Martin, 1979b; reviewed in van Kleek, 1989) and observations of adults and children with unilateral brain damage (e.g., Delis, Robertson, & Efron, 1986; Robertson, Lamb, & Knight, 1988; Stiles-Davis, Janowsky, Engel, & Nass, 1988) demonstrate differential sensitivity of the left and right hemispheres to local versus global levels of visual stimuli. Studies using event-related potentials indicate that although global information and local information accumulate simultaneously, global information accumulates faster than local information at the earliest stages of processing, making it more salient (Hübner, 1997; Shedden & Reid, 2001). Tasks that increase processing demands at later stages (e.g., by including inconsistent stimulus–response mapping) allow the accumulation of local information to continue, reducing the perceptual advantage of global information (Shedden & Reid, 2001). The magnitude of the overall global advantage is modulated by an attentional mechanism. For example, in divided attention tasks, reaction times to global versus local targets can be modulated by varying the probability with which the target appears at the global level (Kinchla, Solis-Macias, & Hoffman, 1983). Neuropsychological studies also demonstrate the separability of the overall global advantage and attentional mechanisms. Lesions in the posterior superior temporal gyrus and adjacent parietal lobe disrupt attentional control (changes in response time as a function of the probability of the target appearing at the global level), but not the overall global advantage; lesions in the caudal lateral parietal lobe disrupt the overall global advantage, but not attentional control (Robertson & Lamb, 1991).

Our task was a directed attention task in which participants were instructed to attend to either the local or the global level. Children's greater sensitivity to the global level of our hierarchical forms may be due to either the perceptual mechanisms or attentional mechanisms discussed by Robertson and Lamb (1991). It is possible that the perceptual channels, particularly in the left hemisphere, that amplify higher spatial frequencies are less efficient than the channels that amplify lower spatial frequencies—a hypothesis that is supported by our knowledge about the development of visual acuity. Visual acuity at birth is 30–60 times worse than that seen in normal adults (reviewed in Maurer & Lewis, 2001). Although it improves rapidly during the first months of life, it is still not near adult levels at the end of the first year (e.g., Maurer & Lewis, 2001; Mayer et al., 1995), and it is not until seven years of age that contrast thresholds become adultlike (Ellemberg, Lewis, Maurer, Liu, & Brent, 1999). The slow development of visual acuity may create a bias in infants to attend to global shape–a bias that continues into childhood. Children may begin to overcome the global bias only after contrast sensitivity reaches adult levels, and it may take several years of experience attending to the local level before the global bias decreases to adult levels.

It is also possible that children are less able to control the allocation of attentional resources to the local versus global level of hierarchical stimuli. This hypothesis is consistent with other studies demonstrating that children are less able to ignore distractors than are adults (Goldberg, Maurer, & Lewis, 2001; Ridderinkhof & van Molen, 1995). Goldberg et al. asked adults and 10-year-olds to discriminate between two possible targets that were surrounded by distractors that were either compatible or incompatible. At both ages, responses were slower when the distractors were incompatible than when they were compatible, but the effect was stronger in 10-year-olds. These two hypotheses are not mutually exclusive; both perceptual and attentional processes may contribute to children's insensitivity to the local level of hierarchical stimuli, relative to adults.

That both perceptual and attentional mechanisms may be immature in 10-year-olds is consistent with our knowledge of neural development. The parietal lobe, which has been implicated in attentional control (Robertson & Lamb, 1991), does not reach maximal size until 10-12 years of age (Giedd et al., 1999), and the temporal lobe, which has been implicated in an overall global advantage (Robertson & Lamb, 1991), does not reach maximal size until 16.5 years (Giedd et al., 1999). Although frontal damage does not affect either the overall global advantage or attentional control (Robertson & Lamb, 1991), it is of interest that the pre-frontal cortex, which is important for ignoring distractors in adults (Denckla, 1996; Godefroy, Lhullier, & Rousseaux, 1996), does not reach adult levels of synaptic density until about age 15 (Huttenlocher, 1979, 1990; Levin et al., 1991; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). In addition, performance on tasks that involve the pre-frontal cortex continues to improve even after 16 years of age (Levin et al., 1991). To determine when the processing of hierarchical shapes becomes adultlike, we tested 10-year-olds, 14-year-olds and adults in Experiment 2.

Experiment 2

In Experiment 1, 6-year-olds and 10-year-olds showed a stronger bias toward global processing than adults when presented with hierarchical stimuli. In Experiment 2, we explored when that processing becomes adultlike by testing 10-year-olds, 14-year-olds, and adults on a harder version of the task. We added a third shape and decreased presentation times to 50 ms in order to increase sensitivity to age differences and to allow direct comparisons with performance on a lateralized version of the same task in which the same subjects participated (Experiment 3).

Method

Participants

The participants included three groups of 24 subjects: 10-year-olds (±3 months), 14-year-olds (±3 months) and adults (18–28 years). Half of the subjects in each group were female. To be included in the data analyses, each subject had to meet the inclusion criteria for both Experiments 2 and 3. Recruitment and visual screening of subjects were identical to those described in Experiment 1, with the addition of screening for handedness, which is known to be related to hemispheric specialization.

The handedness test was adapted from Peters (1998) and only subjects who met the criteria for right-handedness were included. An additional 42 subjects were tested, but excluded from the final analysis: 24 failed visual screening (five 10-year-olds; 18 14-year-olds; and one adult), three moved the joystick erratically throughout the procedure (two 14-year-olds and one adult), six experienced mechanical/experimenter error (four 14-year-olds and two adults) and nine made eye movements on more than 15% of the trials in Experiment 3 (six 10-year-olds and three 14-year-olds).

The 14-year-olds took part in a short face-processing task prior to the hierarchical shapes task. Because this task required participants to discriminate faces based on the shape of individual internal features on some trials and the shape of the external contour on other trials, we predicted that it would not bias the results on the subsequent task. We also note that, despite the prior testing, 14-year-olds performed as well as adults (see Results).

Stimuli

Nine hierarchical shapes were presented. The hierarchical shapes represented all possible combinations of a global triangle, a global square, and a global circle made out of smaller triangles, circles, or squares. The size of both the individual elements and of the global shapes was identical to those used in Experiment 1. Stimuli were superimposed on a central fixation cross, which disappeared when stimuli were presented.

Procedure

The procedure began with obtaining informed consent and, when appropriate, assent, and completion of visual screening and the handedness test. There were 18 trials in each of eight blocks—four blocks of global (G) trials and four blocks of local (L) trials. Within each block, half of the trials were incongruent and for half of the trials the correct response was "different." Trials were presented in a different random order to each subject. Instructions and four practice trials were given prior to each block. For adults, the first set of four blocks occurred in one of the four possible orders (G-L-G-L, G-L-L-G, L-G-L-G, L-G-G-L), followed by the second set of four blocks in the same order. For children, we used only the alternating orders, with half of the children beginning with a global block and half beginning with a local block. We did so because it appeared to make the task more interesting for children, because it equalized the impact of children's difficulties in switching strategies (Pick & Frankel, 1974) across the two conditions, and because preliminary analyses for adults indicated no effect of order.

Results

Data were analyzed in the same way as in Experiment 1. Fig. 3 shows the mean raw scores for proportion correct and reaction times of correct responses for each age group. The ANOVA on proportion correct revealed a significant effect of age, $F(2, 69) = 3.983$, $p =< .05$, and a significant age × level of processing interaction,

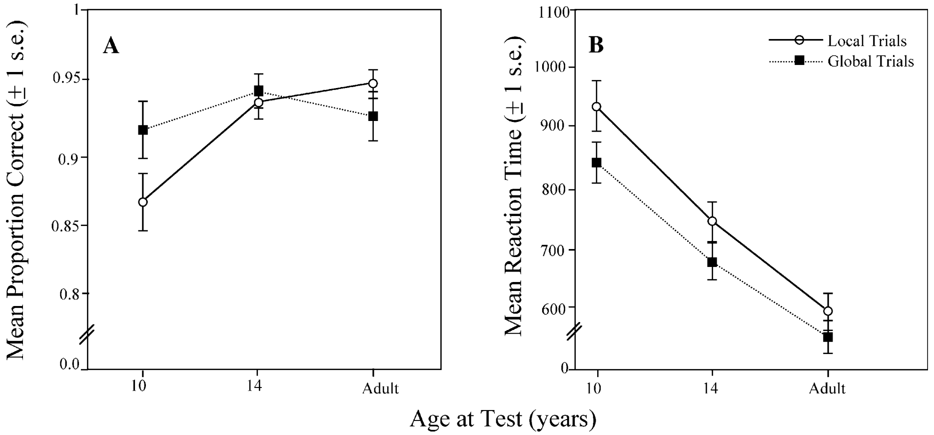

Fig. 3. Mean proportion correct (±1 *SE*; A) and mean reaction times (±1 *SE*; B) of the raw scores for 10-year-olds, 14-year-olds, and adults in Experiment 2. Other details as in Fig. 2.

$F(2,69) = 6.19$, $p < .01$. Accuracy on local trials varied with age, $F(2,69) = 9.67, p < .001$: 10-year-olds were less accurate than adults (Dunnett's test, $p < .05$), whereas 14-year-olds were adult-like ($p > .05$). Accuracy on global trials did not vary with age ($p > .1$). Furthermore, only 10-year-olds' accuracy differed between local and global trials (analyses of simple effects, $p < .01$): 10-year-olds were more accurate on global trials ($M = .917$) than they were on local trials ($M = .867$).

The ANOVA on standardized reaction times revealed a main effect of level of processing, $F(1,69) = 39.77$, $p < .0001$, but no age × level of processing interaction ($p > .1$). All age groups were faster on global trials than they were on local trials (see Fig. 3).

Discussion

The results from Experiment 2 parallel those of Experiment 1, despite decreased presentation times and an increase in the number of hierarchical forms. All groups showed greater sensitivity to the global level of organization than to the local level: reaction times of all age groups were faster on global trials than on local trials. As in Experiment 1, 10-year-olds had a stronger bias than adults. They made significantly more errors than adults on local, but not global trials, and unlike adults, they were less accurate on local trials than on global trials. In contrast, 14-year-olds were equally accurate on local and global trials and were as accurate as adults on both types of trial. Thus processing of hierarchical shapes in our task is adultlike by 14 years of age, and performance becomes adultlike earlier for global trials than for local trials. Fourteen-year-olds may perform like adults because of the changes in neural architecture. For example, the parietal lobe has achieved maximal size by 12 years-of-age and the temporal lobe should be approaching maximal size (Giedd et al., 1999). In addition, increased synaptic density in the pre-frontal cortex (e.g., Sowell et al., 1999), an area of the brain that has been implicated in adults' ability to ignore distractors (Denckla, 1996; Godefroy et al., 1996), may have improved the ability of 14-year-olds to ignore the global shape when asked to make decisions about local elements.

Robertson and Lamb (1991) have argued that in adults, higher spatial frequencies are processed faster by a subsystem in the left hemisphere whereas lower spatial frequencies are processed faster by a subsystem in the right hemisphere. A global advantage may occur because the subsystem responding to global information operates at a faster rate. This argument is generally supported by ERP (e.g., Evans, Shedden, Hevenor, & Hahn, 2000) and fMRI (Martinez et al., 1997) data. In addition, interference between the hemispheres modulates the magnitude of the global advantage (e.g., Evans et al., 2000; Kinchla et al., 1983; reviewed in Robertson & Lamb, 1991). Ten-year-olds' relative insensitivity to local elements may reflect either an immaturity in the subsystem that processes higher spatial frequencies more quickly than low spatial frequencies in adults, or an immaturity in the interactions between the cerebral hemispheres. To begin exploring these hypotheses, we tested adults and children on a lateralized version of our hierarchical shapes task.

Experiment 3

Many types of study indicate specialization of the two hemispheres for global versus local processing. With event-related potentials, there is a larger P1 and N2 response at LH sites when attention is directed to the local level of stimuli than when attention is directed to the global level; in contrast, there is a larger N2 response at RH sites when attention is directed to the global level, but no difference in the P1 response (Evans et al., 2000; Heinze & Munte, 1993; Proverbio, Minniti, & Zani, 1998). fMRI studies have shown that there is greater activity in the RH on global trials than on local trials but no differences in the LH (Martinez et al., 1997). The precise results from behavioural studies vary but, in general, adults are faster at global processing when stimuli are presented in the left visual field and hence are transmitted first to the right hemisphere (LVF/RH); they are faster at local processing when stimuli are presented in the right visual field and hence transmitted first to the left hemisphere (RVF/LH) (e.g., Blanca et al., 1994; Hellige, 1996; Ivry & Robertson, 1998; Martin, 1979b; reviewed in van Kleek, 1989).

An association of the right hemisphere with global processing and the left hemisphere with local processing also has been found in patients with brain damage restricted to one hemisphere. When asked to copy hierarchical letters, patients with right-sided damage reproduce the small letters accurately but do not arrange them to form the correct global shape, whereas patients with damage restricted to the left hemisphere copy the correct global form but tend to omit the smaller letters (e.g., Delis et al., 1986; see also Robertson et al., 1988). A similar pattern was observed when 5-year-olds who had been diagnosed at birth with unilateral brain damage were asked to draw houses (Stiles-Davis et al., 1988). It is not surprising that these children show evidence of hemispheric specialization given the evidence for specialization of the hemispheres for local versus global processing during early infancy. Infants 4–9 months old learned to discriminate briefly presented faces and geometric patterns (e.g., a diamond comprised of circles) based on their local features when the stimuli were presented in the RVF/LH but failed to learn when the stimuli were in the LVF/RH. They learned to make discriminations based on the arrangement of the elements when the stimuli were presented in the LVF/RH but performed less well when they were in the RVF/LH (Deruelle & de Schonen, 1995, 1998). The authors conclude that the RH is dedicated to configural processing, whereas the LH, although biased toward local processing, is sensitive to some aspects of configural change. Together, the results suggest that cortical mechanisms in the right hemisphere that are specialized for processing global shape underlie global precedence.

Hemispheric specialization likely functions to increase processing efficiency by allowing parallel processing of different levels (Evans et al., 2000; Navon, 1977). Ivry and Robertson (1998) argue that laterality effects emerge at postsensory stages of processing, because laterality effects are apparent in identification tasks, but not detection tasks (Kitterle, Christman, & Hellige, 1990), and because patients show deficits in the processing of hierarchical stimuli only if the damage extends into the temporal/parietal junction (Robertson et al., 1988). According to their theory, the specialization of the hemispheres for local versus global processing is a manifestation of the differential amplification by the two hemispheres of higher versus lower spatial frequencies. Effectively, the right hemisphere performs a low-pass filter over the visual field, whereas the left hemisphere performs a high-pass filter. The extent to which differential sensitivity to high versus low spatial frequencies will result in more efficient processing of local versus global shape will depend on the extent to which the two hemispheres are able to process local versus global information separately, yet in parallel, i.e., on attentional mechanisms (Evans et al., 2000; Robertson & Lamb, 1991). This, of course, does not exclude the possibility of additional influences on, or other origins of, the visuo-spatial hemispheric asymmetries (e.g., practice effects, exposure duration; see Sergent, 1987).

Thus, differences in the ability of children versus adults to attend to the local and global levels of stimuli may be the result of immaturities in the subsystems within each hemisphere that process high and low spatial frequencies and/or possible differences in attentional mechanisms. There is some evidence that between 10 and 12 years of age each cerebral hemisphere becomes more able to shield itself from simultaneous activity of the other (Merola & Liederman, 1985). When asked to name two upright and two inverted letters that were all presented simultaneously, 12- and 14-year-olds performed better when the two upright letters were presented together in one visual field and the two inverted letters were presented together in the other visual field, than they did when one upright and one inverted letter was presented in each visual field. Presumably, when presented with conflicting tasks, 12- and 14-year-olds are able to use the two hemispheres in parallel. In contrast, 10-year-olds did not benefit from the presentation of two tasks in opposite visual fields, a result suggesting immature processing interactions between the hemispheres. Thus it seemed reasonable that hemispheric specialization may become adultlike around 14 years of age. A review of visual half-field studies with children (Hiscock, 1988) reported inconsistent results across studies, some of which reported adult-like patterns in children, some of which reported patterns opposite to those seen in adults, and some of which reported no evidence of lateralization. In Experiment 3 we tested 10-year-olds, 14-year-olds, and adults on a lateralized version of the task used in Experiment 2. We did not include younger children because pilot work indicated that they could not consistently maintain fixation.

Method

Participants

The participants were the same individuals who participated in Experiment 2; all of the participants completed the central version of the task prior to the lateralized version.

Stimuli and apparatus

The nine hierarchical shapes that were presented centrally in Experiment 2 were used in the current experiment. The inner edge of each stimulus was 2° to the left or right of the central fixation cross. A low-light camera (SONY CCD-TR3400) mounted on top of the computer monitor recorded the subjects' eyes and displayed them on a monitor (JVC TM-131SCTSU) visible to the tester. Each of three testers was trained to detect eye movements of 1° or more; trials in which the tester detected an eye movement during the presentation of the stimuli were eliminated from further analysis. The mean proportion of trials that were excluded due to eye movements was .01 (range = 0–.04) for adults, .05 (0–.13) for 10-year-olds, and .054 (.01–.13) for 14-year-olds.

Procedure

Upon completing the central task (Experiment 2) participants performed the lateralized task. There were 36 trials in each of eight blocks—four blocks of global (G) trials and four blocks of local (L) trials. The central fixation cross remained on the screen throughout the trial and subjects were instructed to maintain fixation on it. Within each block, stimuli were presented in the LVF on half of the trials, half of the trials were incongruent, and for half of the trials the correct response was "different". The two successive members of a pair were both presented in the same visual field, but trials involving the LVF and RVF were intermixed randomly. Instructions and eight practice trials were given prior to each block. For each participant, the order in which blocks were presented was the same as it was in Experiment 2.

Results

The data on incongruent trials were analyzed with age (10, 14, adult) as a between-subject factor and level of processing (local, global) and visual field (left, right) as within-subject factors.The data for accuracy are illustrated in Fig. 4. As shown in Fig. 4, there were no differences between 14-year-olds and adults. Ten-year-olds were

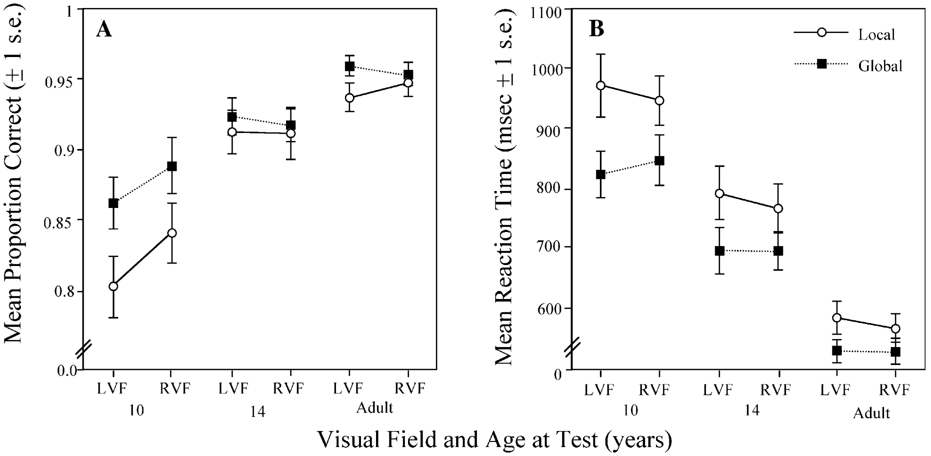

Fig. 4. Mean proportion correct (±1 *SE*; A) and mean reaction times (±1 *SE*; B) of the raw scores for 10-year-olds, 14-year-olds, and adults on the lateralized version of the task in Experiment 2. Other details as in Fig. 2.

less accurate in every condition and, unlike other ages, were more accurate on global trials than on local trials (and when stimuli were presented in the RVF (LH) than when stimuli were presented in the RVF (LH)).The ANOVA on proportion correct revealed main effects of age, $F(2,69) = 17.69$, $p < .0001$, and level of processing, $F(1,69) = 15.17$, $p < .001$, but no main effect of visual field ($p > .1$). There was a significant interaction between age and both level of processing, $F(2,69) = 4.62$, $p < .05$, and visual field, $F(2,69) = 3.52$, $p < .05$, but no significant interaction between level of processing and visual field, $p > .1$. Analyses of simple effects revealed an effect of level of processing for 10-year-olds, $F(1,69) = 22.26$, $p < .001$, who were more accurate on global trials ($M = .880$) than on local trials ($M = .828$), but not for adults or 14-year-olds (*p*s > .10). The effect of age was significant on both local, $F(2,69) = 17.11$, $p < .001$, and global trials, $F(2, 69) = 12.34$, $p < .001$. Ten-year-olds were less accurate than adults on both local and global trials (Dunnett's, *p*s < .05), whereas 14-year-olds were adultlike (*p*s > .05). Analyses of simple effects revealed a significant effect of age when stimuli were presented in the LVF/RH, $F(2,69) = 21.8$, $p < .001$, and when stimuli were presented in the RVF/LH, $F(2,69) = 10.05$, $p < .001$. Ten-year-olds were less accurate than adults when stimuli were presented in either the LVF or the RVF (Dunnetts, *p*s < .05), whereas 14-year-olds were adultlike (Dunnetts, *p*s > .05). The source of the interaction between age and visual field was differential performance across visual fields by 10-year-olds, $F(1,69) = 9.8$, $p < .01$, but not by either adults or 14-year-olds (*p*s > .10). Ten-year-olds were more accurate when stimuli were presented in the RVF/LH ($M = .870$) than when stimuli were presented in the LVF/RH ($M = .839$).

The ANOVA on standardized reaction times revealed a main effect of level of processing, $F(1,69) = 95.46$, $p < .0001$, and a significant level of processing × visual field interaction, $F(1,69) = 5.12$, $p < .05$. Reaction times were faster on global trials than on local trials when stimuli were presented in either visual field (LVF: $F(1,69) = 75.62$, $p < .001$; RVF: $F(1,69) = 47.17$, $p < .001$). As shown in Fig. 4, across all ages, on global trials reaction times did not differ across visual field ($p > .10$), but on local trials reaction times were faster when stimuli were presented in the RVF/LH than when stimuli were presented in the LVF/RH, $F(1,69) = 6.195$, $p < .05$. Age did not interact with level of processing or visual field.

Discussion

Although performance on the central version of the task did not become adultlike until after 10 years of age, the results from the lateralized task in Experiment 3 suggest that 10-year-olds' greater bias toward the global shape cannot be attributed to weaker hemispheric specialization. Ten-year-olds, but not older subjects, were more accurate in both types of processing when the stimuli were presented in the RVF/LH. This is not likely to be a robust finding: it appears sporadically in the literature (e.g., Martin, 1979b) but is not reported consistently (see Hiscock, 1988 for a review). Of more interest is the fact that all groups responded faster on global trials than on local trials whether stimuli were in the LVF/RH or the RVF/LH (i.e., both hemispheres showed a global advantage), and that response times on global trials were independent of visual field. In contrast, on local trials, all groups responded faster when stimuli were presented in the RVF/LH than when stimuli were presented in the LVF/RH (see also Martinez et al., 1997). The finding that global processing is not strongly lateralized but that local processing is more efficient in the left hemisphere is consistent with other studies (Evans et al., 2000; Martin, 1979b; Martinez et al., 1997). Our results suggest that the occipitotemporal regions of the two hemispheres show adultlike differential sensitivity to local versus global processing by 10 years of age–at least under the conditions of our task in which attention was directed to the local versus the global level of stimuli.

Despite evidence that the division of labor between the hemispheres for local and global processing does not change after 10 years of age, both Experiments 2 and 3 indicate that the efficiency of local processing is adultlike in 14-year-olds, but not 10-year-olds. In both experiments, 10-year-olds made more errors on local trials than they did on global trials, and on the central version of the task (Experiment 2) they made more errors than adults on local trials but not on global trials. Our results suggest that it is important to distinguish between *specialization* of the two hemispheres (i.e., variability in their sensitivity to different types of information) and either the expertise with which each hemisphere processes the information for which it is specialized or the ability to control the allocation of attention to the outputs of these channels. The poor performance of 10-year-olds on local trials in both the central and lateralized versions of our task may reflect both the difficulty in ignoring distractors that was discussed in Experiment 1, and poor ability of the two hemispheres to process information without mutual interference (i.e., immature attentional mechanisms). When presented simultaneously with two conflicting tasks, adults and 14-year-olds perform better when each task is presented to a different hemisphere (Merola & Liederman, 1985), presumably because the two hemispheres are able to allocate attention to two different tasks and process those tasks in parallel (e.g., Evans et al., 2000). In contrast, 10-year-olds' performance is not affected by this manipulation, presumably because the two hemispheres do not process information in parallel (Merola & Liederman, 1985). If processing in the two hemispheres is less independent in 10-year-olds than it is in 14-year-olds and adults, age differences in accuracy should be apparent on local trials, for which the left hemisphere is superior at all ages, but not on global trials, for which there is not strong evidence of lateralization at any age. To the extent that the RH of 10-year-olds becomes involved on local trials—even when stimuli are presented in the RVF/LH—efficiency should decrease, as was evident in Experiments 1, 2, and 3. Thus, our data are consistent with the hypothesis that processing of hierarchical stimuli is not adultlike until after 10 years of age because that processing is less localized.

General discussion

Despite evidence that both global precedence (Colombo et al., 1995; Frick et al., 2000; Ghim & Eimas, 1988) and hemispheric specialization (Deruelle & de Schonen, 1995, 1998) are present during infancy, our results indicate that the processing of hierarchical shapes continues to develop into adolescence. The results indicate protracted development of processing hierarchical stimuli with slower development of local than of global processing: 6-year-olds in Experiment 1 performed at chance when instructed to attend to the local level, and above chance but worse than adults when instructed to attend to the global level. Ten-year-olds in both Experiments 1 and 2 were less accurate than adults on local trials, but as accurate as adults on global trials. Only the 14-year-olds in Experiment 2 had adultlike accuracy on both local and global trials. Children's greater bias toward the global level of organization does not seem to be attributable to differences in the speed with which the hemispheres process local versus global levels of hierarchical stimuli. All age groups had faster response times on local trials when stimuli were presented in the RVF/LH than when stimuli were presented in the LVF/RH, and had no difference between visual fields on global trials. This is consistent with the literature on adults' reaction times (e.g., Blanca et al., 1994; Martin, 1979b; Martinez et al., 1997).

It is somewhat surprising that hemispheric specialization is present in infancy, but that the ability to attend to the local level is not adultlike until a later age. Several factors likely contribute toward the slow development of processing the local elements of hierarchical shapes. First, prior to 2 years of age the corpus callosum does not allow functional integration of visual integration, hence the two hemispheres are operating independently (Liegeois, Bentejac, & de Schonen, 2000). Only from the age of two years is there a need to coordinate processing between the two hemispheres, and their ability to do so efficiently may not emerge until adolescence (e.g., Merola & Liederman, 1985). Second, high spatial frequency channels do not become adultlike until at least 7 years of age. It is at this age that visual acuity and contrast thresholds for high spatial frequency stripes are first adultlike (Ellemberg et al., 1999). Even at age 7 we do not know whether these channels process high spatial frequencies as rapidly as they do in adults. To the extent that global precedence is the result of global information being more salient because it accumulates faster than local information (Hübner, 1997; Shedden & Reid, 2001), it should be enhanced by immature (i.e., slow) high spatial frequency channels. Finally, numerous studies have shown that the ability to ignore distractors is slow to develop (Goldberg et al., 2001; Ridderinkhof & van Molen, 1995). Thus, in children, the difference in the rate at which higher versus lower spatial frequencies are processed is likely to be greater than in adults, and children also will find the global form harder to ignore.

In summary, we have shown that adultlike sensitivity to the local levels of visual forms develops between 10 and 14 years of age, but that the hemispheres are differentially sensitive to the local versus global levels of visual patterns by 10 years of age—at least under our testing conditions. The adult pattern of hemispheric specialization was evident in our task in which we directed attention to either the local or global level. It is possible that hemispheric specialization would be less evident in children under a divided attention task in which subjects are asked to detect a target (e.g., a circle) that may appear without warning at either the local or the global level. With divided attention, interference between global and local levels might increase and, in 10-year-olds, hemispheric specialization might not look adultlike. This difference is evident in the success with which children successfully complete setting the table when asked to "Make sure that everyone has a fork" (directed attention) versus "Make sure that everything we need is on the table."

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