Research Article

Microgenesis and Ontogenesis of Perceptual Organization

Evidence From Global and Local Processing of Hierarchical Patterns

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ABSTRACT—*In two experiments, visual search and speeded classification were used to study perception of hierarchical patterns among participants aged 5 to 23 years. Perception of global configurations of few-element patterns and local elements of many-element patterns showed large age-related improvements. Only minor age-related changes were observed in perception of global configurations of many-element patterns and local elements of few-element patterns. These results are consistent with prior microgenetic analyses using hierarchical patterns. On the one hand, the rapid and effortless grouping of many small elements and the individuation of few large elements both mature by age 5. In contrast, the time-consuming and effortful grouping of few large elements and the individuation of many small elements improve substantially with age, primarily between ages 5 and 10. These findings support the view that perceptual organization involves multiple processes that vary in time course, attentional demands, and developmental trajectories.*

The consciously perceived visual world is strikingly different from the unstructured mosaic of intensities and colors that stimulates the retina. Internal processes of perceptual organization have therefore been postulated to structure these bits and pieces of visual information into the larger coherent units that people experience as environmental objects (Wertheimer, 1923/1955).

Many modern computational theories of vision assume that perceptual processes of organization—such as grouping and segmentation (Koffka, 1935; Kohler, 1929/1947)—operate early and preattentively to deliver candidate units for further processing (e.g., Marr, 1982; Treisman, 1982). Recent findings suggest, however, that some forms of grouping and segmentation take place early, rapidly, and effortlessly, whereas others occur later, consume time, and require controlled attentional processing (e.g., Behrmann & Kimchi, 2003; Ben Av & Sagi, 1995; Han, Humphreys, & Chen, 1999; Kimchi, 1998, 2000; Kimchi & Razpurker-Apfeld, 2004; Kurylo, 1997; Palmer, Brooks, & Nelson, 2003; Rensink & Enns, 1995).

The present studies were designed to examine whether organizational processes that differ in these ways for adult observers also differ in perceptual development. Our guiding hypothesis was that those processes that are time-consuming and effortful for adults will have a longer developmental progression than those processes that are accomplished rapidly and effortlessly. Such differential age-related changes would provide converging evidence for the view that perceptual organization involves multiple processes that vary in time course and attentional demands. We addressed this issue in the context of grouping and individuation in hierarchical patterns.

In adults, microgenetic studies of perceptual organization in hierarchical patterns showed marked differences in primed matching and visual search tasks as a function of the nature of the patterns (Kimchi, 1998). In particular, the global configuration of patterns containing many, relatively small elements was primed at brief exposures and was accessible to rapid search, whereas the local elements of such patterns were primed only at longer exposures and searched inefficiently. The global advantage typically observed with briefly presented many-element patterns (e.g., Navon, 1977) is consistent with these findings. The converse pattern of results was obtained with configurations composed of few, relatively large elements, however: The elements were primed at brief exposures and

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searched efficiently, whereas the global configuration was primed at longer exposures and searched less efficiently.[1]

These findings suggest that grouping many relatively small elements into a global configuration differs from grouping a few relatively large elements: The former process is rapid and effortless, whereas the latter consumes time and requires attention. The individuation of elements also differs for few versus many elements: Few large elements are individuated rapidly and effortlessly, whereas the individuation of many small elements occurs later and demands attention. Kimchi (1998) has further suggested that early and rapid grouping of many small elements and individuation of a few large elements are desirable for a system whose goal is object identification and recognition, because many small elements in close proximity to one another are likely to be texture elements of a single object, whereas a few large elements are likely to be several discrete objects or several distinctive parts of a complex object.

The literature on the development of perceptual organization is somewhat confusing. Infants appear to be sensitive to both global and local structures of a visual pattern, but to have greater sensitivity to global structure (e.g., Frick, Colombo, & Allen, 2000; Ghim & Eimas, 1988; Quinn, Burke, & Rush, 1993; Quinn & Eimas, 1986). Studies with older children indicate that grouping and individuation continue to develop into adolescence, but there is no clear agreement on the relative developmental rates of these processes. For example, increasing the sparsity of the elements in hierarchical patterns shifted younger children's biases toward the local level more readily than adults', both in simple similarity judgments (Dukette & Stiles, 1996) and in reproduction from memory (Dukette & Stiles, 2001). In contrast, increasing the density of the elements did not influence children's reproduction of the local elements (Dukette & Stiles, 2001), suggesting that individuation abilities are elaborated earlier in development than grouping abilities. Enns, Burack, Iarocci, and Randolph (2000) and Burack, Enns, Iarocci, and Randolph (2000) examined visual search for hierarchical displays and found large improvements with age in search rates for targets that differed from distractors in global orientation; no age difference was observed in search rates for targets that differed in local orientation, independent of task difficulty. These results also suggest a longer developmental progression for grouping than for individuation abilities. However, Mondloch, Geldart, Maurer, and de Schonen (2003) used a same/different task under limited exposure and found that children made significantly more errors than adults on local but not global trials and, unlike adults, were less accurate on local trials than on global trials. These results suggest longer developmental progression for local than for global processing.

These apparent contradictions may be partly due to the use of different tasks, measures, and displays, but they may also have resulted from asking the wrong questions. Rather than asking whether grouping differs from individuation, researchers might more profitably have asked whether different groupings and, likewise, different individuations vary in their developmental courses. In particular, the microgenetic results suggest that grouping in many-element patterns may differ developmentally from grouping in few-element patterns, and that individuation in many-element patterns may differ developmentally from individuation in few-element patterns.

In the present study, we examined these questions by comparing the performance of 5- to 14-year-old children and young adults in two tasks—visual search (Experiment 1) and speeded classification (Experiment 2)—involving both few- and many-element hierarchical displays.

EXPERIMENT 1: VISUAL SEARCH

In this experiment, participants searched as quickly and accurately as possible for a diamond among a variable number of square distractors. The target was present either at the local level (local target) or at the global level (global target) of either a few- or a many-element pattern. The primary dependent variable was search rate, defined as the slope of the best-fitting linear reaction time (RT) function over the number of items in the display. Target search is considered efficient and effortless if the time to detect the target is independent or nearly independent of the number of items in the display. If the time to detect a target increases as the number of items in the display increases, then search is considered inefficient and attention demanding (e.g., Duncan & Humphreys, 1989; Enns & Kingstone, 1995; Treisman & Gormican, 1988; Trick & Enns, 1998).

Given the evidence from microgenetic studies of grouping and individuation processes (Kimchi, 1998), we expected larger improvements with age in search rate for global targets in few-element than in many-element displays, and larger age-related improvements in search rate for local targets in many-element than in few-element displays.

Method

Participants

Eighty participants were tested, 20 in each age group: 5-year-olds (mean = 5.4 years, range = 5–6.1), 10-year-olds (mean = 10.2 years, range = 9.8–10.7), 14-year-olds (mean = 14.3 years, range = 13.2–14.7), and 23-year-olds (mean = 23 years, range = 20–28). All participants had normal or corrected-to-normal vision.

Apparatus and Displays

Display presentation and data collection were controlled by a Dell GX-260 (adults) or an IBM T21 portable computer (children). Participants responded by pressing on the keys of a

[1]Note that the critical stimulus factors are relative (rather than absolute) size and number of elements (see Kimchi, 1992, 1998, for a detailed discussion).

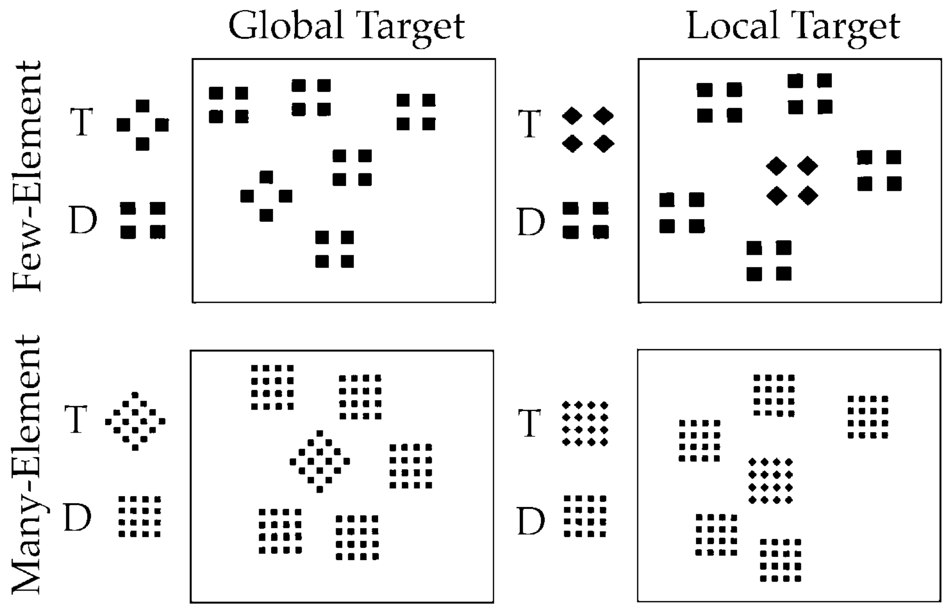

Fig. 1. Examples of displays in the visual search task of Experiment 1. An example is shown for each combination of pattern (many elements or few elements) and target (global or local). The target (T) and distractors (D) for each example are indicated. All the examples presented here illustrate the display size of 6.

computer keyboard (adults) or by moving a joystick upward or downward (children).

The few-element patterns were composed of 4 relatively large elements, and the many-element patterns of 16 relatively small elements. Target and distractor items are presented in Figure 1. At a viewing distance of 70 cm, a global configuration subtended $1.64° \times 1.64°$; a local element subtended $0.57° \times 0.57°$ in the few-element patterns and $0.25° \times 0.25°$ in the many-element patterns. Display sizes of 2, 6, or 10 items were used. The items were presented in jittered random locations in a 5×4 matrix subtending $15.95° \times 12.88°$.

Design and Procedure

The experiment employed an orthogonal combination of five variables: a between-subjects factor of age (5, 10, 14, or 23 years) and within-subjects factors of pattern (few elements or many elements), target (global or local), trial type (target present or absent), and display size (2, 6, or 10). The four combinations of pattern and target were administered in separate blocks of 72 trials each, preceded by 24 practice trials. Display size and trial type were randomized within block, with each combination occurring on an equal number of trials. The blocks' order was counterbalanced across participants. Considerable practice and feedback were given to ensure that the children understood the task and were not distracted from it; in addition, each block was divided into six subblocks of 12 trials each and administered on a separate day. To increase children's motivation, in each session we used vivid pictures to present a story about a character on a mission (e.g., a monkey trying to reach bananas) and told the children that their own progress in the task would help the character reach its goal.

Each trial started with a central fixation cross that appeared for 500 ms, followed immediately by the target display, which remained present until the participant responded or 3 s (adults) 7 s (children) had elapsed.

Results and Discussion

Participants in all age groups were highly accurate; mean error rate (ER) was 2.7%, 1.7%, 2.3%, and 3.7% for the 5-, 10-, 14-, and 23-year-olds, respectively. Accuracy data were analyzed by a mixed-design analysis of variance (Target × Pattern × Display Size × Trial Type × Age). All main effects were significant, as were the interactions not involving age. ER was higher for target-present trials (average = 3.5%) than for target-absent trials (average = 1.8%), $F(1, 76) = 55.72$, $p < .0001$, $\eta_p^2 = .42$, suggesting that most errors were misses rather than false alarms. The only significant interaction involving age was with trial type, $F(3, 76) = 3.33$, $p < .025$, $\eta_p^2 = .12$, indicating that adults were slightly more liberal in their accuracy criterion than younger children, mainly in the target-present trials. Otherwise, the analysis did not indicate speed-accuracy trade-offs.

All summaries and analyses of RT were based on participants' median RTs for correct responses. Two RT measures were examined: baseline RT (RT for a display size of 2), conventionally considered to measure response speed independent of search rate, and the slope of the best-fitting linear function relating RT to display size, conventionally considered to measure the involvement of attention.

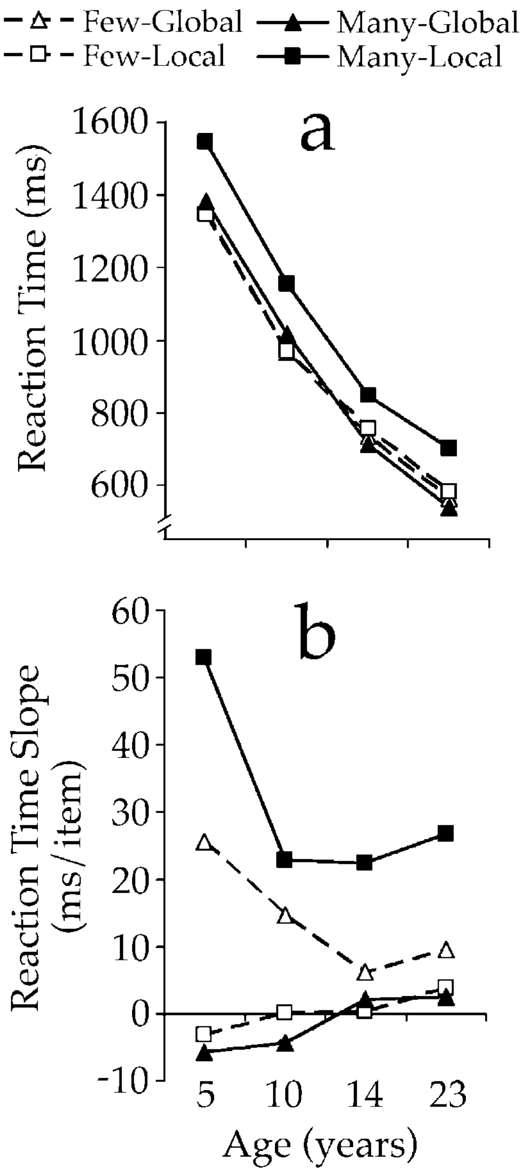

Fig. 2. Results of the visual search task for target-present trials in Experiment 1: mean baseline reaction times (a) and search slopes (b) for global and local targets as a function of pattern (many elements or few elements) and age.

Mean baseline RTs and RT slopes for global and local targets on target-present trials are presented in Figure 2 as a function of pattern and age (target-absent data are presented separately in Table 1).[2] A mixed-design analysis of variance (Target × Pattern × Age) conducted on the baseline RTs (Fig. 2a) showed, as expected, that RT improved with age, $F(3, 76) = 108.32$, $p < .0001$, $\eta_p^2 = .81$. Target interacted with pattern, $F(1, 76) = 38.12$, $p < .0001$, $\eta_p^2 = .33$, but the Target × Pattern × Age interaction was not significant, $F < 1$, indicating no developmental differences in target-distractor discriminability. RTs to global and local targets were equally fast in the few-element condition, $F < 1$, and a global advantage was observed in the many-element condition, $F(1, 76) = 65.03$, $p < .0001$, $\eta_p^2 = .46$; these effects did not vary with age, Fs < 1.

The central analysis concerned the RT slopes as an index of attentional involvement. This analysis revealed reliable developmental differences in search rate that depended on both the target and the pattern (Fig. 2b), $F(3, 76) = 10.61$, $p < .0001$, $\eta_p^2 = .30$. The RT slopes for global targets in the many-element displays and for local targets in the few-element displays were essentially zero, indicating an efficient, effortless search that did not vary with age, $F(3, 76) = 2.23$, $p > .10$, and $F < 1$, respectively. The RT slopes for finding local targets in the many-element displays were considerably steeper, indicating an inefficient, effortful search that improved with age, $F(3, 76) = 6.11$, $p < .0009$, $\eta_p^2 = .19$. A post hoc Duncan analysis revealed a significant decrease in the RT slope between 5 and 10 years of age ($p < .05$), with virtually no changes from age 10 to 23. The slopes for finding global targets in the few-element displays were also steep and improved significantly with age, $F(3, 76) = 6.20$, $p < .0008$, $\eta_p^2 = .20$, with a significant improvement from 5 to 10 years of age ($p < .05$).

In summary, age trends in search rates for global and local targets on trials in which the target was correctly detected were different in the many- versus the few-element patterns. When the target differed from the distractors in global configuration, search rates improved significantly with age in the few-element condition, but not in the many-element condition, indicating the predicted longer developmental progression for grouping a few large elements than for grouping many small elements. When the target differed in local elements, search rates improved significantly with age in the many-element condition, but not in the few-element condition, indicating the predicted longer developmental progression for individuating many small elements than for individuating few large elements.

EXPERIMENT 2: SPEEDED CLASSIFICATION

Experiment 2 was designed to provide an independent test of the same developmental hypothesis using a speeded classification task similar to that used by Palmer and Nelson (2000). Participants were presented with an array of five columns of few- or many-element patterns. In incongruent displays, the patterns in the central column contained elements similar to the elements of the patterns on one side but had a configuration similar to that of the patterns on the other side. The task was to indicate whether the central column belonged with the patterns

[2]Our RT analyses focused on target-present data because only target-present trials required a discrimination of target from distractors, and because target-absent slopes provide less reliable measures of search efficiency because of variable criteria used for deciding target absence (Chun & Wolfe, 1996). Target-absent data showed a similar pattern of results; the Target × Pattern × Age × Trial Type interaction was not significant, $F < 1$ and $F(3, 76) = 1.10$, $p > .36$, for baseline RT and RT slopes, respectively. The steeper slopes for target-absent than for target-present trials in all conditions (even those in which target-present slopes were essentially zero) suggest that participants in all age groups adopted a more conservative criterion for deciding target absence than target presence.

TABLE 1
Mean Baseline Reaction Times (RTs) and RT Slopes on Target-Absent Trials in Experiment 1

	Age (years)							
	5		10		14		23	
Pattern and target	Baseline RT (ms)	RT slope (ms/item)	Baseline RT (ms)	RT slope (ms/item)	Baseline RT (ms)	RT slope (ms/item)	Baseline RT (ms)	RT slope (ms/item)
Few elements								
Global target	1,492	63	1,130	26	838	14	602	23
Local target	1,441	39	1,082	11	803	14	618	15
Many elements								
Global target	1,542	50	1,066	16	774	6	572	7
Local target	1,814	115	1,299	51	980	54	775	63

on the left or right side on the basis of similarity in global configuration (global classification), on some trials, or local elements (local classification), on the other trials. RT and accuracy were measured to determine which classification was easier, indicating which pattern aspect—global configuration or local elements—was more accessible. We also used congruent displays in which the central patterns were similar in both elements and configuration to the patterns on one side and dissimilar in both aspects to the patterns on the other side. The difference between classification performance for congruent versus incongruent displays was taken as a measure of the interference from the task-irrelevant aspect.

On the basis of the results of Experiment 1, we expected larger age-related improvements in global classification for the few- than for the many-element displays, and in local classification for the many- than for the few-element displays. Such a pattern of results would provide converging evidence of a longer developmental progression for grouping a few large elements into a global configuration than for grouping many small elements, and for individuating many small elements than for individuating a few large elements.

Method

Participants

Seventy-two new participants were tested: twenty 5-year-olds (mean = 5.4 years, range = 4.11–5.10), twenty 10-year-olds (mean = 10.4 years, range = 9.8–10.7), twelve 14-year-olds (mean = 14.2 years, range = 13–14.4), and twenty 22-year-olds (mean = 22 years, range = 20–26).

Apparatus and Displays

The apparatus was the same as in Experiment 1. Few- and many-element hierarchical patterns (of the same sizes as in Experiment 1) were arranged in an array of five columns of four patterns each, subtending 19.65° × 15.95°. Examples of incongruent and congruent displays are presented in Figure 3.

Design and Procedure

The experiment employed an orthogonal combination of six variables in a mixed design: age (5, 10, 14, or 22 years), pattern (few elements or many elements), classification task (global or local), congruency (congruent or incongruent), central pattern (diamond made of circles, diamond made of squares, square made of circles, or square made of squares), and side (right or left). The four combinations of pattern and task were administered in separate blocks of 80 trials each (divided into eight subblocks of 10 trials each for children), preceded by 8 (adults) or 24 (children) practice trials. Congruency, central pattern, and side were randomized within block, with each combination occurring on an equal number of trials. Participants indicated whether the central column belonged to the right or left side by pressing a right or a left key on a keyboard (adults) or by moving a joystick to the right or left (children). All other aspects of the procedure were the same as in Experiment 1.

Results and Discussion

Mean correct RTs and ERs for incongruent displays are presented in Figures 4a and 4b, for each task as a function of age. Preliminary analysis showed no effects of central pattern or side, nor any significant interactions involving these factors. The collapsed data were submitted to a mixed-design analysis of variance (Task × Pattern × Age). The analysis showed an improvement with age in both speed, $F(3, 68) = 160.06$, $p < .0001$, $\eta_p^2 = .88$, and accuracy, $F(3, 68) = 3.61$, $p < .02$, $\eta_p^2 = .14$. For all age groups, local classification was faster and more accurate than global classification in the few-element condition, whereas global classification was faster and more accurate than local classification in the many-element condition, $F(1, 68) = 92.45$, $p < .0001$, $\eta_p^2 = .58$, for RT and $F(1, 68) = 40.66$, $p < .0001$, $\eta_p^2 = .37$, for ER.

There was, however, a significant Age × Task × Pattern interaction, $F(3, 68) = 5.19$, $p < .003$, $\eta_p^2 = .19$, with larger age-related improvements in global classification time in the few- than in the many-element condition, and in local classification time in the many- than in the few-element condition (Fig. 4a). These differential age-related improvements were significant

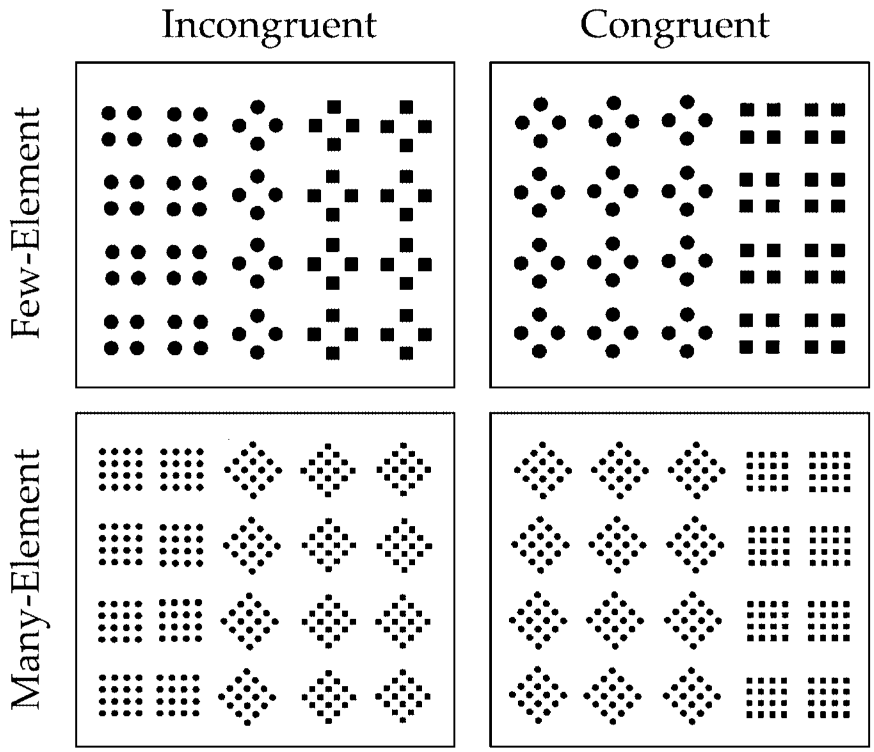

Fig. 3. Examples of incongruent and congruent displays in the few-element and many-element conditions for the speeded classification task in Experiment 2.

for the transition from age 5 to 10, $F(1, 38) = 5.39$, $p < .03$, $\eta_p^2 = .12$, but not for later transitions, $F < 1$.

There were also reliable differential age-related improvements in accuracy (Fig. 4b), $F(3, 68) = 2.79$, $p < .05$, $\eta_p^2 = .11$. Pronounced reductions in ER with age were observed for global classification in the few-element condition, $F(3, 68) = 3.10$, $p < .035$, $\eta_p^2 = .12$, with a significant decrease between age 5 and 10 ($p < .05$), and for local classification in the many-element condition, $F(3, 68) = 2.35$, $p < .08$, $\eta_p^2 = .09$, with a significant decrease between age 5 and 14 ($p < .05$). No age-related changes in accuracy were observed for the local classification of few-element patterns or for the global classification of many-element patterns, Fs < 1.

For each subject in each task, interference scores were calculated by subtracting mean RT (or ER) on congruent trials from mean RT (or ER) on incongruent trials. The mean interference scores as a function of age are depicted in Figures 4c and 4d. A mixed-design analysis of variance (Task × Pattern × Age) showed a significant decrease in interference RT with age, $F(3, 68) = 28.81$, $p < .0001$, $\eta_p^2 = .56$. For all age groups, global-to-local interference was larger than local-to-global interference in the many-element condition, whereas the opposite results were found in the few-element condition, $F(1, 68) = 76.96$, $p < .0001$, $\eta_p^2 = .53$, for RT and $F(1, 68) = 27.89$, $p < .0001$, $\eta_p^2 = .29$, for ER. There were, however, larger decreases with age in global-to-local interference RT in the many- than in the few-element condition, and in local-to-global interference RT in the few- than in the many-element condition, $F(3, 68) = 4.43$, $p < .007$, $\eta_p^2 = .16$ (Fig. 4c). These differential age-related improvements were significant for the transition from age 5 to 10, $F(1, 38) = 4.47$, $p < .05$, $\eta_p^2 = .11$, but not for later transitions, $F(2, 49) = 1.81$, $p > .17$. The similar differential age-related improvements in interference ER (Fig. 4d) did not reach statistical significance.

These results show that the developmental trends of global and local classification depend on the specific nature of the hierarchical patterns being viewed. Differential age-related changes were clearly evident in the classification accuracy data (Fig. 4b) and converged nicely with the results of Experiment 1. When classification was based on global configurations, 5-year-olds made significantly more errors than older participants in the few-element condition, whereas all age groups yielded similar error rates in the many-element condition. However, when classification was based on local elements, 5-year-olds made significantly more errors than older participants in the many-element condition, whereas all age groups yielded similar error rates in the few-element condition. Similar age trends were evident in the RT data (Figs. 4a and 4c). The age-related increase in speed of global classification and decrease in local-to-global interference were significantly larger in the few- than in the many-element condition. In contrast, the increase with age in speed of local classification and the decrease with age in global-to-local interference were significantly larger in the many- than in the few-element condition.

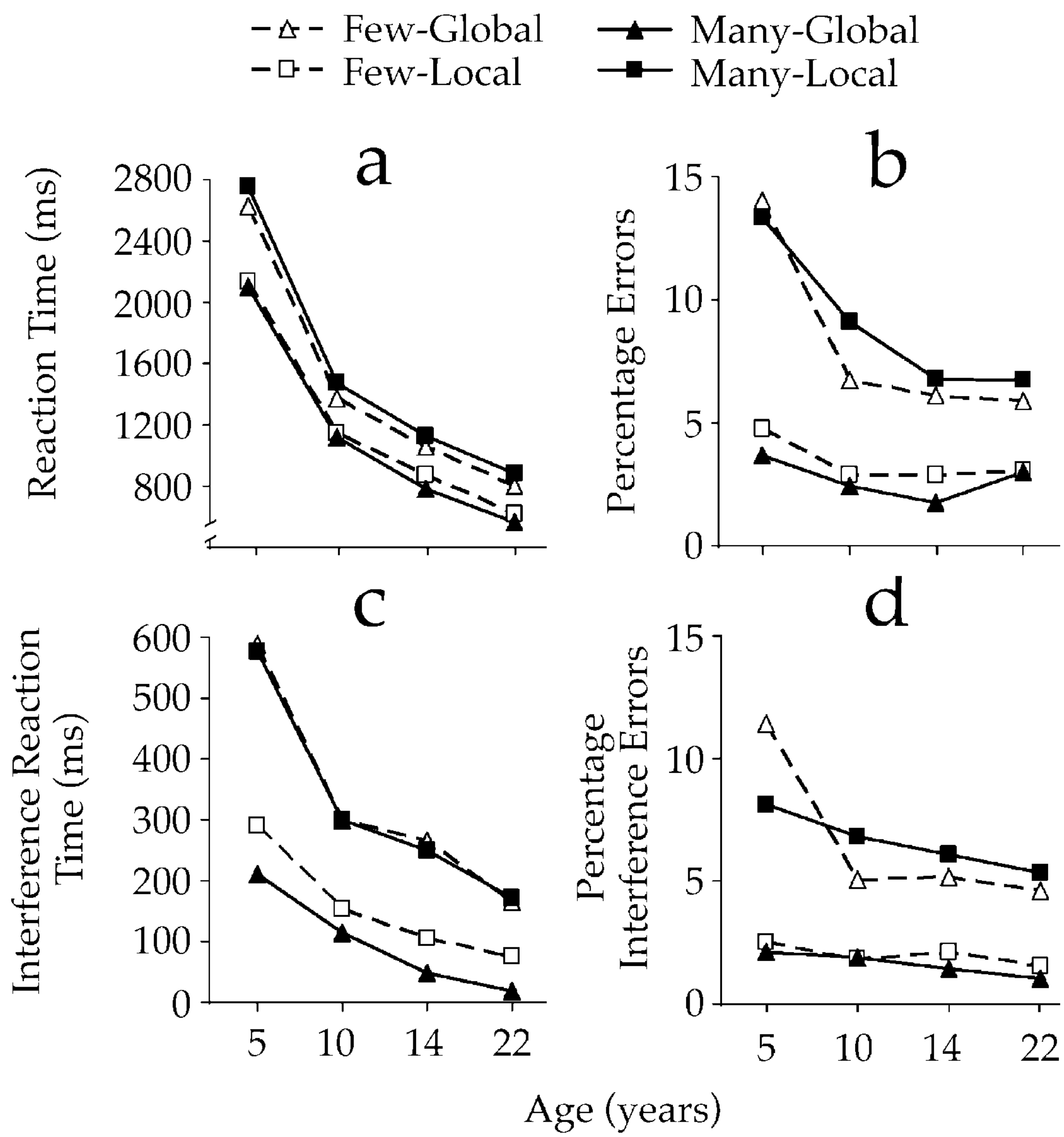

Fig. 4. Results of the speeded classification task in Experiment 2. The top panels present mean reaction times (a) and error rates (b) for global and local classifications in incongruent displays as a function of pattern (many elements or few elements) and age. The bottom panels present mean interference scores for reaction time (c) and error rate (d) for global and local classifications as a function of pattern and age (see the text for details).

GENERAL DISCUSSION

The results of these experiments are consistent with previous findings (Kimchi, 1990) in showing that children's sensitivity to the number and relative size of the elements of hierarchical patterns is similar to that of adults: In both visual search and speeded classification, participants in all age groups showed a local bias for few-element patterns and a global bias for many-element patterns.

The main finding of the present study, however, is that age trends differed for the perception of global configuration and local elements depending on the specific nature of the displays. Search rates for global targets and accuracy of global classification improved with age for the few-element patterns, but not for the many-element patterns. Search rates for local targets and accuracy of local classification improved with age for the many-element patterns, but not for the few-element patterns. In addition, the largest age-related increases in classification speed and decreases in task-irrelevant interference were found for global classification in the few-element condition and for local classification in the many-element condition. These differential age-related improvements were observed mainly for the transition from ages 5 to 10.

The present findings provide converging evidence for the conclusion that has emerged from the microgenetic results concerning the organization of hierarchical patterns in adult observers (Kimchi, 1998). The processes that are accomplished rapidly and effortlessly in the course of processing—namely, grouping of many small elements and individuation of a few large elements—mature at a relatively early age. In striking contrast, the effortful and time-consuming processes—grouping of a few large elements and individuation of many small elements—develop with age, improving significantly between ages 5 and 10 and reaching adultlike levels between 10 and 14 years of age.

The present findings also help resolve the apparent contradiction in the developmental literature. On the one hand, Enns et al. (2000) and Burack et al. (2000) used few-element patterns and found age-related improvements in search rates for globally defined but not for locally defined targets. These results were compatible with Enns and Kingstone's (1995) findings with adults. On the other hand, Mondloch et al. (2003) used many-element patterns and found age-related improvements for local but not for global processing. Thus, these seemingly conflicting results are actually consistent with our results and provide further evidence for different developmental trajectories for global and local processing in many-element versus few-element patterns.

How might processing change developmentally to produce this pattern of results? We can only speculate. Given the visual system's bias for early and rapid grouping of many small elements, individuating elements in many-element patterns requires attentional change, for example, narrowing the spatial focus (Nakayama, 1990) or refocusing on a different level of detail (Austen & Enns, 2000). This is more difficult for younger children than for adults, presumably because the ability to deploy attention flexibly improves with age (e.g., Enns & Girgus, 1985; Plude, Enns, & Brodeur, 1994). Organizing early and rapidly individuated few large elements into a global configuration requires integrating the elements and perceiving the spatial relations among them. Hence, the developmental progression for grouping in few-element patterns may be a result of improvements with age in spatial abilities (e.g., Stiles, 2001).

In sum, the present study shows that organizational processes vary in their relative rate of development, with some processes attaining ultimate levels of functioning earlier than others (see also, e.g., Enns et al., 2000; Kovács, 2000; Mondloch et al., 2003). Furthermore, the processes that exhibited different developmental trajectories are the ones identified by microgenetic analysis as differing in time course and attentional demands. Thus, the present results support the view that perceptual organization involves multiple processes, some early and effortless, and others late, time-consuming, and requiring controlled attentional processing.

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