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The nature of individual face recognition in preschool children: Insights from a gaze-contingent paradigm

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ABSTRACT

The development of individual face recognition has been intensively studied and supports early expertise in childhood. However, how the differential use of holistic and analytical face processing modes contribute to the well-documented prolonged development of individual face recognition until adulthood remains poorly understood. We applied a gaze-contingency approach to study individual face recognition in 5-year-old children and young adults, allowing selective manipulation of processing modes and providing insights into facial information use through fixation patterns. Although both age groups relied on similar processing modes, children were less efficient in compensating for processing manipulations, in particular when analytical processing was emphasized. They were also less flexible in using facial information. Our findings suggest that efficiency in adaptively exploiting visual information contributes to still developing individual face recognition abilities in children.

1. Introduction

From birth on, faces give us fundamental information about other persons we interact with, in particular about their identity and their emotional state. Research on face perception has provided insights into highly specialized processing mechanisms, at the behavioral level as well as at the neural level (Calder, 2011). The development of these remarkable processing capacities has been intensively studied, and there is evidence of early expertise in face perception (for review see Höhl & Peykarjou, 2012). However, mature individual face recognition performance is not reached before early adulthood (Carey & Diamond, 1994; Germine, Duchaine, & Nakayama, 2011; McKone, Crookes, Jeffery, & Dilks, 2012). The reasons behind this prolonged development are not fully understood. Although increasing general cognitive capacities during development certainly play a critical role, the efficient use and interplay of holistic and analytical processing of faces might be particularly subject to developmental changes.

The holistic and the analytical processing modes provide a cardinal distinction between different ways by which visual information can be processed. Although this principle distinction can be indeed applied to object recognition in general, a clear differentiation between both processing modes has been primarily provided for face perception, because human faces are visual stimuli made of multiple parts arranged in specific configurations (Sergent, 1989). The holistic processing mode refers to the perception of the face as a single unit, without part decomposition (Rossion, 2013; Sergent, 1984; Tanaka & Farah, 1993; Young, Hellawell, & Hay, 1987). The term “holistic” is used here as a synonym of configural or configurational processing (Rossion, 2008, 2013), although some authors refer to configural as a specific type of information on faces, namely metric distances between features

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(e.g. Leder & Bruce, 2000; Maurer, Le Grand, & Mondloch, 2002). In contrast, the analytical processing mode emphasizes sequential processing of single facial features, independently of the facial context (e.g. Bruyer & Coget, 1987; Macho & Leder, 1998; Schwarzer & Massaro, 2001). A cornerstone in face perception research is the fundamental finding that human adults process faces more holistically than other objects (for review see Farah, Wilson, Drain, & Tanaka, 1998). However, analytical processing also contributes to face perception (e.g. Bruyer & Coget, 1987; Collishaw & Hole, 2000; Schwaninger, Lobmaier, & Collishaw, 2002).

Both face processing modes have been investigated across early infancy and childhood in order to obtain insights into their contributions to the developmental course of face perception. Using paradigms tailored to test infants, holistic face processing has been shown already in the first year of life (Cashon & Cohen, 2004; Schwarzer, Zauner, & Jovanovic, 2007; Turati, Sangrigoli, Ruely, & Schonen, 2004; Turati, Di Giorgio, Bardi, & Simion, 2010). At preschool age, similar tasks as in adults can be used to assess holistic face processing. For instance, individual face recognition performance can be measured in a composite face paradigm in which a top half of a face has to be identified when combined with the bottom half of another face (Hole, 1994; Young et al., 1987; for review see Rossion, 2013). Findings typically show reduced accuracy and prolonged response times when both halves are aligned in comparison to a condition with misaligned halves. This composite face effect emphasizes the role of holistic processing in face perception. Composite face effects have been consistently described in preschool children, indicating holistic face processing in early childhood (Carey & Diamond, 1994; de Heering, Houthuys, & Rossion, 2007; Macchi Cassia, Picozzi, Kuefner, Bricolo, & Turati, 2009; Mondloch, Pathman, Maurer, Le Grand, & de Schonen, 2007). Further evidence comes from the part-whole effect. In a part-whole task, a face part has to be recognized either in isolation or embedded in the whole face. Performance is better in the whole-face condition, supporting holistic processing (Tanaka & Farah, 1993; for review see Tanaka & Simonyi, 2016). Pellicano and Rhodes (2003) investigated the part-whole effect in preschool children and adults. Their results corroborate holistic face processing at preschool age. Moreover, another study by Tanaka, Kay, Grinnell, Stansfield, and Szechter (1998) demonstrated that there are no relevant differences in the part-whole effect when comparing children ranging in age from 6 to 11 years. Results of this study support the view that holistic face processing – at least as measured behaviorally - is not subject to major changes across childhood. Across different studies, thus, there is consistent evidence that already young children rely on a holistic processing mode in face perception.

Concurrently, the use of the analytical face processing mode has been explored in infants and young children by several studies. Cashon and Cohen (2004); Schwarzer and Zauner (2003) as well as Zauner and Schwarzer (2018) showed that during certain time windows infants prefer to process single facial features independently of each other, i.e. prefer analytical processing. In these studies, infants of different ages were habituated to two different faces and were then tested with so-called switch-faces, in which single features of the habituation faces were switched. It was found for 3- and 6-month-old infants (Cashon & Cohen, 2004) as well as for 4-month-old infants (Zauner & Schwarzer, 2018) that they do not respond to the switch-faces with a novelty response, suggesting that they did not engage in holistic processing but rather process the faces by single features or feature-by-feature. Dominance of analytical processing has also been demonstrated in children aged between 7 and 10 years in a categorization task (Schwarzer, 2000). Faces had to be categorized into two categories which were constructed either to focus on single face features, i.e. analytical processing, or to consider the overall similarity of the faces, i.e. holistic processing. Results showed that in both children groups the analytical processing mode dominated over the holistic processing mode. Adults, in contrast, predominantly used the holistic processing mode. Schwarzer, Huber, and Dümmler (2005) provided evidence that particular processing modes in this categorization task are accompanied by different gaze patterns. Independently of age, holistic processors focused their fixations on the area of the eyes and nose, suggesting that the center of mass of the face is the most informative area for holistic processing (see also Orban de Xivry, Ramon, Lefèvre, & Rossion, 2008; Rossion, 2013). In contrast, analytical processors showed more feature-specific gaze behavior, focusing their fixations on particular features used for subsequent processing.

In summary, previous research has demonstrated that holistic as well as analytical face processing modes are already operating in young children. However, the mere existence of both processing modes does not indicate whether children use them as efficiently and in the same manner as adults. The goal of the present study was to investigate whether and how children and adults differ in their use of holistic and analytical face processing modes using a gaze-contingent face recognition paradigm for the first time in children. Gaze-contingency is not only an elegant way to drive holistic or analytical face processing modes (van Belle, de Graef, Verfaillie, Rossion, & Lefèvre, 2010; van Belle, Lefèvre et al., 2010), but it also provides further insights into the facial information used, thanks to the analysis of fixation patterns.

Originally prevalent in studies on eye guidance during reading (Rayner, 1998) and scene perception (Underwood & Radach, 1998), gaze-contingency was introduced much later in the field of face processing as a method to manipulate perceptual processing in face recognition tasks (Caldara & Miellet, 2011; van Belle, de Graef, Verfaillie, Busigny, & Rossion, 2010; van Belle, Lefèvre et al., 2010; van Belle, Lefèvre, & Rossion, 2015). By selectively masking fixated parts, holistic processing is promoted because the local analysis of part-based information is hindered (i.e. a gaze-contingent mask condition, see Fig. 1). Contrariwise, by restricting available visual information to fixated parts, holistic processing is hindered (i.e. a gaze-contingent window condition, see Fig. 1). Gaze-contingency in this way provides an appropriate method to manipulate the availability of the holistic and the analytical processing mode, respectively. In addition, this paradigm yields fixation patterns that can be used to evaluate which visual information is used and thus how efficiently the available processing modes are exploited (van Belle et al., 2011).

Here we focused on the comparison of face processing in 5-year-old children and adults. We presumed that the original procedure could be adapted for this age so that performance on the same task could be measured in adults and children. Moreover, since acquisition of literacy in children might have relevant effects on face processing modes (Dehaene-Lambertz, Monzalvo, & Dehaene, 2018), we intended to avoid possible confounding by focusing on preschool children. The gaze-contingency method allowed us to investigate how children and adults cope with conditions in which either holistic or analytical processing is promoted and to uncover corresponding developmental differences.

2. Methods

2.1. Participants

A total of 25 children (12 girls) at the age of five participated in our study. Exact age ranged from 62 to 71 months ($M = 68.0$, $SD = 1.9$). All children attended local playschools in the area of Giessen. Literacy was ruled out by a standardized test for assessing reading comprehension skills (Lenhard & Schneider, 2006). In order to avoid unnecessary frustration, we refrained from carrying out the test if children and accompanying parents both denied any reading and writing skills. The adult comparison sample comprised 19 subjects (15 females) ranging in age from 19 to 35 years ($M = 23.8$, $SD = 4.3$). Adult subjects were undergraduate students enrolled in the psychology program at the Justus-Liebig-Universität Gießen and fulfilled requirements of the study program with their participation. All students were naive with respect to the purpose of the study. Informed consent was given by the accompanying parents of the children and the adult participants, respectively, according to the Declaration of Helsinki (World Medical Association, 2013). Methods and procedures were approved by the local ethics committee.

2.2. Stimuli

The original stimuli introduced in the study of van Belle, de Graef, Verfaillie, Rossion (2010) were used. Stimuli were based on 10 female and 10 male neutral adult faces chosen from the KDEF (Karolinska Directed Emotional Faces) database (Lundqvist, Flykt, & Öhmann, 1998). The KDEF database provides two sets of photographs for each face which were taken at different moments in time and differ slightly in lighting conditions. External parts were removed from the faces and all processed faces had approximately a height of 15.4° and a width of 11.1°. Individual face recognition was measured in a delayed recognition paradigm. In the encoding phase, a single face was presented to the subjects. In the recognition phase, the memorized face was taken from the other photograph set and was paired with a new face of the same sex. Subjects were required to decide which face they had seen in the encoding phase.

2.3. Apparatus

Stimuli were generated using Matlab with the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002). The experiment was run on a Dell Precision 380 computer and stimuli were displayed on a 22 inch Samsung SyncMaster S2233 LED monitor with a refresh rate of 120 Hz. The spatial resolution was set to 1680 × 1050 pixels. Subjects were seated in a darkened room at a distance of 48 cm in front of the monitor. Eye movements were registered by a SR Research Eyelink 1000 Tower Mount system at a sampling rate of 1000 Hz. Viewing was binocular and subjects' head was stabilized by a chinrest. A 9-point calibration was applied and accuracy was accepted if the procedure yielded values of average error not larger than 0.4° and worst error not larger than 0.7°.

2.4. Procedure

The procedure of each trial is illustrated in Fig. 1. Trials started with a central fixation cross subjects had to fixate. A drift check was performed in order to assure that the initial calibration of the eye tracking system was still valid and relevant distortions, e.g. by head movements, could be excluded.

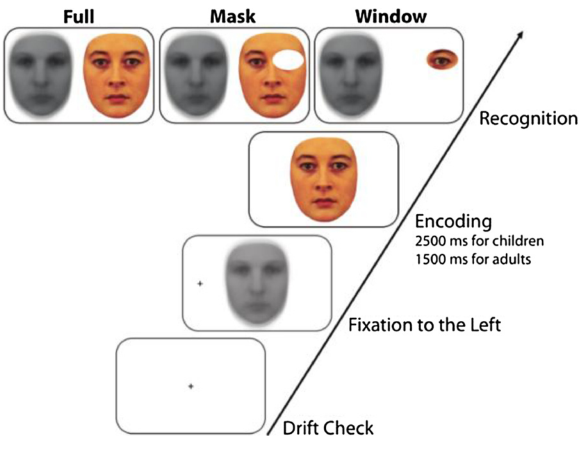

Fig. 1. Illustration of procedure. After a central drift check a blurred face appeared together with a fixation cross on the left. As soon as fixated the cross disappeared and the subject made a saccade back to the central target face that became fully visible for the encoding time defined for children and adults, respectively. The target face was subsequently replaced by a pair of faces, a distractor face and the target face. Subjects were asked to recognize the target face. Available visual information was manipulated by one of three different viewing conditions. There were no time constraints for recognition and no performance feedback was provided.

As soon as the calibration was confirmed a central blurred face was displayed together with a fixation cross at an eccentricity of 11° left of the center of the screen. The blurred face showed a grey-scale average image of all faces. Subjects had to saccade to the new fixation cross, which disappeared when fixated. Its disappearance indicated for the subjects to saccade back to the central face. The blurred face then turned into the target face subjects had to encode. The target face was visible for 2500 ms for children and for 1500 ms for adult subjects. Based on pilot data we had to provide a prolonged encoding phase for children in order to enable them to accomplish the recognition task with a sufficient performance. After encoding time, the target face was replaced by a pair of two faces, namely the memorized face and a new face. The two faces were presented at an eccentricity of 11° right and left from the center of the screen, respectively. Subjects could explore both faces without temporal constraints. During exploration, only the fixated face was visible, and the face that was not fixated was replaced by the grey-scale average face. The decision which face had been seen before was made via push buttons held in both hands. Subjects were instructed to make their decisions as quickly and as accurately as possible. No feedback about performance was given.

There were three different viewing conditions in the recognition phase. In the full view condition faces were visible without restrictions. This condition served as our baseline condition because individual face recognition was measured without manipulation of processing modes. In the mask condition, the fixated part was covered by a gaze-contingent mask. This manipulation promotes holistic processing, as explained in the introduction. In the window condition, on the contrary, only the fixated part was visible through a gaze-contingent window, forcing part-based processing. Window and mask were shaped elliptical and subtended approximately 2.9° horizontally by 2.1° vertically.

The experiment was subdivided into 3 blocks each consisting of 20 trials for the children and 40 trials for the adult subjects. Thus, a total of 60 and 120 trials were run in the child sample and the adult sample, respectively. The reduced trial number in the child sample was chosen in order to meet children's limited resilience in the experimental task. Accuracy of fixation data and thereby accuracy of the gaze-contingent manipulations were supported by repeating the calibration procedure before every block. Each viewing condition was applied in one third of the trials. Conditions were randomized within blocks so that subjects could not anticipate the next viewing condition during the encoding phase and had to switch between the processing modes.

The experiment was preceded by detailed instructions that assured understanding of the task. First, the different trial phases and conditions were visualized by plates showing example stimuli. When subjects could follow the instructions correctly, at least five to ten full view practice trials were run so that subjects became used to the task and could effortlessly handle the input devices. We described the task as a memory game to the children, but instructions were kept similar to those for adult subjects. Motivation and resilience of children were further facilitated by providing the opportunity to engage in either a game of darts or a tin can alley game after each finished block. Adults completed the procedure in about 40 min, while for children it took maximally 50 min, depending on the extent of breaks needed.

2.5. Data analysis

2.5.1. Performance data

We analyzed response times (RT) and accuracy rates, i.e. proportion of correct responses. We first removed outlier trials in which RT exceeded individual mean RT by more than two standard deviations. In addition, we determined within each age group and each viewing condition outlier data by inspection of boxplots. RT values deviating more than three times the interquartile range from the range borders were considered as extreme outliers. We identified extreme outlier data only in a single case, namely for a child subject in the mask condition, and discarded the RT value. RT analysis included only trials with correct responses. As a measure of overall efficiency of performance we calculated inverse efficiency scores, i.e. RT divided by accuracy. Inverse efficiency scores provide a combined measure of RT and errors and allow evaluation of performance unbiased by existing speed-accuracy tradeoffs (Townsend & Ashby, 1983).

In order to ease comparison between effects of viewing condition we normalized performance measures for each subject to full view condition, i.e. to our baseline condition. The normalization procedure took inevitable performance differences between children and adults into account and yielded parameters that were directly comparable. Decrease in performance in the mask and window conditions relative to the full view condition is given by the following indices: $\text{Index}_{Mask} = (\text{Performance}_{Full} - \text{Performance}_{Mask}) / (\text{Performance}_{Full} + \text{Performance}_{Mask})$ and accordingly $\text{Index}_{Window} = (\text{Performance}_{Full} - \text{Performance}_{Window}) / (\text{Performance}_{Full} + \text{Performance}_{Window})$. Since the relative performance decrease in the conditions with restricted viewing was of primary interest, statistical analyses were run only on index measures. We submitted data to 2-factorial analyses of variance (ANOVA) with age group as between-subjects factor and repeated measures on the factor viewing condition.

2.5.2. Fixation data

We determined number of fixations per trial and average duration of fixations per trial. Data from trials not yielding a correct response were discarded. Corresponding to analysis of performance measures we calculated indices normalizing data to full view condition (see above). Indices emphasize differences in fixation measures in the mask and window condition relative to the full view condition. Statistical analyses were consistent with the procedure for performance data.

We were further interested in the regional distribution of fixation patterns across the faces. We generated statistical fixation maps for eye movements using the *i*Map3 toolbox for Matlab (Caldara & Miellet, 2011). *i*Map3 provides a novel approach to data-driven fixation maps. Instead of analyzing eye movement parameters in pre-defined regions of interest, data are considered pixel-wise and fixation maps are statistically compared correcting for multiple comparisons in pixel space. Fixation maps can be based on number of fixations or fixation duration. Fixation maps display areas for which a greater number of fixations or longer fixation durations are

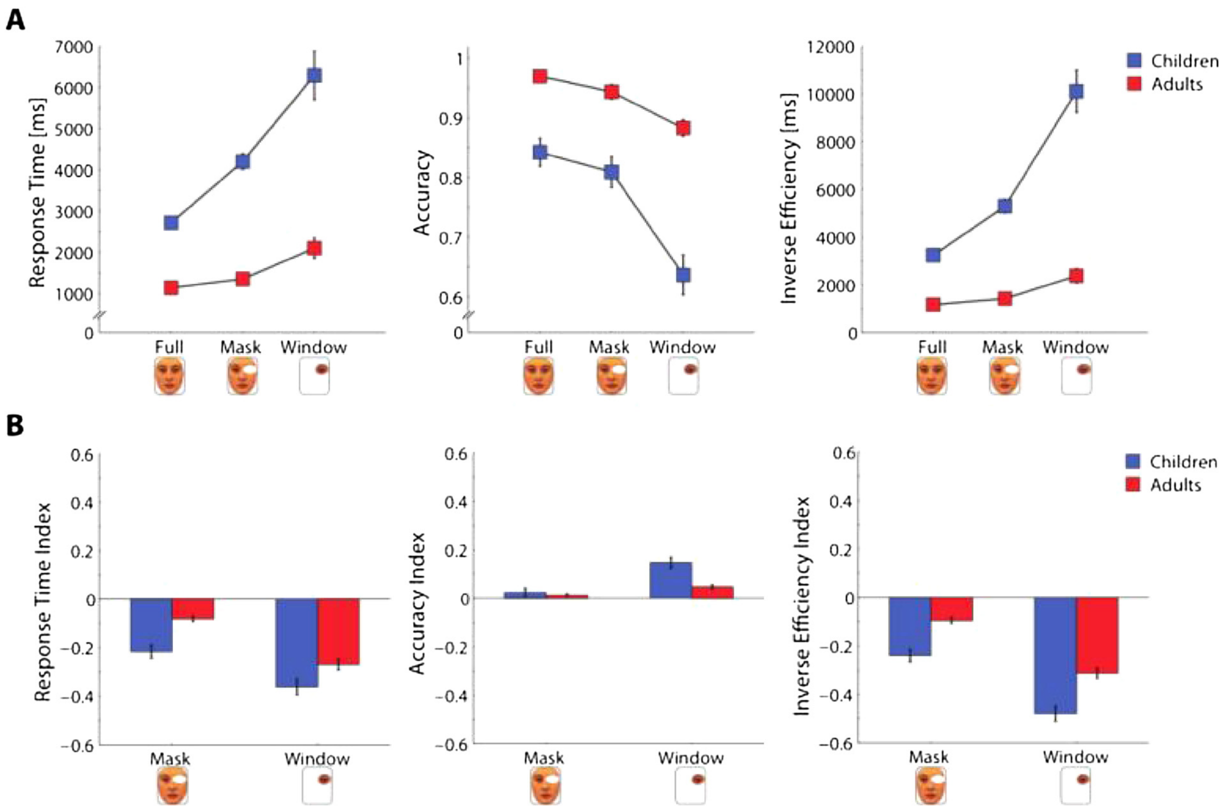

Fig. 2. Performance data. (A) From left to right figures show response time in correct trials, accuracy (proportion of correct responses), and inverse efficiency (response time divided by accuracy), respectively. Data for the three different viewing conditions are plotted in blue for children and in red for adults. Error bars indicate standard errors of the mean. (B) From left to right figures give index measures for response time, accuracy and inverse efficiency, respectively. Indexes normalize performance in the mask and the window condition to performance in the full view condition (for formulas see method section). Blue bars illustrate children's data; red bars illustrate adults' data. Error bars indicate standard errors of the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

observed than for other areas. Contrast fixation maps indicate differences between two maps, illustrating e.g. a bias towards more fixations or longer fixation durations within a specific area.

We generated fixation maps for each viewing condition separately for both age groups including all child and adult subjects, respectively. Data from trials with incorrect responses were removed. Fixation positions were smoothed using a Gaussian kernel with a standard deviation of 25 pixels (0.8°) in order to account for variability in eye tracking accuracy. Position data for left and right faces in each trial were collapsed and mapped on an exemplary face taken from the stimuli battery. Since statistical analyses require sufficient data points per pixel, a minimal number of data points per pixel was chosen according to the given group sizes, i.e. 14 points in the child group and 13 points in the adult group. Differences in fixation parameters between mask and window condition, respectively, and full view condition were analyzed by contrast maps. Significance thresholds were set to $p < 0.05$ for single maps and to $p < .025$ for contrast maps. Correction for multiple comparisons was based on 1000 bootstraps.

3. Results

3.1. Performance data

Before analyzing performance data, we evaluated accuracy rates in order to exclude subjects who were not able to accomplish the face recognition task better than at chance level. We required each subject to reach an accuracy rate of at least 0.60 in the full view condition. According to this criterion we had to exclude 4 children from our sample. The remaining subjects showed accuracy rates well above chance in all viewing conditions.

Panel A of Fig. 2 illustrates results for performance measures in the different viewing conditions and age groups. Corroborating findings from previous studies, our results supported lower face recognition performance in children than in adults. Children also showed much longer response times than adults in all viewing conditions. Fastest responses were given in the full view condition and slowest in the window condition. Response times in the mask condition lied in between. For accuracy rates, corresponding results were observed. Highest accuracy was achieved in the full view condition, but performance decreased in the conditions with restricted viewing. Accuracy was worst in the window condition. Inspection of inverse efficiency scores yields similar patterns and thus supports that results are not biased by speed-accuracy tradeoffs. Comparison of performance profiles suggests that age-related performance differences are particularly pronounced in the window condition, i.e. when analytical processing is forced.

Analysis of index measures that ease the comparison between children and adults despite substantial baseline differences provide further evidence for differential advantages of adults in the mask condition and in the window condition. Panel B of Fig. 2 gives index measures indicating the decrease in performance in the mask and window conditions relative to the full view condition. Index measures were submitted to ANOVAs. For response time index we found significant main effects of *age group*, $F(1, 37) = 20.92$, $p < 0.001$, $\eta^2 = .36$, and *viewing condition*, $F(1, 37) = 63.11$, $p < 0.001$, $\eta^2 = .63$. The interaction effect did not reach significance, $F(1, 37) = 0.52$, $p = .477$, $\eta^2 = .01$. Given that our index measures describe relative performance changes, the main effect of *age group* supports that response time increase due to any viewing manipulation was more pronounced in children. The main effect of *viewing condition* indicates that the window condition elicited a stronger increase than the mask condition in both age groups. We found no evidence that differences between children and adults were in particular pronounced in a specific viewing condition that hindered either the holistic processing mode or the analytical processing mode, respectively.

Results for accuracy index yielded significant main effects of *age group*, $F(1, 37) = 11.62$, $p = .002$, $\eta^2 = .24$, and *viewing condition* $F(1, 37) = 28.44$, $p < 0.001$, $\eta^2 = .44$. However, these main effects were qualified by a significant interaction, $F(1, 37) = 8.87$, $p = .005$, $\eta^2 = .19$. Please note that in the mask condition indeed neither children nor adults showed a significant accuracy decrease. Thus, similar results were determined for both age groups ($t(37) = 0.60$, $p = .551$). In contrast, the window condition triggered a decrease in accuracy and children were more strongly affected than adults ($t(37) = 3.98$, $p < .001$). Considering the ANOVA on inverse efficiency index, systematic biases of speed-accuracy tradeoffs appear unlikely. Results resembled those for response time index, i.e. showed significant main effects of *age group*, $F(1, 37) = 46.62$, $p < 0.001$, $\eta^2 = .56$, and *viewing condition*, $F(1, 37) = 91.51$, $p < 0.001$, $\eta^2 = .71$, without a significant interaction, $F(1, 37) = 0.32$, $p = .575$, $\eta^2 = .01$.

In summary, performance data in the unrestricted full view condition support that the individual face recognition task was more difficult for children than for adults. Children responded slower and made more errors. When perceptual processing modes were challenged by gaze-contingent manipulation of available information, performance decreased in both groups, but children were overall more vulnerable to restrictions of available information. They showed a more pronounced increase in response times in the mask condition as well as in the window condition. Furthermore, the additional accuracy decrease found in the window condition was stronger in children than in adults. However, most importantly, our results indicate that consistently across age groups that detrimental effects were more pronounced when the holistic processing mode rather than the analytical processing mode was hindered. Thus we conclude that children as well as adults seem to rely on a similar face processing pattern, i.e. process and recognize faces better when they rely on the holistic processing mode than on the analytical processing mode. Accuracy decrease under conditions when analytical processing is fostered while holistic processing is hindered even suggests that this pattern is more prominent in children.

To summarize, our findings support that children differ from adults in the efficiency to use different perceptual processing modes and especially in the efficient use of the analytical processing mode. Moreover, more pronounced vulnerability to manipulated processing modes might also indicate less flexibility in switching from one processing mode to another, as it was required in our task. We speculate that these functional disadvantages contribute to immature face recognition performance in children.

3.2. Fixation data

Fixation data complemented performance data and provided more detailed insights into the use of facial information when processing modes are manipulated. Results for fixation measures in the different viewing conditions and age groups are given in panel A of Fig. 3.

In comparison with adults, children required more fixations before they made a decision and their fixations lasted longer overall, indicating again that the task was more difficult for children. Viewing condition affected number of fixations and duration of fixations differentially. Number of fixations per trial was lowest in the full condition, the baseline condition, and increased when processing modes were biased. Average duration of fixations in a given trial decreased in the mask condition and increased in the window condition. Number and duration of fixations yielded no consistent evidence which manipulation elicited most pronounced differences between children and adults. Whereas for the number of fixations the difference was most pronounced in the mask condition, duration of fixations differed particularly in the window condition. This pattern suggests that manipulation of processing modes elicits differential compensation strategies in children and adults.

Index measures helped to clarify the effects on fixation measures. Panel B of Fig. 3 shows index measures of fixation data and thereby illustrates results relative to the baseline, i.e. the full view condition. The ANOVA on number of fixations index showed a significant main effect of *age group*, $F(1, 37) = 6.60$, $p = .014$, $\eta^2 = .15$, but there was no significant effect of *viewing condition*, $F(1, 37) = 1.04$, $p = .314$, $\eta^2 = .03$. The main effect of age groups was qualified by a significant interaction effect, $F(1, 37) = 4.84$, $p = .034$, $\eta^2 = .12$. In the mask condition, children showed a more pronounced increase in number of fixations than adults ($t(37) = -4.44$, $p < .001$). In contrast, indexes for the window condition were equivalent in both groups ($t(37) = -0.43$, $p = .670$). Analysis of duration of fixations indexes yielded a reverse pattern. We found significant main effects of *age group*, $F(1, 37) = 5.31$, $p = .027$, $\eta^2 = .13$, and *viewing condition*, $F(1, 37) = 113.10$, $p < 0.001$, $\eta^2 = .75$. Again these effects were qualified by a significant interaction, $F(1, 37) = 12.10$, $p = .001$, $\eta^2 = .25$. Here, age groups did not differ in their increase data in the mask condition ($t(37) = 0.20$, $p = .845$), but clearly in the window condition ($t(37) = -3.60$, $p = .001$). In the mask condition, children and adults showed similarly decreased fixation durations. Longer fixation durations were observed in the window condition. This increase was more pronounced

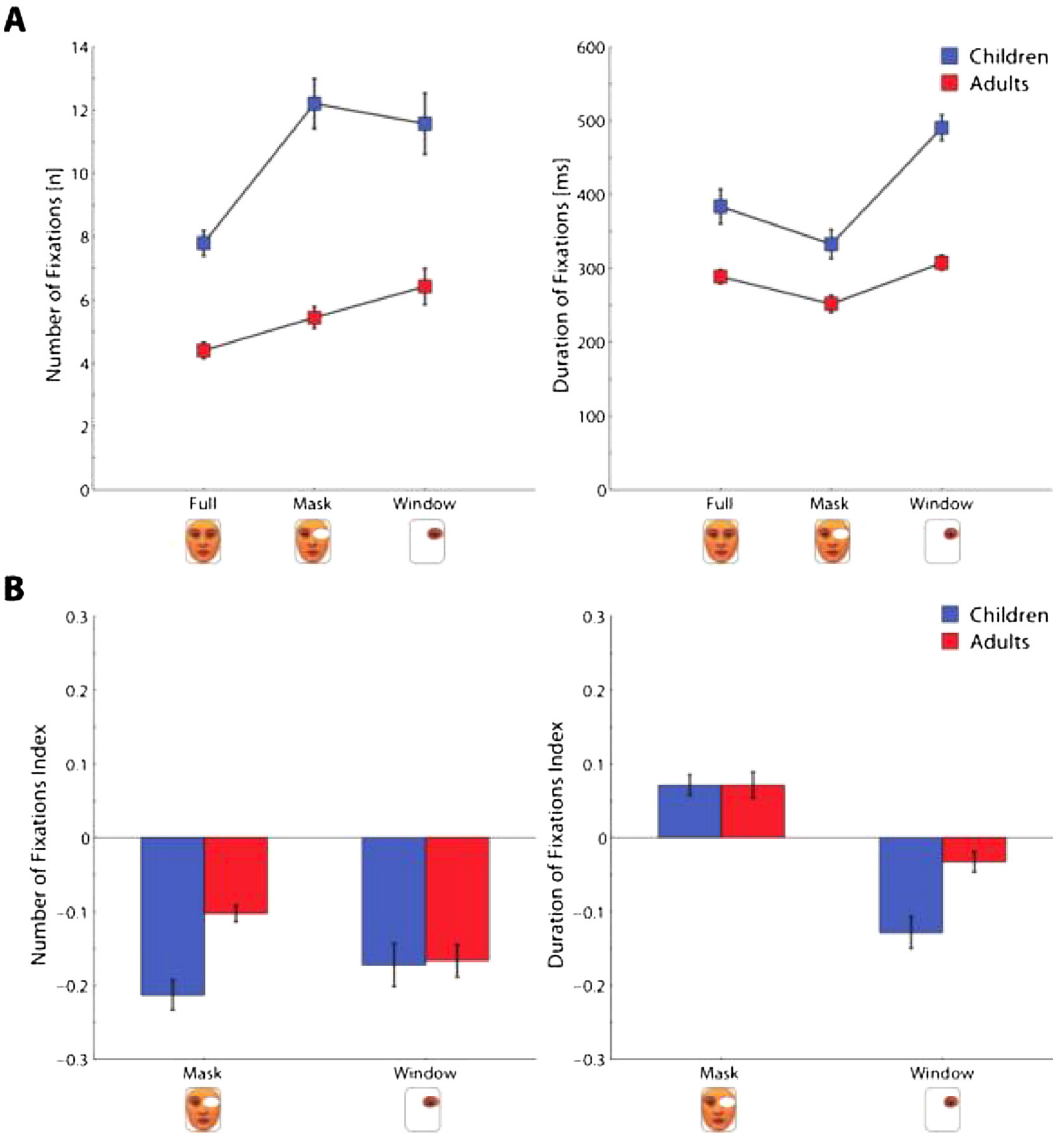

Fig. 3. Fixation data. (A) The left and right figures depict number of fixations and average duration of fixations per trial, respectively. Only data from correct trials are included. Results for the three different viewing conditions are plotted in blue for children and in red for adults. Error bars indicate standard errors of the mean. (B) The left and right figures give index measures for number of fixations and average duration of fixations per trial. Indices normalize parameters in the mask and the window condition to parameters in the full view condition (for formulas see method section). Only data from correct trials are included. Blue bars illustrate children's data; red bars illustrate adults' data. Error bars indicate standard errors of the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

in the child group.

Regional distribution of fixation patterns is illustrated in Fig. 4 by heat maps. Regional biases found by comparing patterns in the conditions with restricted information with those in the full view condition are supplemented in Fig. 5.

Panel A of Fig. 4 highlights areas for which more fixations were observed. We overall found a T-shaped distribution emphasizing the region of the eyes and the nose for all viewing conditions. Children in general tended to concentrate fixations more to the region just between the eyes and at the top of the nose, respectively, whereas adults showed a broader distribution within the T-shape. When processing modes were challenged, these differences appeared even more pronounced.

Further support came from contrast maps, which are given in panel A of Fig. 5. Children showed an additional bias towards the eye region in both the mask and the window condition. In contrast, regional distribution of fixations in adults appeared stable in the face of manipulated processing modes.

Areas of longer fixation durations are given in panel B of Fig. 4. Increase of fixation durations similar to increase of fixation number concentrated on the T formed by the eyes and the nose. Heat maps for children again supported that viewing restrictions elicited a bias towards the eyes. Contrast maps shown in panel B of Fig. 5 provide statistical evidence. In the mask as well as in the

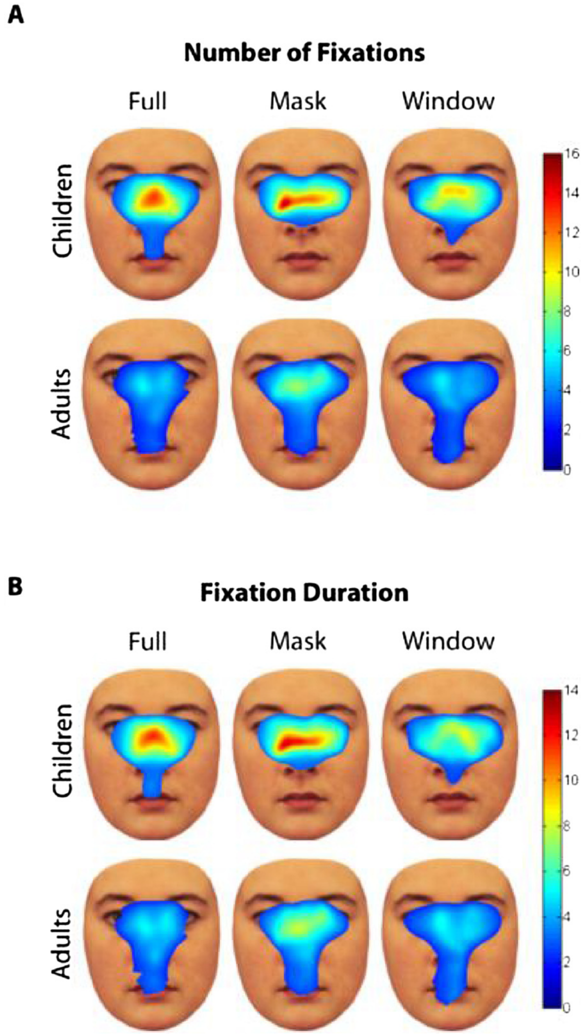

Fig. 4. Statistical fixation maps for children and adults in each viewing condition. Heat maps display significant areas after correction for multiple comparisons ($p < .05$). Color coding indicates t-values. Only data from correct trials were included in the analyses. Fixation positions were smoothed using a Gaussian kernel with a standard deviation of 25 pixels, equivalent to 0.8°. Data were collapsed across left and right faces in each trial and mapped on an exemplary face. (A) Heat maps based on number of fixations. Areas with greater numbers of fixations per trial are illustrated. (B) Heat maps based on fixation duration. Areas of longer fixation durations are given. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

window condition longer fixation durations shifted to the eye region compared to the full view condition. This pattern was found only in the mask condition for adults.

3.3. Summary of results

Our findings support that in 5-year-old preschool children similar face processing mechanisms are operative as in adults. In both age groups holistic processing is most critical to behavioral performance, and recognition rates dramatically drop when primarily part-based information is available and thus analytical processing is emphasized. Restrictions of part-based information also impair performance, but to a lesser degree. However, our results suggest additional specific vulnerabilities in children. When the relative availability of holistic and analytical processing modes is manipulated, fixation patterns in children reveal less flexibility to use different processing modes efficiently. Fixation patterns primarily support holistic processing, but appear less suited for analytical processing. Thus, the development of the analytical processing mode in particular might lag behind. These age differences in using different perceptual modes can be linked to individual face recognition performance and presumably contribute to immature face recognition performance in children.

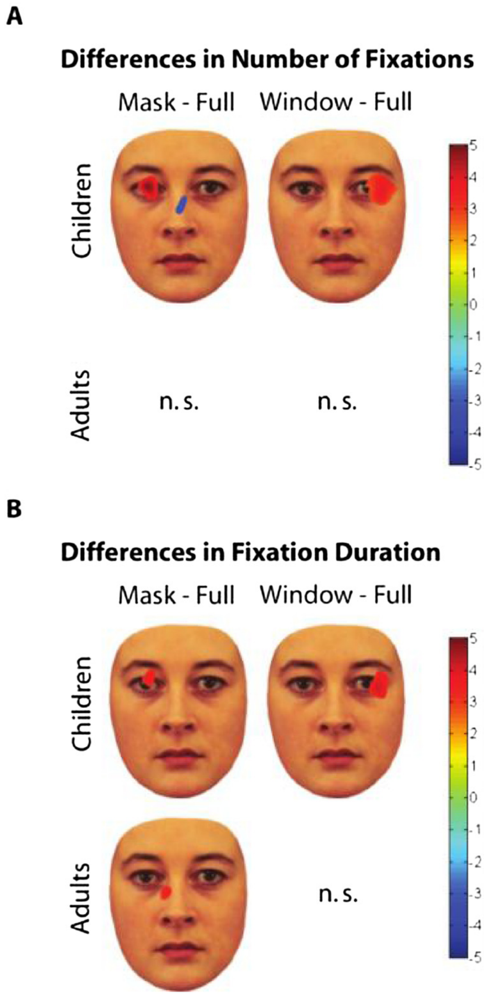

Fig. 5. Contrast maps for children and adults comparing mask and window conditions, respectively, with the full view condition. Heat maps display areas of significant differences between the viewing conditions after correction for multiple comparisons ($p < .025$). Color coding gives t-values. Warm colors indicate a bias for the mask and window conditions, respectively; cold colors indicate a bias for the full view condition. Maps without any significant area are omitted (n.s.). Only data from correct trials were included in the analyses. Fixation positions were smoothed using a Gaussian kernel with a standard deviation of 25 pixels, equivalent to 0.8°. Data were collapsed across left and right faces in each trial and mapped on an exemplary face. (A) Heat maps based on number of fixations. Warm colors give areas with a greater number of fixations in the mask and window conditions, respectively; cold colors give areas with a greater number of fixations in the full view condition. (B) Heat maps based on fixation duration. Warm colors give areas of longer fixation durations in the mask and window conditions, respectively; cold colors give areas of longer fixation durations in the full view condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4. Discussion

Our study was concerned with the processes which contribute to individual face recognition in 5-year-old preschool children and adults. In particular, we were interested in whether children and adults differ in their relative use of holistic and analytical processing modes. Using the gaze-contingency method we manipulated availability of both processing modes and thus were able to investigate their relative contributions to individual face recognition performance. In addition, analysis of fixation patterns revealed specific compensation strategies in the face of restricted visual information. Our results support the view that children and adults basically rely on the same processes when recognizing individual faces, i.e. on holistic and analytical processing modes. However, they differ in how efficiently they exploit each processing mode. When availability of a specific mode is challenged, performance in children is more affected than in adults. Children show more pronounced impairments in processing speed, accuracy, and fixation patterns. The regional distribution of fixation patterns appears less suited to use both processing modes flexibly. In particular, the analytical processing mode is less supported in children than adults.

By measuring individual face recognition under different viewing conditions that promoted either holistic or analytical processing, i.e. the mask or the window condition, we aimed to determine the relative impact of processing modes in children and adults.

Note that the gaze-contingent manipulation is inherently linked to differences in availability of spatial frequencies. Whereas the mask condition provides perifoveal information emphasizing low spatial frequencies, the window condition provides foveal information emphasizing high spatial frequencies. This does not interfere with the intended manipulation of processing modes, since, if anything, holistic processing depends more on low spatial frequencies and analytical processing depends more on high spatial frequencies (Goffaux & Rossion, 2006). Moreover, in previous studies using this paradigm in adults, Van Belle and colleagues (van Belle, de Graef, Verfaillie, Busigny, 2010; van Belle, de Graef, Verfaillie, Rossion et al., 2010) also showed that their results were largely independent of the size of the stimuli presented to their observers.

Many studies before have been based on the logic that developmental changes in the use of processing modes should be observable in the difference between holistic and part-based conditions. Crookes and McKone (2009) pointed out some major problems inherent to such an approach, namely baseline differences and age-specific restriction of performance range, which complicate any conclusions. They argued that most results showing immaturity of face processing mechanisms in children are due to these methodological issues. In our study, we considered face recognition under unrestricted viewing conditions as baseline and aimed to minimize performance differences. We allowed children a prolonged encoding time and required an accuracy rate of at least 0.60 in the full view condition. It should be noted that encoding times lay well above previously reported processing times that are needed to build holistic representations (Hole, 1994; Jacques & Rossion, 2009), so that this age-specific adaptation was very unlikely to bias processing mode in the encoding phase. Since we did not reach a complete baseline match, we also normalized performance under specifically manipulated viewing conditions to performance under full view condition.

Comparable processing modes during face recognition in children and adults are supported by performance indices for response time and accuracy. Validity of results is further confirmed by inverse efficiency scores, which take systematic speed-accuracy tradeoffs into account. For children as well as for adults, restriction of holistic processing was particularly detrimental. Restriction of part-based information also elicited a performance decrease, but to a much lesser degree. Adults' performance pattern in our study is congruent with previous evidence from the gaze-contingent face recognition paradigm (compare van Belle, de Graef, Verfaillie, Rossion et al., 2010) and these findings support the dominant role of holistic processing in face perception already early in childhood, thus adding support from other paradigms (e.g. de Heering et al., 2007; Macchi Cassia et al., 2009; Mondloch et al., 2007; Pellicano & Rhodes, 2003). Moreover, children's recognition accuracy was especially vulnerable when part-based information was promoted and they were required to select critical features. This might indicate that it is easier for children to rely more on holistic information compared to adults. Notably, some studies reported stronger holistic interference in children than in adults, i.e. children showed more difficulties to inhibit holistic processing (de Heering et al., 2007; Nakabayashi & Liu, 2013). Our results qualify previous evidence for children's preference for analytical processing in specific face processing tasks (Cashon & Cohen, 2004; Schwarzer & Zauner, 2003; Schwarzer, 2000; Zauner & Schwarzer, 2018). Divergent findings might be based on the considered age range as well as on the specific task characteristics. The preference for analytical processing has been shown to fluctuate across childhood (compare Schwarzer & Zauner, 2003; Zauner & Schwarzer, 2018). Furthermore, critical tasks in which a dominance of analytical processing was found were quite different from our face recognition task, i.e. measured habituation or categorization, respectively. In the categorization task, for example, children preferred to analyze the faces by focusing on one consistent face feature throughout all trials. In the window condition of the present study, however, the chosen face feature depended on children's fixations within the face. We assume that the window condition used here was cognitively far more demanding for the children than the analytical processing in the categorization task. Thus, our findings suggest that although children might prefer the analytical processing mode in some tasks, they presumably are not efficient in its use in tasks which require a more flexible use of analytical processing.

In summary, 5-year-old preschool children in our study, similarly to adults, relied particularly on holistic processing in individual face recognition: their performance was significantly more affected by a restriction of holistic processing than by a restriction of analytical processing. However, our data also showed that children do not reach recognition performance equivalent to adults and that they are more vulnerable to manipulations of processing modes. Gaze behavior under specific viewing conditions allows additional clarification of how children cope with increasing demands on face processing.

Since high-resolution acquisition of visual information in faces is substantially determined by fixations, looking behavior of subjects sheds further light on processing mechanisms and several studies have shown the critical role of eye movements in face recognition (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Hsiao & Cottrell, 2008; Peterson & Eckstein, 2012). Here, we analyzed number and duration of fixations as well as their regional distribution under conditions with different viewing constraints. These fixation measures reveal underlying visual strategies that differ in their efficiency to compensate for biased processing modes. In a nutshell, subjects could apply two principle compensation strategies. First, they could aim for more fixations in order to sample information from more spatial locations. Another strategy would be to spend more time on each fixation position in order to process given information more exhaustively.

We observed specific compensation strategies in children and adults when visual information was manipulated. Overall, restriction of information induced an increase in number of fixations. Subjects tried to compensate for the missing information by gathering information from more locations. When analytical processing was hindered, children and adults showed decreased fixation durations, but at the same time an increased number of fixations. The decrease of fixation durations can be most likely attributed to the fact that the fixated part of the face was covered and thus information could not be processed in detail. This pattern also indicates that holistic processing at a given fixation location was accomplished rather quickly, presumably providing just a gist of relevant information. However, more fixation locations were required to reach correct recognition. This increase in number of fixations was more pronounced in children than in adults. In this way, they were able to compensate efficiently for the manipulation and could keep accuracy in the recognition task stable just like adults. In contrast, when holistic processing was hindered, adults foremost increased the number of fixations while their durations were only minimally increased compared to baseline. Notably, the increase in number of fixations was much more pronounced than when a relative lack of analytical processing had to be compensated. This pattern suggests that the relative lack of holistic processing was compensated by sampling information from more locations, but that local information processing did not require increased time resources. Although children showed an equivalent increase of number of fixations compared to baseline as adults, this increase was not more pronounced than when a lack of analytical processing had to be compensated. Furthermore, duration of fixations increased substantially, indicating that analytical processing required extensive time resources in children. We assume that children's more pronounced accuracy decline when emphasis was put on analytical processing was based on an insufficient increase of fixation number and at the same time immature capacities to process isolated facial features.

Regional distribution of fixation patterns during face recognition under unrestricted viewing conditions has been described by several studies. There is coherent evidence that only few fixations are sufficient for successful recognition and that these fixations are located around the top of the nose (Hsiao & Cottrell, 2008; Orban de Xivry et al., 2008; Peterson & Eckstein, 2012). This fixation location has been proposed to be optimal because it allows appreciation of the face as a whole, corresponding to the dominance of an early holistic representation (Rossion, 2008, 2013). In acquired prosopagnostic patients with impaired holistic face processing, substantial deviations from this fixation focus can be shown, the patients focusing on facial parts such as the mouth (Orban de Xivry et al., 2008; van Belle et al., 2011). However, a recent study calls attention to substantial individual differences in preferred fixation location during face recognition that do not affect processing efficiency (Peterson & Eckstein, 2013). Children in our study showed in all viewing conditions a clear focus on the eye region including the top of the nose. There we determined more fixations and higher fixation durations. This strategy might be beneficial in the mask condition when holistic processing is promoted (Peterson & Eckstein, 2012). In contrast, optimality of this strategy is arguable in the window condition when a broader coverage of facial features might be advantageous. Regions which also carry relevant part-based information, e.g. the mouth, were largely neglected. Spatial shifts in consequence of processing mode manipulation were observed towards the eyes, but irrespective of whether holistic processing or analytical processing was hindered. This strategy presumably is especially inefficient in the window condition and could also contribute to the marked decline in face recognition accuracy. For adults, the regional distribution appeared more diffuse, following a coarse T shape under all viewing conditions. Restrictions of processing modes elicited only minor changes in distribution of fixation patterns. We only found an increase of fixation durations at the top of the nose in the mask condition in which holistic processing was promoted. This seems consistent with the assumption that this fixation location is best suited to process the face as a whole. Given a broader fixation distribution already in the baseline condition adults were most likely well prepared to use both holistic and analytical processing modes efficiently so that further spatial shifts were redundant. We further speculate that individual differences might be more pronounced in adulthood when an idiosyncratic optimal point of fixation might have developed (compare Peterson & Eckstein, 2013, 2014). Regional distribution of fixation patterns overall confirms more pronounced, but presumably less efficient compensation efforts in children than in adults.

In summary, fixation patterns reveal that restrictions of visual information challenge face processing more in children than in adults. Children engage in more pronounced compensation strategies, but these are less efficient than in adults, in particular when the use of analytical processing is emphasized.

Performance data and fixation patterns converge to indicate that, though similar visual processing modes are in principle available to children and adults, children are particular vulnerable when the flexible, adaptive use of these modes is required. Previous studies have often proposed that a principle shift from analytical to holistic processing modes represents a crucial functional transition during development (compare Cohen, 1998; Cohen, Chaput, & Cashon, 2002). Our findings suggest that, at least at preschool age, capacities to alternate between both processing modes might be even more critical. However, it has to be explicitly noted that our conclusions are limited to the specific task and stimuli we used, i.e. an individual face recognition task. Since face perception represents a highly specialized capacity, whether our findings extend to other visual cognitive domains remains to be determined.

5. Conclusions

Exploiting the advantages of an original gaze-contingent method we provide evidence for holistic and analytical processing in an individual face recognition task in 5-year-old preschool children. Our findings corroborate that already early in childhood holistic face processing plays a crucial role in face perception. However, they also reveal that children have in particular problems to use the analytical processing mode efficiently. Moreover, they seem less able to exploit the different processing modes flexibly according to specific task requirements. We suggest that these developmental differences contribute to still developing face recognition performance in children. Since we exclusively focused on face perception in our study, it remains to be clarified whether the observed vulnerabilities in children's processing of visual information are limited to this domain or do transfer to object perception in general.

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