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Developmental eye movement strategies for decoding facial expressions of emotion

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ABSTRACT

In our daily lives, we routinely look at the faces of others to try to understand how they are feeling. Few studies have examined the perceptual strategies that are used to recognize facial expressions of emotion, and none have attempted to isolate visual information use with eye movements throughout development. Therefore, we recorded the eye movements of children from 5 years of age up to adulthood during recognition of the six "basic emotions" to investigate when perceptual strategies for emotion recognition become mature (i.e., most adult-like). Using *i*Map4, we identified the eye movement fixation patterns for recognition of the six emotions across age groups in natural viewing and gaze-contingent (i.e., expanding spotlight) conditions. While univariate analyses failed to reveal significant differences in fixation patterns, more sensitive multivariate distance analyses revealed a U-shaped developmental trajectory with the eye movement strategies of the 17- to 18-year-old group most similar to adults for all expressions. A developmental dip in strategy similarity was found for each emotional expression revealing which age group had the most distinct eye movement strategy from the adult group: the 13- to 14-year-olds for sadness recognition; the 11- to 12-year-olds for fear, anger, surprise, and disgust; and the 7- to 8-year-olds for happiness. Recognition performance for happy, angry, and sad expressions did not differ significantly across age groups, but the eye movement strategies for these expressions diverged for each group. Therefore, a unique strategy was not a prerequisite for optimal recognition performance for these expressions. Our data provide novel insights into the developmental trajectories

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underlying facial expression recognition, a critical ability for adaptive social relations.

Introduction

In our daily lives, we repeatedly look at the faces of others to understand, consciously or unconsciously, how they are feeling. We search for signals from the face to decode and integrate critical socioemotional information, which can help us to respond appropriately in different social settings. This important social skill, the recognition of emotion from the face, emerges during early infancy and develops over time from our first social experiences. Emotion recognition forms part of a wider set of social processing skills that comprise social cognition, the effective development of which is necessary to understand how both ourselves and others navigate the social world (Happé & Frith, 2013). Impaired emotion processing has negative consequences for social functioning and well-being (e.g., Carton et al., 1999; Denham et al., 2003; Izard et al., 2001), and facial expression recognition performance during early childhood is predictive of later social and academic competence (Izard et al., 2001). Therefore, research defining the parameters of the typical development of emotion recognition is valuable and essential; moreover, such functional visual signatures also inform understanding of atypical development.

The process of recognition implies past experience; to recognize something, we must have seen it previously. This dimension of temporality makes the study of emotion recognition particularly relevant to development. To date, many developmental studies have focused on establishing by which age certain emotional expressions can be recognized. Largely, behavioral and (where possible) neuroscientific approaches have been used to study the development of emotion recognition. Very few studies have examined the perceptual strategies that are used to recognize an emotion throughout typical development. This is surprising given the importance of accurate emotion perception to our social functioning and well-being. Therefore, the focus of this study was to investigate the eye movements of children and young adults to isolate which information from the face is fixated to recognize an emotion across development. Eye movements reveal which visual input is selected for cognitive visual tasks (Liversedge & Findlay, 2000). In this way, they provide an indication of the online cognitive processes underlying a given task, in this instance facial expression recognition (Liversedge & Findlay, 2000). A sequence of eye movements reveals where our overt visual attention is directed moment by moment, and which input, or information from the face, is necessary to recognize an emotional expression. With their high temporal resolution, eye movements provide valuable measures, in addition to accuracy and reaction times, about cognitive visual functioning (Eckstein et al., 2017). By comparing visual scan paths with behavioral performance across development, it is possible to establish which perceptual strategies are effective, which information is needed to recognize an emotion, and at which stage of development perceptual strategies become mature. Defining such functional visual signatures is also informative for the understanding of atypical development (children with autism spectrum conditions, anxiety disorders, atypical psychosocial or visual experience, etc.) and possible interventions.

A limited number of studies have investigated the eye movements and perceptual strategies used by adults during facial expression recognition. Such studies reveal which information from the face is necessary to categorize an emotional expression in maturity. Studies with adults have shown unique scan patterns according to the emotion observed, and the diagnostic information for each emotion is also unique (Jack et al., 2009; Schurgin et al., 2014). These studies have shown, for example, that to recognize disgust fixations are most densely populated toward the upper lip, eyes, nose, and nasion area between the eyes. For happiness, the mouth is more predominantly fixated than the eyes, whereas for anger the eyes are more densely fixated and fixations to the mouth are more concentrated on the upper lip. For both sadness and surprise, both the eyes and mouth show predominant fixations, with a slight increase in density to the eyes for sadness. Finally, both the eyes and mouth are fixated for fear expressions, with some central fixations also being made to the nose. The distinctive scan patterns elicited by each emotion may reflect the characteristic facial muscle configurations that are expressed when experiencing a given emotion. These essential muscle movements were notably coded into a system, the Facial Action Coding System (FACS), by Ekman and Friesen (1978) in their seminal research on the facial expression of human emotion.

The scan patterns outlined above describe the typical fixations of adult Western Caucasians. Several studies have revealed group differences across cultures in the facial information processed to recognize several of the classically studied emotions of fear, anger, disgust, happiness, sadness, and surprise (Jack et al., 2009, 2012). Broadly, these studies reveal that due to differences in the information processed from the face, East Asian observers show poorer performance in the recognition of fear and disgust in comparison with Western Caucasian observers. Further group differences in scan patterns for emotion recognition have also been established between healthy adult and clinical populations. Such studies show, similar to findings of cultural differences, that inattention to certain features of the face drives deficits in emotion recognition. For example, poorer performance in fear recognition for patients with bilateral amygdala damage compared with healthy controls has been linked to a lack of attention to the eye region during the processing of fear expressions (Adolphs et al., 1994). Here, we aimed to establish how perceptual strategies in emotion recognition change across development, from early childhood up to adulthood, by identifying which information from the face is processed at which stage of development and at which age these strategies mature to become most similar to those of adults.

Infant and child eye movement studies of emotion recognition are very limited in number, with slightly more studies directed toward understanding the development of general face processing abilities. Behavioral studies of emotion recognition in infants have established that by 7 months of age infants can discriminate between basic facial expressions of emotion (e.g., Barrera & Maurer, 1981; Field et al., 1982; Geangu et al., 2016; Serrano et al., 1992). The first study to examine the scan patterns of infants using several different emotional expressions within the same paradigm revealed that infants' scanning behavior varies according to the expression observed (Hunnius et al., 2011). Following on from an earlier event-related potential study that established an enhancement in 3-month-old infants' attention toward fearful versus neutral faces (Hoehl & Striano, 2010), Hunnius et al. (2011) investigated scanning behavior toward threat-related versus non-threat-related emotional expressions. Overall, scanning behavior in 4-month-old infants, 7-month-old infants, and adults toward threat-related emotional expressions showed an avoidant looking pattern with reduced dwell times and fewer fixations to the inner features of the face. However, only adults showed greater eye contact avoidance when looking at threat-related emotional expressions. The authors propose that this result indicates a general avoidant reaction toward threatening facial expressions is present from early life (but for alternative findings, see Bayet et al., 2017), whereas eye contact avoidance appears to be a learned response to social threat that develops later (Hunnius et al., 2011).

In contrast, an earlier study investigating the scanning behavior of 7-month-old infants for fewer expressions—fear, happy, and neutral—found no overall differences in the scan patterns across the emotions studied. and found that infants were slower to disengage attention from fearful faces (Peltola et al., 2009). However, similar to Hunnius et al. (2011), overall the infants scanned the eye region more than other areas of the face when viewing emotional expressions. Using alternative eye-tracking measures with 14-month-old infants also viewing fearful, happy, and neutral faces, Gredebäck et al. (2012) found that scan patterns did differ according to the expression viewed, the familiarity of the face, and the infants' experience of parental leave (i.e., whether the infants had primarily been at home with their mother or with both parents). In this way, the study showed for the first time that infants' everyday interaction with their parents influences their perception of emotional expressions. Taken together, with the limited number of infant eye-tracking studies available and some of those with equivocal results, more studies are necessary to draw any firm conclusions about scanning behavior in infants when processing emotional expressions. A tendency toward differential scan patterns for different emotions, as well as an early preference to fixate the eye region, has been shown.

To the best of our knowledge, only one study has examined the development of eye movement strategies in healthy school-aged children during facial expression recognition (Naruse et al., 2013). Two further studies have recorded children's eye movements while examining expressive faces, but there was no task (only passive viewing) and the studies' aims did not address the development of expression recognition, rather face processing in general, and attentional biases in children of mothers with major depressive disorder (Meaux et al., 2014; Owens et al., 2015). A third study similarly did not address the development of eye movement strategies across age groups but aimed to establish whether training-related improvements in the recognition of happy, sad, and fear expressions are facilitated by changes in eye movement behavior in 9-year-old children and adults (Pollux et al., 2014). As predicted, training-related improvements in recognition of all three expressions for the 9-year-old child group were shown to correspond with changes in gaze strategy, with more fixations being directed toward the eyes for all expressions after training, resulting in a more adult-like strategy. No gaze instructions were given during the training sessions, suggesting that the changes in gaze strategies resulting in greater recognition accuracy were a result of increased exposure to these expressions, demonstrating the effect of experience on emotion processing.

In the single childhood developmental study of eye movements during emotion recognition identified from the literature, Naruse et al. (2013) studied three groups of school-aged children (6–8 years, 8–10 years, and 10–12 years) and six expressions (angry, happy, sad, surprised, disgusted, and neutral) to determine developmental changes in eye movements and accuracy during emotion recognition. Recognition accuracy improved for four of the six expressions (no improvements were shown for angry and happy expressions) between the youngest and older age groups. However, how these behavioral improvements related to changes in gaze strategies was not established given that the analysis of gaze count and fixation time for the established regions of interest (inner face area and the eyes; for a critical appraisal on the use of regions of interest, see Caldara & Miellet, 2011) did not reveal any significant differences between groups for the expressions showing improved accuracy. Overall, the youngest age group showed a shorter gaze time for four of the expressions compared with the middle and older age groups. No adult group was included to approximate the maturity of the different age groups' gaze strategies. Therefore, further investigation is needed to establish how gaze strategies change across development, when strategies become mature, and how strategies relate to performance.

Finally, although Birmingham et al., (2012) did not study eye movements, they used a comparable novel technique to examine developmental changes in attention during facial expression recognition in children aged 5 to 12 years and an adult control group. To measure attentional biases during emotion recognition, the children explored blurred images of faces with a mouse-controlled window of $2 \times 2^{\circ}$ that renders clear the part of the face revealed by the window (i.e., the moving window technique). An overall attentional bias toward the left eye of the face emerged in the oldest child age group of 11- to 12-year-olds and persisted in the adult group. No specific attentional biases for emotion category (happiness, anger, disgust, and fear), age group, and region of interest of the face explored were reported, so how attention changes according to age and emotion category is still to be established. A representation of how biases in attention change across age groups for each emotion is necessary to determine how these changes relate to improvements in recognition accuracy.

As described, there are a limited number of studies examining the perceptual strategies used to achieve emotion recognition across childhood, and none has included all the basic expressions, an adult control group, and a measure of information use. Therefore, we designed an eye movement study to identify how gaze strategies change across development, from early childhood up to adulthood, during recognition of the six basic emotions. A gaze-contingent design was included because natural viewing conditions cannot provide conclusive results on information use given that a visual fixation does not correspond to the exact location of visual attention. A visual fixation identifies foveal but not extrafoveal information use, and therefore the fovea may be fixated on a specific location, however, visual input can at the same time be sampled by peripheral vision (for further details see Caldara et al., 2010; Miellet et al., 2012). Thus, we recorded the natural and gaze-contingent eye movements of eight different developmental groups from 5 years of age up to adulthood during the recognition of fear, anger, disgust, happy, sad, and surprise expressions and used *i*Map4, a robust data-driven toolbox (Lao et al., 2017), to map the ocular strategy used by each age group to recognize each emotion.

The *i*Map4 toolbox uses the raw fixation locations and durations of eye movements recorded during the emotion recognition task to identify which areas of the face were significantly fixated for each emotional expression and age group to map the fixation strategy. By not defining regions of interest and using only the raw fixation locations and durations for the eye movement analysis, the approach is data driven. Comparisons across fixation strategies for each age group and emotion can then be made to establish whether different areas of the face were fixated across groups and to further identify any age-related changes in strategies for each emotion. If improvements in accuracy across age groups coincide with changes in gaze strategies, the efficiency of the strategies can be deemed superior. In line with previous developmental findings (e.g., Gao & Maurer, 2010; Rodger et al., 2015, 2018; Thomas et al. 2007), we expected that the adult group would have the highest accuracy levels across emotion categories (except happiness and fear, for which performance is frequently comparable between adults and younger age groups) and that the youngest developmental age group would have the lowest levels of recognition accuracy. Using a novel approach, we also aimed to establish at which age the perceptual strategies for emotion recognition become most similar to those of the adult group.

Method

Participants

A total of 128 participants of eight different age groups took part in the study. The age groups, each composed of 16 participants, were defined as follows: 5- to 6-year-olds (*M* = 6 years 3 months; 7 female); 7- to 8-year-olds (*M* = 8 years 1 month; 11 female); 9- to 10-year-olds (*M* = 10 years 1 month; 9 female); 11- to 12-year-olds (*M* = 11 years 11 months; 10 female); 13- to 14-year-olds (*M* = 14 years 1 month; 12 female); 15- to 16-year-olds (*M* = 15 years 9 months; 14 female); 17- to 18-year-olds (*M* = 18 years 5 months, 10 female); adults (*M* = 22 years; 8 female). The sample size was based on previous eye-tracking studies (Blais et al., 2008, 2017; Kelly et al., 2011; Naruse et al., 2013; Pollux et al., 2014; Yitzhak et al., 2022). Three previous developmental eye-tracking studies included samples of 14 or 16 participants per age group (Kelly et al, 2011; Naruse et al, 2013; Pollux et al., 2014). We aimed to have 20 participants per age group in our study, however due to a large amount of noise in 4 of the youngest age group participants' data (the 5- to 6-year-old group), the sample was reduced to 16 participants per age group.

Children were recruited from local schools and parental consent was obtained for all children under 16 years of age who participated in the study. Adults were recruited from the University of Fribourg, and students received experimental time points for participation (students are obliged to participate in a set number of hours of experiments per year). The study was approved by the Department of Psychology ethics committee at the University of Fribourg.

Stimulus and apparatus

A total of 60 gray-scale images (706 $\times$ 706 pixels) were used from the Karolinska Directed Emotional Faces (KDEF) database (Lundqvist et al., 1998), comprising 10 distinct identities (5 female) each displaying six facial expressions (fear, anger, disgust, happiness, sadness, and surprise). Images were cropped around the face to remove distinctive hairstyles using Adobe Photoshop and were aligned along the eyes and mouth using Psychomorph software (Tiddeman et al., 2001). The images were normalized for contrast and luminance using the SHINE (spectrum, histogram, and intensity normalization and equalization) toolbox (Willenbockel et al., 2010) with MATLAB 7.10.0 and were displayed on a 1920 $\times$ 1080 gray background, subtending 14.2 $\times$ 14.2° visual angle, at a distance of 70 cm to simulate a natural viewing distance during social interaction (Hall, 1966). The stimuli were presented on a Dell Professional P2212H monitor using the Psychophysics toolbox (PTB-3) and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen et al., 2002) with MATLAB 7.10.0. The face images were displayed at random locations on the screen to prevent anticipatory eye movements.

Eye movements were recorded with an SR Research Desktop-Mount EyeLink 2 K eye tracker at a sampling rate of 1000 Hz, an average gaze position error of 0.25°, a spatial resolution of 0.01°, and a linear output over the range of the monitor. Only the participants' dominant eye was tracked, although viewing was binocular. A chin/forehead rest was used to help keep the position of the head stable. Eye fixations were calibrated manually prior to beginning the experiment using a nine-point fixation calibration and validation procedure (as implemented in the EyeLink API [application programming interface]; see the EyeLink manual for details) to ensure that the eye tracker could discriminate the pupil/corneal reflection accurately in all gaze directions. At the beginning of each trial, participants were asked to fixate a cross in the center of the screen that served as a drift correction of the gaze estimate. If the drift correction was greater than 1°, then the calibration and validation procedure was repeated until an optimal gaze estimate was achieved.

Design

Participants completed two conditions: a natural viewing condition and a gaze-contingent "expanding spotlight" condition. The order of conditions was randomized across participants. A total of 60 expressions were randomly viewed in each condition (6 basic expressions from 10 distinct identities [5 male and 5 female]) beginning with 4 additional expressions as practice trials.

The expanding spotlight technique

The expanding spotlight is a novel gaze-contingent technique developed by Miellet et al. (2013) that allows the precise measurement of the quantity and quality of the information sampled (the information span) at every point on the face that is fixated. The expanding spotlight is a gaze-contingent Gaussian aperture that expands with time (1° every 25 ms) as the observer fixates an area of the stimulus. Each time the participant fixates the stimulus, the gaze-contingent spotlight renders the fixated area of the stimulus clear. The area outside of the spotlight is an average nondiscernible face template, composed of all the stimuli used in the experiment, to allow participants to plan saccades naturally during face viewing. A video of the expanding spotlight technique can be viewed in the online Supplementary material. To begin with, the spotlight is a Gaussian aperture of 2° representing foveal vision. It expands at a rate of 1° per 25 ms at each novel fixation point the participant makes without expansion limit constraints. In this way, the quality and quantity of information needed from a fixated area of the face are established with the spotlight use. Further details on the choice of expansion rate and information visible from the face with various sizes of apertures can be found in Miellet et al. (2013). Here, the expanding spotlight reveals the quantity and quality of information used across development to recognize different facial expressions of emotion. In this way, we can isolate which information and how much information from the fixated areas of the face is used to further characterize gaze strategy changes across the developmental age groups.

Procedure

To familiarize the children with the computerized emotion recognition task, each child was shown six faces expressing the six basic emotions on individually printed sheets of paper and was asked to respond to the question "How do you think this person is feeling?" To facilitate the familiarization task for the youngest children in particular, the first image presented was a happy face. If children were unsure of an emotional expression in the familiarization task, they were told what the expression was. The children were then asked if they could repeat this task by looking at similar images on a computer screen. The above protocol was also used for the adolescent and adult participants except that no familiarization task was used. Each condition began with four practice trials. For the expanding spotlight condition, participants were told that the faces would be slightly blurred but to try to look at them as normally as possible. A fixation cross that served as a drift correction of the gaze estimate was presented in the center of the screen before each expression for 500 ms. A randomly selected stimulus was then presented for 500 ms at a random location on the screen. Children under 12 years of age responded verbally to the expression stimuli, and the experimenter keyed the responses. Participants over 12 years of age also responded verbally to the stimuli to maintain task consistency across age groups and then used the mouse to select one of seven labels (fear, anger, disgust, happiness, sadness, surprise, or don't know) presented on the screen after the stimulus. Children were also told that if they were unsure of an expression, they could say "next" or "don't know." Such responses were then coded as "don't know" by the experimenter. After a response was made, a new face was presented.

Data analyses

Behavioral performance was measured by the number of correctly recognized trials.

Eye movements

Only correct trials were included for the eye movement analysis. Saccades and fixations were determined by a custom algorithm using parameters from the EyeLink software (including a saccade velocity threshold of 30°, a saccade acceleration threshold of $4000°/s^2$, and the merging of fixations that were close spatially and temporally (<50 ms, <0.3°). For each participant, the numbers of fixations and fixation durations were calculated for each trial. The *i*Map4 toolbox was then used to compute statistical fixation distribution maps for each of the eight age groups in the study. The *i*Map4 toolbox is an open-source MATLAB toolbox that uses a data-driven approach and robust statistical analysis to compute and compare fixation distributions across groups. Initially, descriptive statistics for the experimental conditions (developmental age group and emotion category) are calculated, including the mean number of fixations and the mean fixation duration. These measures can be viewed visually by the fixation maps that *i*Map4 produces, with heat spots representing the most densely fixated regions for each condition. The spatial mapping of fixations across age groups and emotion categories is then statistically analyzed using linear mixed modeling to identify significant differences in fixation strategies across groups. Full details of the statistical analysis and processing stream used in *i*Map4 can be found in Lao et al. (2017).

Multivariate distance analysis

To increase the sensitivity of the comparisons of fixation patterns across age groups for each expression, we further performed multivariate statistical analysis on the similarity between the mean fixation patterns of each group with the adult group fixation map as the baseline. We computed the multivariate similarity distance measurement Mahalanobis distance, a test statistic (for details see, e.g., Zapala & Schork, 2012), to analyze the fixation maps between one age group and the adult group for each expression. The Mahalanobis distance is the multivariate generalization of finding how many standard deviations away a point is from the mean of the multivariate distribution. Technically, it is the Euclidean distance after a whitening transformation. Therefore, distances significantly closer to the adult fixation maps represent greater similarity across fixation maps. We then plotted the changes in similarity to further quantify how the mean fixation pattern evolves across age and when it approaches an optimal adult-like pattern.

Results

Behavioral results

The mean recognition scores for the natural viewing and spotlight conditions are shown in Tables 1 and 2, respectively. For both conditions, across all age groups participants were most accurate in recognizing happy expressions and least accurate in recognizing fear expressions. Adults had the highest accuracy for all emotions in both conditions except for fear and surprise in the natural viewing condition. The 17- to 18-year-old group had marginally higher accuracy for fear, and the 11- to 12-year-old group had marginally higher accuracy for surprise; both differences were nonsignificant (p >.05).

For the natural viewing condition, a mixed model analysis of variance (ANOVA) revealed a significant main effect of emotional expression, $F(3.42, 410) = 205$, p =.001 (Greenhouse–Geisser correction),

Table 1
Mean accuracy: Natural viewing condition.

Age group	Mean recognition accuracy (%)					
	Fear	Anger	Disgust	Happy	Sad	Surprise
5–6 years	17.5 (5.0)	73.8 (4.8)	43.8 (9.9)	99.4 (0.6)	80.6 (2.3)	38.1 (9.4)
7–8 years	14.4 (2.8)	74.4 (2.7)	65.6 (7.7)	100.0 (0)	78.1 (3.0)	68.1 (7.5)
9–10 years	23.1 (5.4)	81.3 (4.2)	56.3 (8.3)	99.4 (0.6)	76.3 (3.3)	75.6 (4.6)
11–12 years	14.4 (3.4)	81.3 (2.0)	80.0 (3.3)	99.4 (0.6)	80.6 (3.3)	88.8 (2.6)
13–14 years	25.6 (4.6)	76.3 (4.3)	75.6 (5.0)	98.8 (0.8)	76.3 (4.5)	80.0 (3.9)
15–16 years	38.8 (6.4)	79.4 (3.2)	68.8 (4.5)	100.0 (0)	77.5 (5.6)	86.3 (2.7)
17–18 years	51.9 (5.6)	73.8 (3.5)	83.8 (4.2)	98.1 (1.3)	76.3 (5.5)	83.1 (3.9)
Adults	50.6 (7.5)	86.3 (2.2)	92.5 (1.7)	100.0 (0)	82.5 (2.9)	85.6 (4.0)

Note. Standard errors of the mean are shown in parentheses.

Table 2
Mean accuracy: Spotlight viewing condition.

Age group	Mean recognition accuracy (%)					
	Fear	Anger	Disgust	Happy	Sad	Surprise
5–6 years	24.4 (5.8)	72.5 (5.2)	53.8 (10.0)	99.4 (0.6)	76.3 (6.2)	53.1 (9.1)
7–8 years	16.9 (5.4)	76.9 (3.0)	67.5 (7.8)	97.5 (1.9)	84.4 (3.9)	71.9 (7.4)
9–10 years	24.4 (5.8)	70.0 (3.2)	56.3 (8.9)	98.1 (1.0)	67.5 (7.8)	69.4 (5.2)
11–12 years	22.5 (4.6)	77.5 (3.9)	82.5 (5.1)	99.4 (0.6)	76.9 (4.0)	86.3 (3.5)
13–14 years	27.5 (4.6)	73.1 (3.9)	80.6 (5.6)	98.1 (1.3)	68.8 (3.8)	86.3 (2.9)
15–16 years	36.9 (5.4)	75.0 (3.4)	65.0 (5.3)	97.5 (1.4)	75.0 (4.1)	86.3 (3.0)
17–18 years	36.3 (4.5)	77.5 (2.8)	78.8 (4.0)	98.1 (1.3)	81.9 (3.8)	76.3 (4.5)
Adults	48.8 (6.3)	80.6 (4.0)	91.3 (1.8)	98.8 (0.8)	84.4 (3.5)	95.0 (1.8)

Note. Standard errors of the mean are shown in parentheses.

a main effect of age group, $F(7, 383) = 16.25$, $p = .001$, and a significant interaction between emotional expression and age group, $F(23.93, 1985) = 4.49$, $p = .001$. The Bonferroni post hoc comparisons for the expression by age group interaction are reported in Table 3. The interaction was mainly driven by the adult and 17- to 18-year-old groups showing significantly greater recognition accuracy than the younger age groups for the expressions of fear and disgust and by the youngest age group having significantly poorer accuracy for surprise than all the other age groups. Mann–Whitney U tests showed that there were no significant differences in recognition scores between male and female participants for any of the age groups: female ($Mdn = 38$) and male ($Mdn = 33$) 5- to 6-year-olds ($U = 36$, $p > .01$); female ($Mdn = 41$) and male ($Mdn = 41$) 7- to 8-year-olds ($U = 30$, $p > .01$); female ($Mdn = 42$) and male ($Mdn = 43$) 9- to 10-year-olds ($U = 28.5$, $p > .01$); female ($Mdn = 42.5$) and male ($Mdn = 43$) 11- to 12-year-olds ($U = 30$, $p > .01$); female ($Mdn = 43.5$) and male ($Mdn = 45$) 13- to 14-year-olds ($U = 20.5$, $p > .01$); female ($Mdn = 45$) and male ($Mdn = 44.5$) 15- to 16-year-olds ($U = 14.5$, $p > .01$); female ($Mdn = 45.5$) and male ($Mdn = 44.5$) 17- to 18-year-olds ($U = 32.5$, $p > .01$); female ($Mdn = 51$) and male ($Mdn = 46$) adults ($U = 48$, $p > .01$).

For the spotlight condition (Table 4), the results of a mixed model ANOVA showed significant main effects of emotional expression, $F(3.38, 405.7) = 177$, $p = .001$ (Greenhouse–Geisser correction), and age group, $F(7, 454) = 10.17$, $p = .001$, and showed a significant interaction between age group and emotional expression, $F(23.93, 1985) = 4.49$, $p = .001$. The significant interaction was driven by the adults having a significantly higher level of accuracy than the youngest four age groups for fear recognition and a significantly higher level of accuracy than the 5- to 6-year-old and 9- to 10-year-old groups for disgust and sadness recognition. Finally, the youngest age group had poorer recognition for sadness than most of the older age groups: 11- to 12-year-olds, 13- to 14-year-olds, 15- to 16-year-olds, and adults.

Table 3
Significant Bonferroni post hoc expression–age group interaction comparisons: Natural viewing condition.

Comparison	Mean correct response difference	Standard error	95 % confidence interval	
			Lower bound	Upper bound
Fear				
5–6 vs 17–18 years	−3.44	0.75	−5.84	−1.03
5–6 years vs adults	−3.31	0.75	−5.72	−0.91
7–8 vs15–16 years	−2.44	0.75	−4.84	−0.03
7–8 vs 17–18 years	−3.75	0.75	−6.15	−1.35
7–8 years vs adults	−3.62	0.75	−6.03	−1.22
9–10 vs 17–18 years	−2.87	0.75	−5.28	−0.47
9–10 years vs adults	−2.75	0.75	−5.15	−.035
11–12 vs15–16 years	−2.44	0.75	−4.84	−0.03
11–12 vs 17–18 years	−3.75	0.75	−6.15	−1.35
11–12 years vs adults	−3.62	0.75	−6.03	−1.22
13–14 vs 17–18 years	−2.62	0.75	−5.03	−0.22
13–14 years vs adults	−2.50	0.75	−4.90	−0.10
Disgust				
5–6 vs 11–12 years	−3.62	0.87	−6.41	−0.84
5–6 vs 13–14 years	−3.19	0.87	−5.97	−0.40
5–6 vs 17–18 years	−4.00	0.87	−6.79	−1.21
5–6 years vs adults	−4.87	0.87	−7.66	−2.09
9–10 years vs adults	−3.62	0.87	−6.41	−0.84
Surprise				
5–6 vs 7–8 years	−3.00	0.75	−5.41	−0.60
5–6 vs 9–10 years	−3.75	0.75	−6.16	−1.34
5–6 vs 11–12 years	−5.06	0.75	−7.47	−2.65
5–6 vs 13–14 years	−4.19	0.75	−6.60	−1.78
5–6 vs 15–16 years	−4.81	0.75	−7.22	−2.40
5–6 vs 17–18 years	−4.50	0.75	−6.91	−2.09
5–6 years vs adults	−4.75	0.75	−7.16	−2.34

Table 4
Significant Bonferroni post hoc expression–age group interaction comparisons: Spotlight viewing condition.

Comparison	Mean correct response difference	Standard error	95 % confidence interval	
			Lower bound	Upper bound
Fear				
Adults vs 5–6 years	2.44	0.75	0.02	4.86
Adults vs 7–8 years	3.19	0.75	0.77	5.61
Adults vs 9–10 years	2.48	0.75	0.02	4.86
Adults vs 11–12 years	2.62	0.75	0.20	5.04
Disgust				
Adults vs 5–6 years	3.75	0.94	0.75	6.75
Adults vs 9–10 years	3.50	0.94	0.50	6.50
Sadness				
5–6 vs 11–12 years	−3.31	0.74	−5.68	−0.95
5–6 vs 13–14 years	−3.31	0.74	−5.68	−0.95
5–6 vs 15–16 years	−3.31	0.74	−5.68	−0.95
5–6 years vs adults	−4.19	0.74	−6.55	−1.82
9–10 years vs adults	−2.56	0.74	−4.92	−0.20

Eye movement results

Mean number of fixations and mean fixation durations across age groups

Tables 5 and 6 show the mean numbers of fixations and fixation durations, respectively, across age groups and emotion categories for correct trials in the natural viewing condition. The youngest age group tended to have the highest mean number of fixations across age groups and emotion categories,

Table 5
Mean numbers of fixations by age group and emotional expression: Natural viewing condition.

	Mean number of fixations					
	Fear	Anger	Disgust	Happy	Sad	Surprise
5–6 years	23 (13)	20 (12)	29 (12)	16 (11)	20 (15)	20 (16)
7–8 years	22 (10)	18 (11)	15 (8)	14 (8)	17 (11)	17 (10)
9–10 years	22 (19)	17 (9)	17 (8)	13 (7)	15 (9)	16 (8)
11–12 years	18 (8)	15 (8)	15 (10)	11 (6)	15 (10)	15 (7)
13–14 years	22 (17)	16 (9)	16 (9)	14 (8)	19 (12)	17 (10)
15–16 years	17 (12)	15 (10)	16 (10)	12 (9)	16 (10)	14 (9)
17–18 years	22 (15)	19 (17)	21 (19)	15 (14)	20 (14)	19 (17)
Adults	15 (15)	15 (13)	15 (12)	11 (8)	14 (11)	13 (9)

Note. Standard deviations are shown in parentheses.

Table 6
Mean fixation durations by age group and emotional expression: Natural viewing condition.

	Mean fixation duration (ms)					
	Fear	Anger	Disgust	Happy	Sad	Surprise
5–6 years	99 (78)	106 (67)	107 (57)	95 (55)	107 (65)	116 (57)
7–8 years	136 (69)	140 (92)	146 (91)	136 (88)	142 (82)	135 (81)
9–10 years	111 (51)	117 (66)	111 (59)	106 (62)	112 (54)	109 (51)
11–12 years	156 (55)	143 (65)	147 (63)	136 (69)	137 (67)	130 (53)
13–14 years	132 (68)	112 (57)	123 (59)	109 (56)	115 (62)	112 (51)
15–16 years	134 (70)	122 (61)	138 (69)	113 (56)	114 (62)	117 (57)
17–18 years	61 (42)	66 (50)	64 (40)	68 (59)	67 (49)	66 (61)
Adults	104 (79)	89 (66)	98 (71)	83 (57)	104 (76)	89 (68)

Note. Standard deviations are shown in parentheses.

whereas the adult group tended to have the lowest ones. The two oldest age groups (adults and 17- to 18-year-olds) and the youngest age group tended to have the shortest mean fixation durations. Across the emotion categories, happiness had both the lowest mean number of fixations and the shortest mean fixation durations across age groups with the exception of the 17- to 18-year-old group, who had the shortest mean fixation duration for fear. Overall, the 17- to 18-year-old group had the shortest mean fixation durations of all age groups. Statistical analyses of the mean fixation durations per group and emotional expression were then completed using *i*Map4.

Natural viewing mean duration fixation maps and comparisons of age group eye movement strategies per expression using linear mixed modeling

To identify which areas of the face were fixated for the longest duration during recognition of the six emotional expressions across groups, fixation duration maps (shown in Fig. 1 for the natural viewing condition and in Fig. 2 for the spotlight condition) were produced using the *i*Map4 toolbox (Lao et al., 2017). To produce the fixation maps, *i*Map4 projects the mean fixation durations (reported in Table 6) according to their coordinates on to the two-dimensional image stimulus space. In this way, the areas of the face that were fixated for longer durations can be visualized by warmer colored clusters. Fig. 1 shows the mean fixation duration maps for each age group per emotion for the natural viewing condition, which we now discuss.

The mean fixation duration maps for each age group and expression were statistically analyzed using the *i*Map4 toolbox. We fitted linear mixed models (LMMs) and computed pixelwise ANOVAs to compare each age group's strategy with the adult group's strategy to identify any significant differences in the areas of the face that are fixated during emotion recognition. Therefore, for the LMMs the fixation duration (Y) was the response variable and age group (AGE) was the predictor; the observers were considered as a random factor. Therefore, the design model could be expressed as Y ~ AGE + (1|observers).

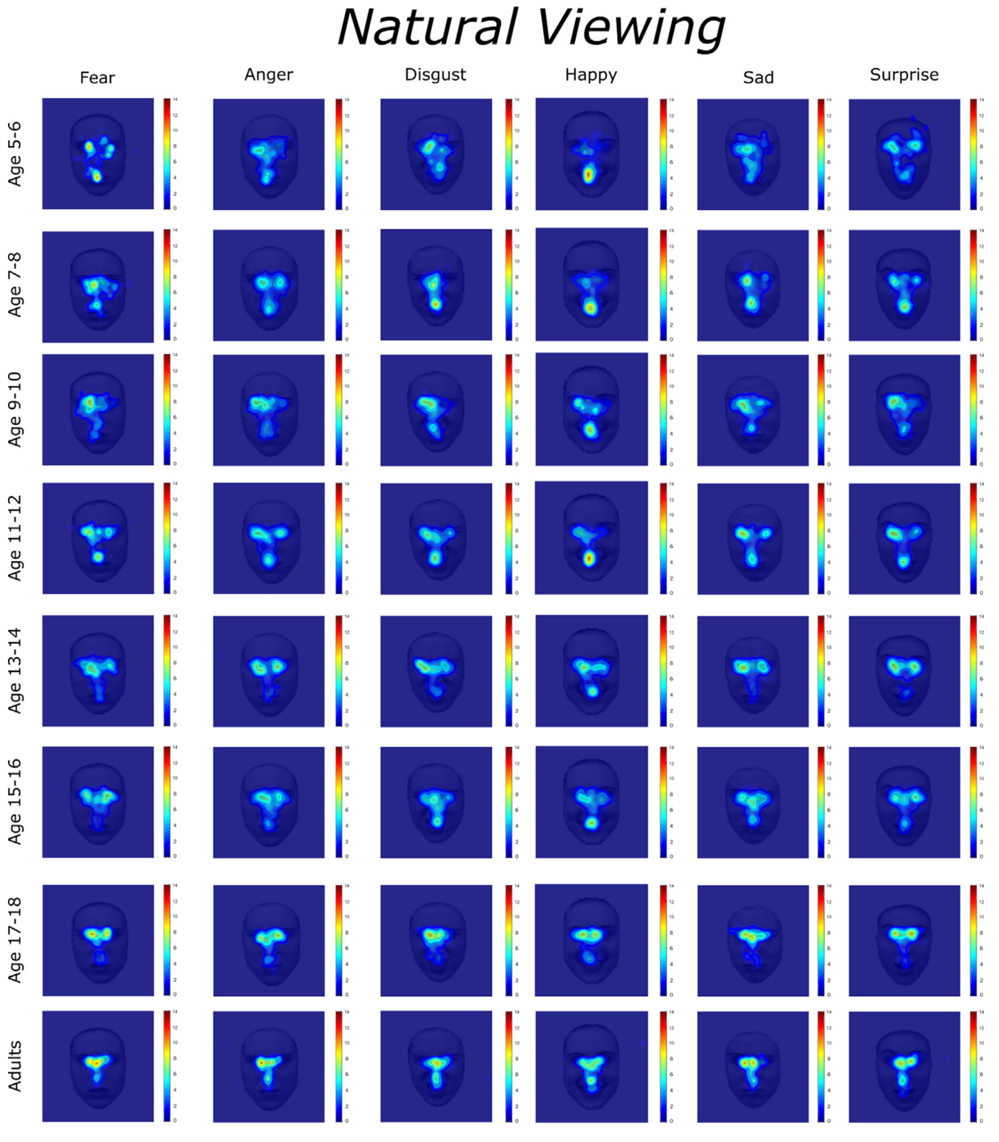

Fig. 1. Natural viewing condition mean fixation duration (ms) color maps for each age group (years) and emotional expression. The color bar represents mean fixation durations from 0 to 14 ms.

Age groups with less significantly different fixated areas of the face were assumed to be more similar to the adult group's strategy for a given expression. Full details of the statistical analysis and processing stream used in *i*Map4 can be found in Lao et al. (2017).

Fear. Across age groups, the mean duration fixation maps show that there was a tendency to fixate the left eye of the face during the recognition of fear expressions (Fig. 1). As well as fixating the left eye, there was some variation from this strategy in several age groups, with the 7- to 8-year-old and 11- to 12-year-old groups also fixating the mouth and the 15- to 16-year-old group also fixating the right eye.

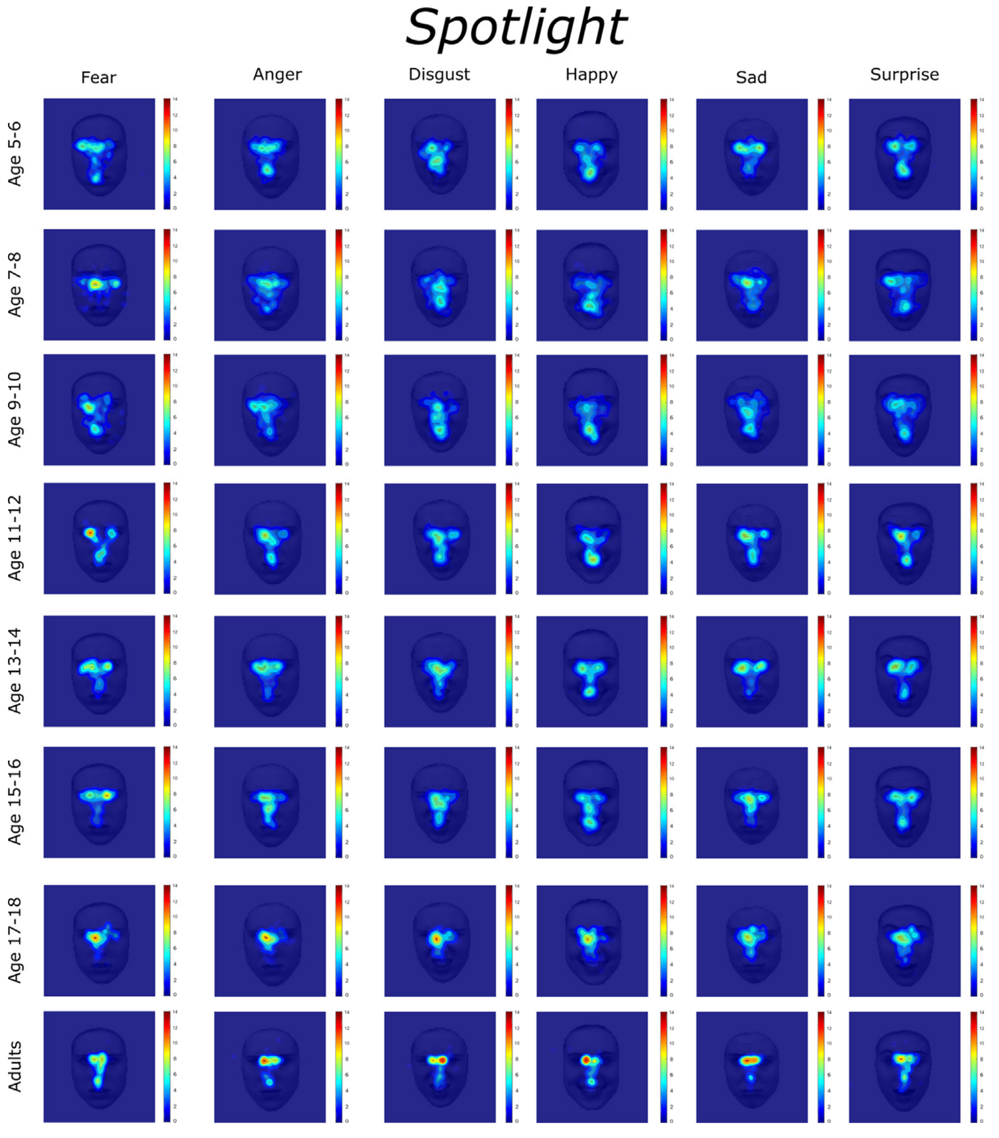

Fig. 2. Spotlight viewing condition mean fixation duration (ms) color maps for each age group (years) and emotional expression. The color bar represents mean fixation durations from 0 to 14 ms.

To statistically compare the differences between each age group's mean fixation durations and the adult group's strategy for fear recognition, we performed a pixelwise LMM using *i*Map4. No significant differences were found between each age group's fixation biases and the adult group's fixation biases for fear.

Anger. During recognition of anger (Fig. 1), there was a tendency across groups to fixate the eyes or left eye, with some minimal fixations also being made to the mouth region for many groups. Again, differences in fixation strategies for several groups were also apparent, with older age groups showing more fixations to both eyes.

The LMM analysis revealed no significant differences between each age group's mean fixation durations and the adult group's mean fixation durations for anger recognition.

Disgust. For the disgust expression, the ocular strategies varied across age groups. The youngest age groups fixated the mouth and left eye more predominantly, and gradually the older age groups (from 13–14 years) fixated more centrally the nasion area between the eyes (Fig. 1).

The results from the LMM revealed no main effects of age. Therefore, there were no significant differences between each age group's mean fixation durations and the adult group's mean fixation durations for disgust recognition.

Happiness. For recognition of happiness, the mouth region was fixated across all groups, and the left eye was also fixated in the younger age groups and both eyes in the older age groups (Fig. 1).

Again, no main effects or significant interaction were found for the LMM comparisons. Therefore, each age group's mean fixation durations did not differ significantly from the adult group's mean fixation durations for happiness recognition.

Sadness. The fixation strategies during sadness recognition were relatively distinct across age groups, although the majority of groups fixated the left eye region (Fig. 1). Overall, the eye region was fixated more than the mouth for all age groups except the 7- to 8-year-olds, who showed predominant fixations to both the left eye and mouth.

The LMM analysis did not reveal any significant differences between each age group's mean fixation strategy and the adult group's mean fixation strategy for sadness recognition.

Surprise. The fixation strategies of the four youngest groups for recognizing surprise expressions were concentrated toward the mouth and the left eye or both eyes (Fig. 1). The older age groups tended to focus more on both eyes.

The LMM comparing each age group's mean fixation duration strategy with the adult group's mean fixation duration strategy revealed no significant differences for surprise recognition.

Age group eye movement strategy comparisons by multivariate distance analysis

The LMM analysis of each age group's strategies for expression recognition and the adult group's strategy did not reveal any significant differences in fixation patterns. To increase the sensitivity of the comparisons between the age groups' scanning strategies and the adult group's strategy, we implemented a multivariate analysis.

To establish how similar the scan patterns across age groups were, and to identify which age groups' strategies were most similar to the adults' mature strategy, we computed a multivariate distance measure (the Mahalanobis distance) between each age group's mean fixation duration maps and the adult group's mean fixation duration maps. To illustrate the results of the multivariate distance computation, we plotted each age group's similarity index (to the adult group) for both the natural viewing and spotlight conditions alongside the behavioral performance for these conditions. Below we describe the results for each expression in the natural viewing condition.

Fear. The multivariate distance analysis identified the 11- to 12-year-old group as the group with the strategy that most differed from the adult group's strategy. This divergence in strategy is illustrated in the plot where similarity dips to the lowest point for this age group (Fig. 3). Beyond 11 and 12 years of age, the older age groups showed an upward trend in similarity to the adult group's strategy, with the 17- to 18-year-olds showing the highest similarity to the adults in their strategy for fear recognition.

Anger. For anger recognition, the 9- to 10-year-olds' strategy was the most dissimilar from the adults' strategy. Again, there was an upward trend for the older age groups to have greater similarity to the adult group's strategy. The 17- to 18-year-olds' strategy again had the highest similarity to the adults' strategy.

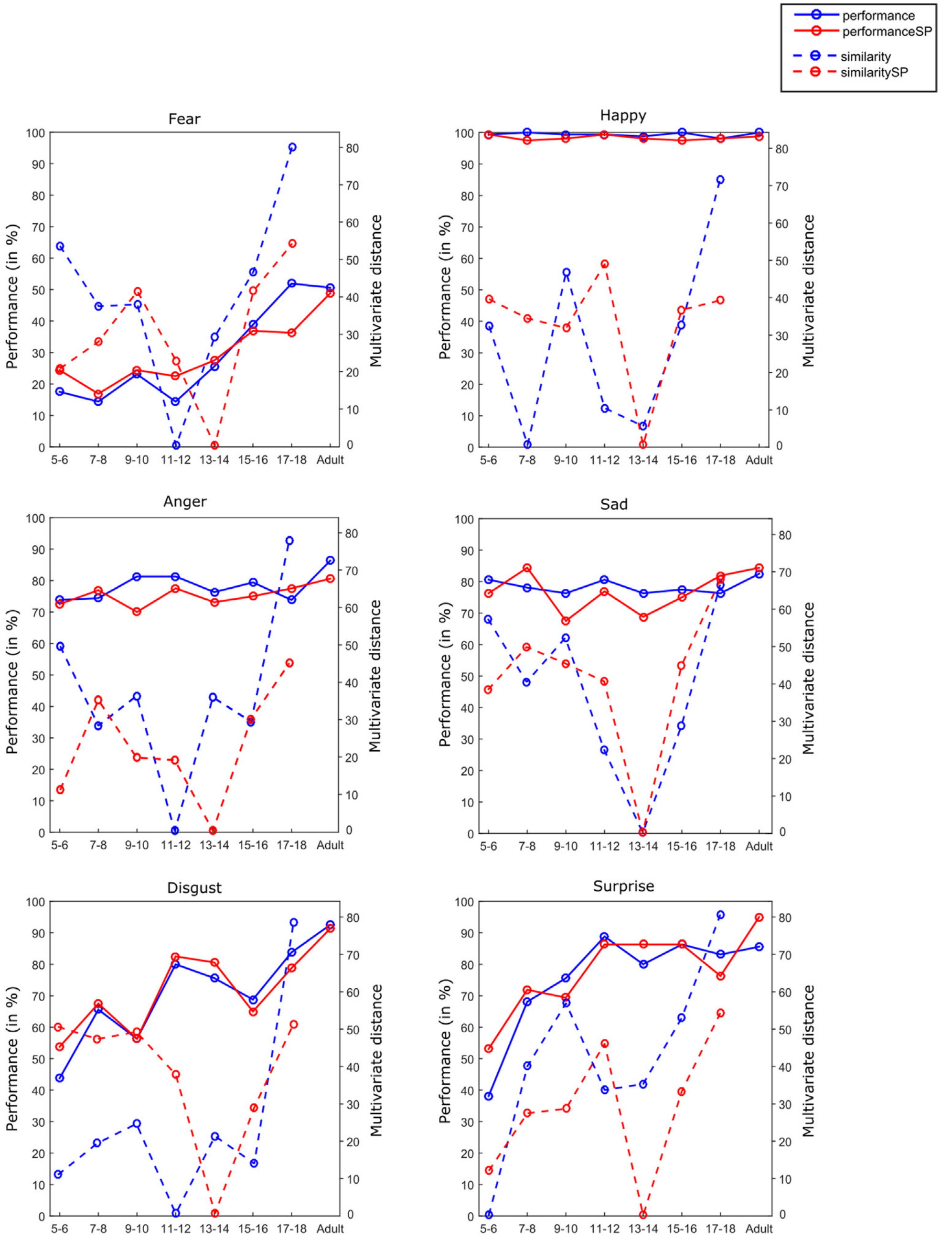

Fig. 3. Multivariate distance analysis and accuracy performance plots. Results for the natural viewing condition are shown in blue, and results for the spotlight (SP) condition are shown in red. Dotted lines plot the multivariate distance (right *y* axis) for each age group compared with the adult group. Straight lines plot the mean recognition accuracy percentage (left *y* axis) of each age group. The multivariate distance was scaled from 0 to 100 to make it comparable across emotions, with 0 being the furthest in similarity from the adult fixation map and 100 being the closest in similarity. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.).

Disgust. Multivariate distance analysis determined that the 11- to 12-year-olds' strategy was the most distinct from the adults' strategy for disgust recognition (Fig. 3). From 13 to 14 years of age, strategies became increasingly similar to that of the adults, with a slight dip in similarity for the 15- to 16-year-olds. The 17- to 18-year-old group showed the greatest similarity to the adult group.

Happiness. The 13- to 14-year-old group was the most dissimilar from the adult group for happiness recognition, with strategies becoming more similar to the adults after this age and the 17- to 18-year-old group again having the most similar strategy to the adult group (Fig. 3).

Sadness. The 13- to 14-year-olds had the least similar strategy to the adults (Fig. 3). After 13 to 14 years of age, the strategies increased in similarity to the adults' strategy, with the 17- to 18-year-olds once again being most similar to the adults.

Surprise. Similar to fear, anger, and disgust expressions, similarity in strategies to the adult group increased from 11 to 12 years of age, with the 17- to 18-year-olds again showing the greatest similarity in strategy to the adults.

Comparison of eye movement strategies across emotional expressions (for all age groups collapsed together)

The results from the LMM analysis showed that there were no significant differences between each age group and the adult group's fixation strategies for each of the emotional expressions tested. Therefore, we decided to verify whether differences in face scanning between each category of emotional expression could be identified as they have been in previous studies, which would require collapsing the age group data. Before collapsing the age groups, we first ensured that there were no significant differences between fixation strategies for each of the expressions for each age group. To do this, for each participant we compared the mean fixation duration maps of each emotion by calculating the Euclidean distance (L^2). We then fitted the obtained L^2 values using a linear regression with age group as a predictor (Fig. 4). No significant differences between the fixation strategies of the expressions were found across groups except for the comparison between fear and surprise in the natural viewing condition. Because no significant differences were found between expressions for each age group, we collapsed the groups to analyze fixation strategies between each of the expressions.

We compared the fixation strategies between each of the expressions with *i*Map4 using LMMs. These analyses revealed significant differences in the scanning patterns between many of the emotional expressions for both the natural viewing and spotlight conditions, as shown in Fig. 5. The *p* values for the clusters illustrating the significant differences between expressions are provided in the Supplementary material.

For both the natural viewing and spotlight conditions, differences in recognition fixation strategies were largely between the same expressions. Fear expressions differed from disgust expressions because the nose area was more significantly fixated for disgust, and in the spotlight condition the left eye was also more significantly fixated for fear. Fear and happiness differed in both conditions because the eyes were more significantly fixated for fear as opposed to the mouth for happiness. Anger and disgust differed because the nose was more significantly fixated for disgust as opposed to the eyes for anger, the left eye in particular for the natural condition. Anger and happiness differed similarly to anger and disgust, with fixations to the mouth for disgust, the eyes for anger, and the left eye in particular for the natural viewing condition. Disgust differed significantly from happy, sad, and surprise expressions. For each of these comparisons, the nose area was more significantly fixated for disgust, whereas the mouth was more significantly fixated for happiness in both conditions and for surprise in the natural condition. Both eyes were also more significantly fixated for surprise recognition as opposed to the right eye in particular for sadness. Happiness also differed significantly from sad and surprise expressions in both conditions, with greater fixations made to the mouth and to the eyes for sad and surprise expressions. Finally, sadness and surprise differed significantly in both conditions, with greater fixations to the mouth for surprise and to the nose area for sadness in the natural viewing condition. For the natural viewing condition, one further pair of expressions significantly differed: fear and anger. Lastly, for the spotlight condition, fear and surprise and anger and surprise expressions also differed.

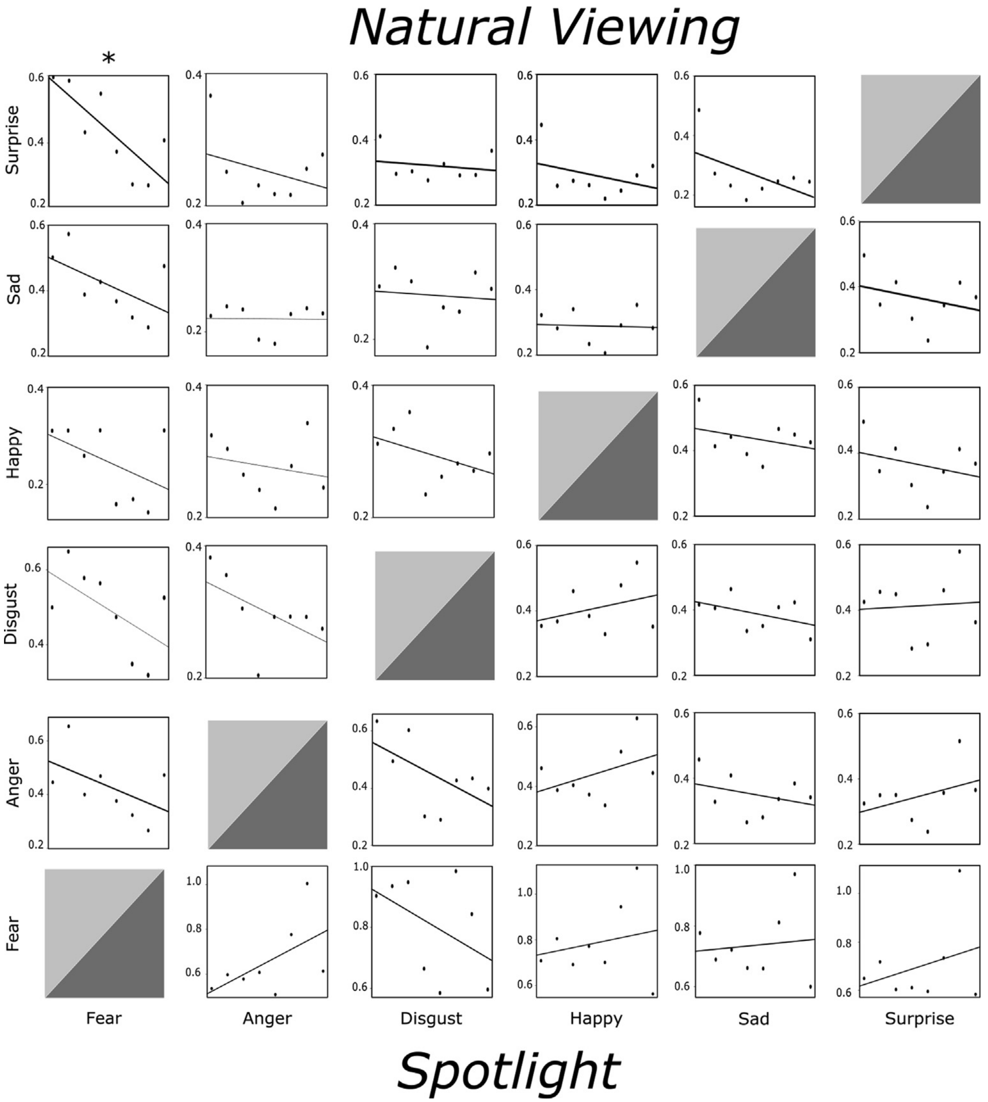

Fig. 4. Linear regression across groups comparing fixation duration differences between each pair of expressions. The L^2 distance was computed for each comparison between expressions for each participant, with the mean L^2 distance of each group represented by a point on the plot (the youngest to oldest groups are represented from left to right). The plots in the upper diagonal represent the comparisons across expressions for the natural viewing condition, and those in the lower diagonal are for the spotlight condition.

Discussion

Our results demonstrate at which age perceptual strategies for emotion recognition become mature, that is, most similar to those of adults. Using a cross-sectional design, eye movements were recorded while children of different developmental age groups, from 5 years up to adulthood, viewed faces expressing the six basic emotions during a recognition task. First, we found that the eye movement strategies of 17- and 18-year-olds, the oldest adolescent group, were most similar to those of adults for recognition of the six emotional expressions tested: fear, anger, disgust, happiness, sadness,

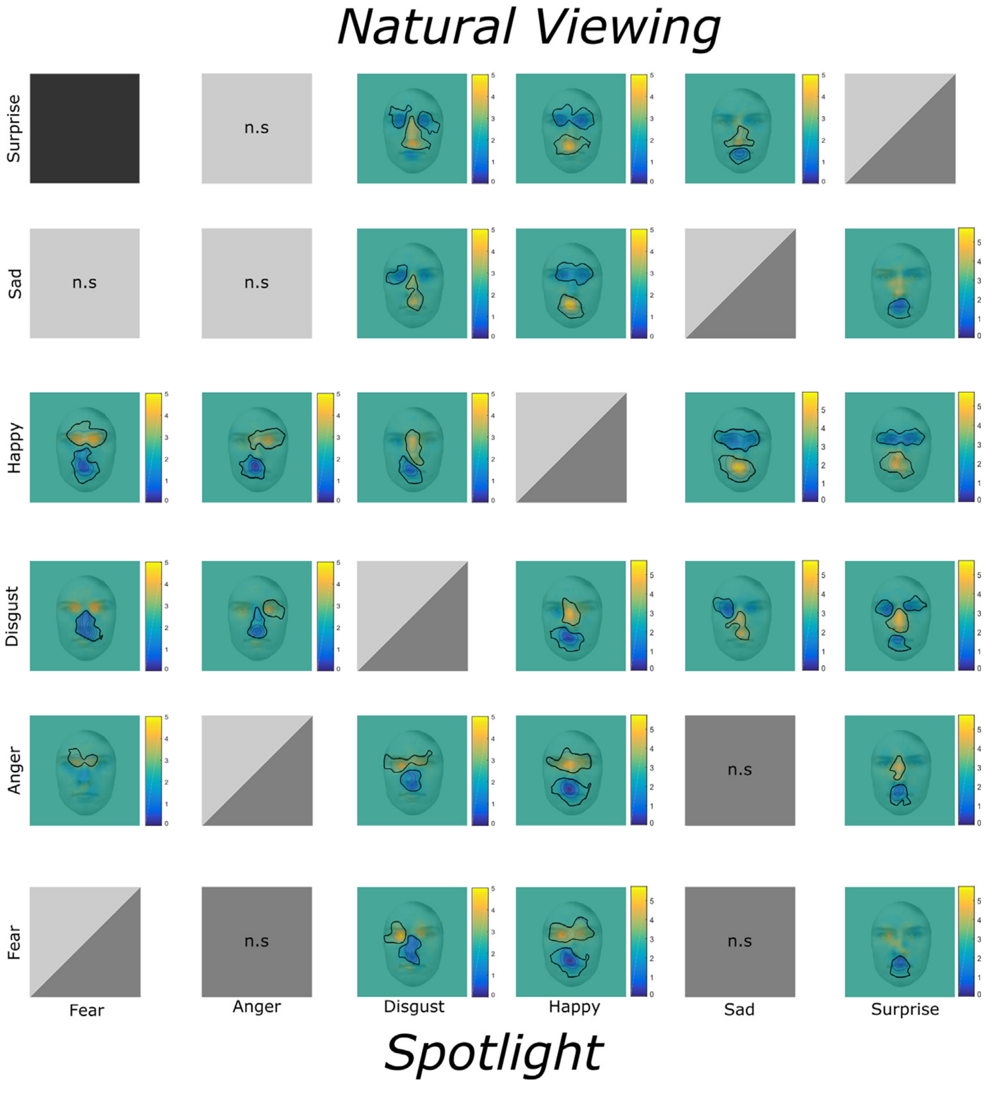

Fig. 5. Mean fixation duration differences between expressions (with age groups collapsed). The clusters outlined in black represent areas of the face that are significantly differently fixated when comparing two expressions. The plots in the upper diagonal represent the comparisons between expressions for the natural viewing condition, and those in the lower diagonal are for the spotlight condition. For the natural viewing condition, the warmer colors represent the clusters fixated that significantly differ for the expression on the *x* axis and the colder colors represent the expression on the *y* axis. For the spotlight condition, the color representation and axes are inverted so that warmer colors illustrate fixation biases for the *y* axis expressions and colder colors illustrate fixation biases for the *x* axis expressions. Gray squares represent no significant differences between the expression comparisons. The black square represents no expression comparison analysis completed because the regression across groups comparing fixation duration differences between surprise and fear was significant. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.).

and surprise. Although this result could be expected, comparisons of the eye movement strategies of each age group with that of the adult group using multivariate distance analysis showed that similarity to the adult strategy did not develop linearly. Notably, we found a developmental dip revealing which age group had the least similar strategy to the adult group for each emotional expression. This dip occurred in the 13- and 14-year-old group for sadness recognition; the 11- and 12-year-old group for fear, anger, disgust, and surprise; and the 7- and 8-year-old group for happiness. Therefore, the dip in strategy similarity to adults did not occur at a uniform age across all expressions, just as recognition performance for each of the expressions does not develop in a uniform way (Gao & Maurer, 2010; Herba & Phillips, 2004; Lawrence et al., 2015; Mancini et al., 2013; Rodger et al., 2015, 2018). Similarly, a recent life span study revealed that emotion recognition evolves non-uniformly throughout the life span (Richoz et al., 2018). Following the developmental dip, strategy similarity to the adult group increased in an upward trend for all expressions except anger, for which there was a slight trough at 15 to 16 years of age, and happiness, for which there was a second marked dip in strategy similarity from 11 to 14 years of age, the ages during which the primary dip was found for all other expressions. A trend toward eye movement strategies becoming more adult-like for facial identity recognition has similarly been shown previously, although the age groups tested were not as young as those tested here and were capped at 12 years of age (Kelly et al., 2011).

Whereas a developmental dip was found for the eye movement strategies of each expression, no such developmental trough was found for recognition performance. Developmental studies of facial identity processing have suggested that a developmental dip occurs in performance at 10 to 14 years of age (e.g., Carey et al., 1980; Flin, 1980; Soppe, 1986). Such a dip is thought to be the result of a change in encoding strategy or of biological changes that occur around the age of puberty (Leder et al., 2003), which could also provide an explanation for the dip in fixation strategy similarity. However, other studies contest such a developmental dip in identity recognition performance (e.g., Diamond et al., 1983; Karayanidis et al., 2009), so the evidence for this is inconsistent. No such U-shaped evolution in performance has been reported for facial emotion processing, a finding that our results replicate.

Regardless of the findings debated for facial identity, the developmental dip found here during early to mid-adolescence might relate to a reorganization of the face processing system resulting from the ability to learn and decode more subtle expression signals, which is typical of more adult-like social interactions. An earlier study indicates that the perceptual representation of emotional expressions becomes more robust throughout adolescence as the response profiles (the sequence of responses across trials) of sad, angry, disgust, and surprise expressions become more similar with age and erroneous responses become less random (Rodger et al., 2018). A potential mechanism underpinning these developments in emotion processing is described by Leppänen and Nelson (2009) in their review of how the developing brain becomes tuned to the social signals of emotional expressions. They highlight the role of experience in the development of emotion recognition by defining an experience-dependent mechanism that is necessary for the development of a mature system. Our perceptual representations of facial expressions are initially coarsely specified and develop into a mature system with adult-like specificity only through exposure to species-typical emotional expressions. The experience-dependent nature of facial expression processing has been evidenced by the disruption caused to typical development by species-atypical parenting and social deprivation (e.g., Pollak & Kistler, 2002) and more recently, for example, by the cultural differences found in eye movement strategies during facial expression recognition (Jack et al., 2009; Jack et al., 2012).

The developmental dip in perceptual strategy similarity occurs during early adolescence when, in addition to the onset of puberty and changes in social experiences and the social environment widening to include closer peer relationships, neuroanatomical development also has an important impact on social cognition. Imaging studies of brain regions involved in social cognition during adolescence show that gray matter volume reaches its peak around the onset of puberty and thins out during the remainder of adolescence (Burnett & Blakemore, 2009; Huttenlocher & Dabholkar, 1997; Huttenlocher et al., 1982). Synaptogenesis is thought to cause regional increases in gray matter volume up to the age of puberty, and gray matter thinning throughout the remainder of adolescence is thought to be the result of subsequent synaptic pruning. These developments lead to more finely tuned neural circuits in the social cognitive regions of the brain, in the prefrontal and visual cortices (Burnett & Blakemore, 2009), including the face-sensitive fusiform gyrus (Cohen Kadosh & Johnson, 2007; Golarai et al., 2007; Scherf et al., 2007), with greater responsiveness found in relevant tasks. These developments in the face-sensitive cortices of the brain have led to the conclusion that specialization for face perception develops up to adulthood, so whereas initial biases toward facial expressions are present during early life, there is increasing domain specificity during adolescence up to adulthood (Cohen Kadosh & Johnson, 2007; Golarai et al., 2007; Leppänen & Nelson, 2009; Scherf et al., 2007). This tuning of neural circuits responsible for facial expression processing coupled with the experience-dependent mechanisms necessary for a mature system may account for the U-shaped developmental trajectories found here in perceptual strategies.

In line with previous studies in both the adult and developmental literature, fear was the most difficult expression to recognize (Calder et al., 2003; Gross & Ballif, 1991; Herba & Phillips, 2004; Mancini et al., 2013; Rapcsak et al., 2000; Rodger et al., 2015, 2018; Widen, 2013). In earlier studies, also comprising the six basic emotions, we found that fear has a higher rate of miscategorizations (Rodger et al., 2015, 2018) across age groups compared with other expressions because it is frequently confused with surprise, and therefore performance is affected. Fear is also the most difficult expression for computational models to recognize because, similarly to humans, it is frequently confused with surprise (Calvo & Nummenmaa, 2016). Low recognition performance for fear across age groups in our perceptual study and others suggests that additional information, perhaps across several modalities or of a contextual nature, is required for more accurate recognition of this expression.

Using the *i*Map4 toolbox, we compared the recognition scanning strategy of each age group for each emotional expression with the adult group's scanning strategy to identify which visual information is processed to recognize an emotional expression throughout development. However, we found no significant differences in the strategies between each group and the adult group using the univariate analysis of *i*Map4. Therefore, we initiated a multivariate analysis to increase the sensitivity of comparisons between age groups and to identify which age group had the most similar recognition strategy to the adult group for each expression. In a separate follow-up analysis, we verified whether differences in scanning strategies were present between the emotion categories using *i*Map4 by collapsing the age group data. This analysis showed that, similar to previous eye movement studies with adults (e.g., Jack et al., 2009; Schurgin et al., 2014), there were differences in scanning strategies across expressions (Fig. 4). The fixation strategies for happiness differed significantly from all other expressions, and this difference was driven by the density of fixations to the mouth for happiness recognition in comparison to all other emotions. Fixations for fear differed significantly from those for happiness and anger in that they were focused mainly toward the eyes. Fear and disgust fixations differed due to the greater duration of time spent fixating the nose area for disgust. Disgust also differed from sadness, surprise, and happiness due to more time spent fixating the nose region for this emotion in comparison with the others. Overall, greater time spent looking at the left eye region differentiated the strategy for anger recognition from that of happy and disgust expressions. Finally, strategies for sadness and surprise recognition differed significantly in that more time was spent looking at the mouth for surprise expressions in contrast to the lower nose area for sadness expressions.

Interestingly, the areas of the face described above that were most densely fixated for recognition of the different expressions are comparable to the diagnostic features necessary for accurate recognition of these expressions. Gosselin and Schyns (2001) implemented an original non-eye-tracking technique, the Bubbles response classification technique, to reveal the use of visual information in recognition tasks. Using this technique with a facial expression recognition task, Smith et al. (2005) identified the diagnostic features of the six basic expressions and a neutral expression. Facial feature use during recognition was analyzed across a range of spatial frequencies and distances. The compilation of information use across all frequency bands revealed which features are necessary to recognize an expression. The diagnostic features described are comparable to the facial features that were more densely fixated for each of the expressions described above, for example, the mouth for happiness and surprise, in contrast to the nose region for disgust. A more recent developmental study using the Bubbles technique showed that children aged 6 to 13 years old show similar feature use when categorizing fear, sad, happy, and anger expressions (Ewing et al., 2017). In comparison with the Bubbles technique, the advantage of eye-tracking methods is that fewer trials are necessary to determine feature use and thus they are more adapted to use with children. In contrast to the Bubbles technique with which Smith et al. (2005) identified feature use during recognition of a single expression, feature use in this study was revealed by performing comparisons between the average fixation maps of each of the expressions.

Studies with varying clinical and cultural groups have shown that visual processing of certain areas of the face are indeed necessary for successful emotion recognition. Performance deficits in fear recognition for patients with bilateral amygdala damage compared with healthy controls are attributed to a lack of attention to the eye region during the processing of fear expressions (Adolphs et al., 1994). When such patients were directed to look at the eyes during a recognition task, they were able to recognize expressions of fear, suggesting that patients' deficit lies in the failure to select the diagnostic features of the face for fear recognition rather than an inability to recognize fear itself (Adolphs et al., 2005; for other types of patients who also do not attend to the eye region, see Caldara et al., 2005; Fiset et al., 2017; Richoz et al., 2015). Similarly, cross-cultural studies have shown that East Asian observers' preferential scanning of the eye region as opposed to wider scanning of different facial regions shown by Western Caucasian observers leads to poorer performance in fear and disgust recognition (Jack et al., 2009, 2012). Therefore, inattention to certain features of the face drives deficits in emotion recognition for both healthy and clinical groups. Here, we revealed for the first time the fixation strategies used by children aged 5 years up to adulthood for recognition of the six basic expressions. The current data can be considered as a benchmark for the processing of facial information during facial expression decoding in typically developing children.

As described above, we found a U-shaped curve across development in eye movement strategy similarity to adults, so the scan patterns throughout development are evolving. However, for three of the six basic expressions tested, no significant differences in recognition performance were found despite diverse strategies being used across groups. Therefore, it is difficult to relate strategies to performance with this finding. It is possible that the diagnostic criteria for some expressions are broader than those for others, which is why performance can remain relatively stable across development for these expressions while strategies change. Other studies have shown that the relationship between eye gaze and behavioral performance is not clear. In comparing training effects on fixation strategies for fearful, sad, and happy faces, Pollux et al. (2014) found that across four training sessions children altered their viewing strategies for all three expressions, with more fixations being directed toward the eyes. However, the benefits of training on performance were restricted to a few of the mid-range intensity stimuli for sad and fearful faces, suggesting that the relationship between performance and eye movements is not linear. Furthermore, the training sessions in this study comprised free viewing as opposed to training directed toward the diagnostic features of the face for each expression. In a study of adults, Yitzhak et al. (2022) found no relationship between fixation patterns and recognition performance for dynamic stimuli. However, as described in the limitations of the study, participants viewed the dynamic facial expression stimuli for the entire 6-s duration of the video clips. Given that expressions are recognized rapidly—for example, about 20 ms for happiness and surprise, or 100 to 200 ms for fear and anger (Du & Martinez, 2013), which take the longest to recognize of the basic emotions—the presentation time in the above study means that many fixations that were included in the analyses took place after recognition had occurred and therefore were superfluous to the task. This was recognized as a limitation by the authors of the study, who subsequently critically reviewed a number of eye-tracking studies to further investigate findings related to fixation patterns and recognition performance (Yitzhak et al., 2021). Mixed findings about this relationship were highlighted across cultural, neuropsychological, age, and gender eye-tracking studies. The authors concluded that more complex eye-tracking analyses examining extrafoveal information processing, such as the spotlight analysis here, are necessary to reach a better understanding of the relationship among eye movements, diagnostic information, and performance for both static and dynamic stimuli.

Conclusion

Our results demonstrate for the first time at which age perceptual strategies for emotion recognition become mature. The eye movement strategies of 17- to 18-year-olds, the oldest adolescent group tested, were most similar to adults for recognition of the six basic emotional expressions tested: fear, anger, disgust, happiness, sadness, and surprise. Multivariate statistical analysis showed that similarity to the adult strategy did not develop linearly from 5 years of age up to adulthood. Notably, we found a developmental dip in strategy similarity to adults from 11 to 14 years of age for all expressions except happiness, for which the dip occurred earlier at 7 to 8 years of age. In contrast, no developmental dip was found for recognition performance. The current data can be considered as a benchmark for the processing of facial information during facial expression decoding in typically developing children.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2022.105622.

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