Impact of Mask Use on Face Recognition in Children: An Eye-Tracking Study

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Abstract

We examined the impact of mask use on face recognition in children across early childhood, middle childhood, and early adolescence. While children across the developmental stages were similarly affected in recognition accuracy and eye movement pattern, they differed in the impact on response time and eye movement consistency during two challenging scenarios where the mask conditions during face learning and recognition did not match. As compared with learning and recognizing unmasked faces, when recognizing masked faces learned without a mask on, similar to adults, children in early adolescence had slower responses, whereas younger children did not. When recognizing unmasked faces learned with a mask on, younger children had decreased eye movement consistency, whereas children in early adolescence did not, similar to adults. These findings suggest that children in early and middle childhood have different vulnerability to mask use in society from adolescents and adults, with important implications for age-specific interventions.

Keywords: face recognition; face recognition development; face mask use; eye movements; EMHMM

Introduction

Since the introduction of mask use during the pandemic to protect ourselves from contagious respiratory viruses, issues related to how it may impact our face recognition ability have been raised. Wearing a mask will cover key facial features including the nose and mouth for face recognition, disrupting the processing of the face as a whole (i.e., holistic processing). This disruption may significantly affect face perception and recognition (Fitousi et al., 2021; Gulbetekin, 2021). Indeed, reduction in face matching or recognition performance with partially occluded faces has been consistently found in adults (Carragher & Hancock, 2020). Consistent with this finding, adults showed poorer performance in recognising a masked face than an unmasked face, and in recognising an unmasked face that was learned with a mask on than without (Hsiao, Liao, et al., 2022). Adults also showed a more eyes-focused eye movement pattern and increased eye movement consistency focusing on the eye region when recognizing masked faces than unmasked faces. Interestingly, individual differences in mask effects in eye movement behavior during face recognition are associated with mask effects in face recognition performance. Specifically, when recognizing unmasked faces that were learned with a mask on, a smaller change in eye movement pattern toward the eye region was associated with greater performance impairment. Similarly, when recognizing masked faces that were learned without a mask on, a smaller increase in eye movement consistency was associated with greater performance impairment. These findings suggest that adults may differ in their ability to adjust their eye movement behavior according to mask conditions during face recognition, resulting in different performance.

Indeed, previous research has shown that adults have an observer-specific eye movement pattern for face recognition that persists over time, and a deviation from this visual routine results in suboptimal performance (Kanan et al., 2015; Peterson & Eckstein, 2013). Thus, when encountering masked faces, individuals may differ in cognitive flexibility for altering visual routines accordingly, and those with poor cognitive flexibility to switch strategies during face learning or recognition are vulnerable to the effects of mask use. This is particularly relevant for children since their face recognition is still developing. As compared with adults, children have less consistent eye movement behavior (or higher entropy/lower predictability) during face recognition, and their eye movement consistency increases gradually with age (Hsiao et al., 2020; Hsiao, An, et al., 2022). Since visual routines can enhance discrimination sensitivity to a stimulus through perceptual learning (Nazir & O'Regan, 1990), children's less consistent eye movements suggest their poorer ability to extract diagnostic features, resulting in poorer recognition performance than adults. This prolonged visual routine development is in contrast to the development of perceptual representations of faces, including holistic face processing and face-space representations, which are reported to mature by age 5-7 (Crookes & McKone, 2009). Some other aspects of face processing, such as configural processing, are also found to develop slowly into adolescence (Mondloch et al., 2002). Given the prolonged development, it is likely that children's face recognition processes would be affected by mask use differently from adults.

Consistent with this speculation, Stajduhar et al. (2022) showed that mask use affected children's face recognition memory more than adults'. This finding suggests that as children grow older, their face recognition performance may be affected less by mask use. In addition, since young children have not developed a consistent visual routine for face recognition, they may have a better ability to adaptively change their eye movement behavior according to mask

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conditions, and this ability may decrease with age when they form a more consistent visual routine for face recognition. Thus, their eye movement behavioral change due to mask use may also reduce with increasing age. However, it remains unclear whether there are indeed developmental changes in how children learn and recognize masked faces.

To fill in these research gaps, here we examined whether mask use led to differential impact on performance and eye movement behavior in face recognition across different developmental stages in children, including early childhood aged 4-6, middle childhood aged 8-10, and early adolescence aged 12-14, and whether there were associations between changes in eye movement behavior and changes in performance due to make use. We hypothesized that the effect of mask use on face recognition performance and eye movement behavior might decrease with age, with the age 12-14 group exhibiting more adult-like mask effect as compared with younger age groups. In addition, similar to the findings from adults, mask effects in recognition performance may be associated with mask effects in eye movement behavior.

Method

Participants

We recruited 217 participants from 3 age groups (*M* = 8.90, *SD* = 3.32), consisting of 74 of 4-6 years old (*M* = 5.00, *SD* = 0.81), 67 of 8-10 years old (*M* = 8.88, *SD* = 0.84) and 76 of 12-14 years old (*M* = 12.70, *SD* = 0.81). All participants have normal or corrected-to-normal vision. According to a power analysis ($\alpha = 0.05$, power = 0.8), the required sample size was 42 to test for a within-between interaction in a 2 (mask *vs*. unmask) × 3 (three age groups) mixed ANOVA, assuming a medium effect size $f^2 = 0.25$. A sample size of 61 was needed to acquire a medium effect size ($f^2 = 0.15$, $\alpha = 0.05$, power = 0.8) in a correlation.

Design

The face recognition task consisted of a learning phase and a recognition phase. For the learning phase, the design included one between-subject variable age group (4-6 *vs*. 8-10 *vs*. 12-14 age group) and one within-subject variable mask condition (masked *vs*. unmasked). The dependent variables were eye movement measures, including eye movement pattern, overall entropy, and marginal entropy of the first three fixations, quantified by EMHMM (see the Eye Movement Analysis section for details). For the recognition phase, we manipulated the mask condition during learning (masked *vs*. unmasked) and during recognition (masked *vs*. unmasked) to create four conditions as listed in Table 1. We then examined the effect of mask use in three scenarios, following Hsiao, Liao, et al. (2022): a) Effect of mask use during learning (condition 4 - condition 2); b) effect of mask use during recognition (condition 4 - condition 3); and c) effect of mask use during the whole task (condition 4 - condition 1). In each scenario, similar to the learning phase, the design consisted of a between-subject variable age group, and a within-subject variable mask condition. The dependent measures were recognition performance in discrimination sensitivity d' and RT and eye movement measures. ANOVA was used.

Since children across groups may differ significantly in overall performance level or eye movement behavior, to normalize for this individual difference when examining the effect of mask use, in a separate analysis we calculated the normalized mask effect measure using the equation $\frac{baseline - mask\ condition}{|baseline| + |mask\ condition|}$ for all dependent variables and used one-way ANOVA to directly examine group differences in the normalized mask effect under different phases/scenarios. We then used correlation analyses to examine the association between the normalized mask effects in recognition performance and in eye movement behavior when a significant group difference was observed to better understand its mechanism.

Table 1: Four mask conditions used in the design

	Learning	Recognition
Condition 1	Masked	Masked
Condition 2	Masked	Unmasked
Condition 3	Unmasked	Masked
Condition 4 (baseline)	Unmasked	Unmasked

Materials and Apparatus

The face stimuli used comprised 256 colored frontal-view Asian face images from a database (Hsiao, Liao, et al., 2022). Half were young adult faces, one-fourth were child faces and one-fourth were old adult faces. Within each age group, half were female images. All faces had neutral expressions and were unfamiliar to participants. The images were cropped to show only facial features, with an aligned distance between the centers of the two eyes, and each face subtended a horizontal visual angle of 6°, equivalent to the size of a face under the functional distance for face recognition (~2 m; McKone, 2009).

The face images were randomly divided into the target or foil sets in the recognition task, with an equal number of faces in each gender by age combination. Different mask conditions (masked and unmasked), lighting conditions (yellow and white light), and mask colors (blue and white mask) were created using Adobe Photoshop. The mask, lighting, and mask color conditions were balanced across trials within each block. Participants' eye movements were recorded by an EyeLink Portable Duo eye tracker (SR Research) using the remote mode with a 1000 Hz sampling rate tracking the dominant eye. Default settings for cognitive research were used for data acquisition following Hsiao, Liao, et al. (2022). A response box was used to record behavioral responses from participants. To minimize head movements, a chin rest was set at 60 cm from a 15.6-inch monitor (1024 × 768 pixels). A nine-point calibration procedure was performed before the experiment and whenever the drift check error exceeded 1° of visual angle.

Procedure

In the face recognition task, each trial started with a drift check at the screen center. The experimenter initiated the stimulus presentation when a stable fixation was observed. In the learning phase, participants viewed 16 faces, one at a time for 5000 ms, randomly appearing on the left or right side of the screen, and were asked to remember the faces. During the recognition phase, they were presented with old faces in a different lighting condition and mask color, along with 16 new faces one at a time. They judged whether they had seen the face during the learning phase and responded using a response box. The task consisted of 8 blocks, each with 48 trials (16 trials in the learning phase and 32 trials in the recognition phase) that included four mask conditions (Table 1). Participants were divided into 8 groups, with a Latin square to assign different stimulus sets to counterbalance across the study and recognition phase of the task in the four mask conditions.

Eye Movement Analysis

The Eye Movement analysis with Hidden Markov Models (EMHMM) method was used to analyze eye movement data (Chuk et al., 2014). A participant's eye movement data in each mask condition for the learning and recognition phase was summarized using a hidden Markov model (HMM, a statistical model to describe sequential data) with personalized regions of interest (ROIs) and transition probabilities among the ROIs. Specifically, during the learning phase, we used one HMM to summarize each participant's eye movement data when viewing unmasked faces and another when viewing masked faces. Each participant had two HMMs for unmasked and masked faces respectively. Similarly, for eye movement data during the recognition phase, each participant had four HMMs summarizing four mask conditions in Table 1 respectively. In each HMM, the optimal number of ROIs was determined by the variational Bayesian expectation-maximization algorithm (VBEM; Bishop, 2006) from a preset range of 1 to 5. Following previous studies (e.g., Hsiao et al., 2022; Zheng et al., 2024), we then clustered all individual HMMs to discover representative eye movement patterns A and B using the variational hierarchical expectation–maximization (VHEM) algorithm (Coviello et al., 2014). We quantified each participant's eye movement pattern along the dimension of the two representative eye movement patterns (pattern A and pattern B) using AB scale, calculated as $\frac{L_A - L_B}{|L_A| + |L_B|}$, where L_A and L_B were the log-likelihoods of a participant's data generated by the HMM of Pattern A and Pattern B respectively. A more positive AB scale indicates higher similarity to Pattern A. In addition to AB scale, we examined participants' eye movement consistency using the overall entropy of the HMMs (Hsiao et al., 2021; Liao & Hsiao, 2024; Liu et al., in press). Entropy is a measure of predictability; higher entropy indicates lower consistency (Cover & Thomas, 2006). Previous studies suggested the importance of early fixations in a trial in accounting for face recognition performance than later fixations (Hsiao & Cottrell, 2008; Chuk et al., 2017). Thus, we also measured the marginal entropy of the first three fixations (i.e., consistency of the first three fixation locations) to understand the temporal dynamics of eye movement consistency in different mask conditions across three age groups.

Results

Face Recognition Performance

We examined the effect of mask use on *d'* and RT using three separate 2×3 ANOVAs. On the effect of mask use during learning (Condition 2 masked-unmasked *vs*. baseline unmasked-unmasked; Table 1), the main effect of mask condition was significant in d', *F*(1, 213) = 202.70, *p* < .001[1], η^2_p = .488, but not in RT, *F*(1, 214) = .00, *p* = .962, η^2_p = .000, suggesting that participants had lower *d'* and similar RT when recognizing faces learned with than without a mask on. The main effect of age group was significant in *d'*, *F*(2, 213) = 18.20, *p* < .001, η^2_p = .146, and marginal in RT, *F*(2, 214) = 2.94, *p* = .055, η^2_p = .027, suggesting that younger age groups had lower *d'* and longer RT than older age groups in general. The interaction between mask condition and age group was significant in *d'*, *F*(2, 213) = 12.60, *p* < .001, η^2_p = .106, but not in RT, *F*(2, 214) = 1.79, *p* = .169, η^2_p = .016, showing that the mask effect in *d'* was larger in older than younger children. This age difference in the mask effect became insignificant after we normalized for individual differences in overall performance level. The one-way ANOVA showed that the three age groups did not differ in the normalized mask effect in either *d'*: *F*(2, 106) = .77, *p* = .466, or RT: *F*(2, 133) = 2.30, *p* = .104.

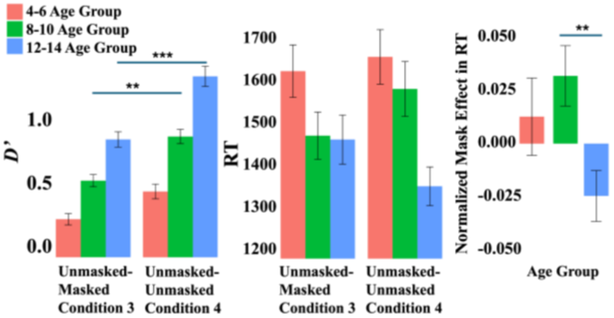

Figure 1: Performance of the three age groups in the scenario of mask use during recognition (Error bars show 1 standard error of the mean, ** $p < .01$, *** $p < .001$)

On the effect of mask use during recognition (unmasked-masked *vs*. unmasked-unmasked), the main effect of mask condition was significant in *d'*, *F*(1, 213) = 52.31, *p* < .001, η^2_p = .197, but not in RT, *F*(1, 214) = .15, *p* = .701, η^2_p = .001 (Figure 1). The main effect of age group was significant in *d'*, *F*(2, 213) = 28.40, *p* < .001, η^2_p = .210, but not in RT, *F*(2, 214) = 2.43, *p* = .090, η^2_p = .022: Younger age groups had lower *d'* than older age groups in general. The interaction between mask condition and age group was significant in

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[1] One participant's response file was missing.

both *d'*, *F*(2, 213) = 2.79, *p* = .064, η^2_p = .026, and RT, *F*(2, 214) = 3.57, *p* = .030, η^2_p = .032. However, the one-way ANOVA on the normalized mask effect in *d'* showed no significant age group effect, *F*(2, 112) = 1.85, *p* = .162. In contrast, the one-way ANOVA on the normalized mask effect in RT consistently showed differential mask effects among the three age groups, *F*(2, 138) = 4.84, *p* = .009. Specifically, the age 12-14 group showed more adult-like behavior (Hsiao, Liao, et al., 2022), responding to masked faces with longer RT than unmasked faces, whereas the age 4-6 and 8-10 group had shorter RT when viewing masked faces than unmasked faces.

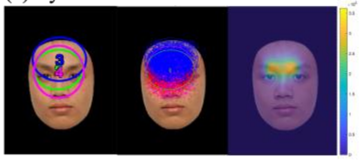
On the effect of mask use in the recognition task (masked-masked *vs.* unmasked-unmasked), the main effect of mask condition was significant in *d'*, *F*(1, 213) = 22.12, *p* < .001, η^2_p = .094, but not in RT, *F*(1, 214) = .08, *p* = .779, η^2_p = .000: Participants had lower *d'* and similar RT when performing the task with masked faces than unmasked face. The main effect of age group was significant in both *d'*, *F*(2, 213) = 34.50, *p* < .001, η^2_p = .245, and RT, *F*(2, 214) = 3.83, *p* = .023, η^2_p = .035: Younger age groups had lower *d'* and longer RT than older age groups in general. The interaction between mask condition and age group was not significant in either *d'*, *F*(2, 213) = .38, *p* = .683, η^2_p = .004, or RT, *F*(2, 214) = .32, *p* = .729, η^2_p = .003. Similarly, the one-way ANOVA on the normalized mask effect showed no significant age group effect.

Eye Movement Behavior During Face Learning

Two representative eye movement patterns during face learning were discovered: eyes-focused (Figure 2a) and nose-focused patterns (Figure 2b). Participants adopting the eyes-focused strategy mainly fixated on the region between the two eyebrows. In contrast, participants adopting the nose-focused strategy mainly fixated on the region around the nose bridge, covering the eye and nose region (red ROI: 59% probability). The two representative HMMs significantly differed according to KL divergence estimates (following Zheng et al., 2024), *F*(1, 432) = 400.40, *p* < .001, η^2_p = .481. Accordingly, here we referred to A-B scale as EN scale (Eyes-Nose scale) to quantify participants' eye movement pattern.

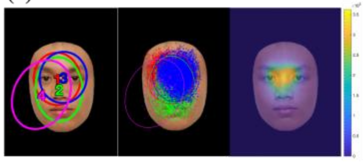
In eye movement behavior, the main effect of mask condition was significant in EN scale, *F*(1, 214) = 240.61, *p* < .001, η^2_p = .529, overall entropy, *F*(1, 214) = 26.42, *p* < .001, η^2_p = .110, marginal entropy of the second fixations, *F*(1, 214) = 5.24, *p* = .023, η^2_p = .024, and marginal entropy of the third fixations, *F*(1, 214) = 5.15, *p* = .024, η^2_p = .023. These results suggested that participants had a more eyes-focused strategy, and more consistent eye movement (lower entropy) when viewing masked than unmasked faces during face learning. The main effect of age group was not observed in EN scale, *F*(1, 214) = .11, *p* = .899, η^2_p = .001, but was significant in entropy, *F*(2, 214) = 12.70, *p* < .001, η^2_p = .106, marginal entropy of the first fixation, *F*(2, 214) = 12.40, *p* < .001, η^2_p = .104, marginal entropy of the second fixation, *F*(2, 214) = 10.20, *p* < .001, η^2_p = .067, and marginal entropy of the third fixations, *F*(2, 214) = 10.30, *p* < .001, η^2_p = .088. This showed that younger age groups had lower eye movement consistency, consistent with Hsiao, An et al. (2022). The interaction between mask condition and age group was not observed in either EN scale or any of the entropy measures. Similarly, the one-way ANOVA on the normalized mask effect showed no significant age group difference in any of the eye movement measures.

(a) Eyes-focused Pattern – Face Learning



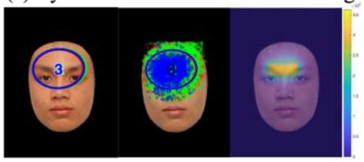
	To 1	To 2	To 3	To 4
Priors	.49	.33	.18	.00
From 1	.53	.46	.01	.01
From 2	.49	.49	.01	.01
From 3	.00	.00	.97	.02
From 4	.24	.23	.10	.43

(b) Nose-focused Pattern – Face Learning



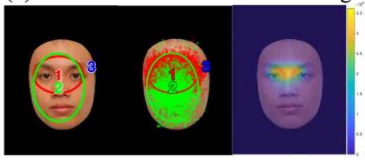
	To 1	To 2	To 3	To 4
Priors	.59	.09	.31	.01
From 1	.95	.04	.01	.00
From 2	.00	1.0	.00	.00
From 3	.00	.01	.99	.00
From 4	.00	.01	.00	1.0

(c) Eyes-focused Pattern – Face Recognition



	To 1	To 2	To 3
Priors	.76	.02	.22
From 1	.33	.54	.14
From 2	.41	.49	.10
From 3	.14	.29	.57

(d) Nose-focused Pattern – Face recognition



	To 1	To 2	To 3
Priors	.93	.06	.00
From 1	.98	.02	.00
From 2	.00	1.0	.00
From 3	.00	.00	1.0

Figure 2: Eyes-focused and nose-focused patterns during face learning and face recognition. Ellipses show ROIs as 2-D Gaussian emissions. Priors show probabilities of the first fixation landing on each ROI and transition matrices show transition probabilities among the ROIs.

Eye Movement Behavior During Face Recognition

Similarly, two representative eye movement patterns during face recognition were discovered: eyes-focused (Figure 2c) and nose-focused patterns (Figure 2d). Participants adopting the eyes-focused strategy mainly fixated on the region between the eyes/eyebrows, whereas those adopting the nose-focused strategy fixated mainly on the nose bridge. The two representative patterns significantly differed according to KL divergence estimates, *F*(1, 865) = 662.05, *p* < .001, η^2_p = .434.

On the effect of mask use during learning, the 2×3 ANOVA showed a main effect of mask condition in EN scale, *F*(1, 213) = 4.31, *p* = .039, η^2_p = .020, overall entropy, *F*(1, 214) = 4.35, *p* = .038, η^2_p = .020, and marginal entropy of the first fixation, *F*(1, 214) = 5.86, *p* = .018, η^2_p = .027. The results suggested that participants had a more eyes-focused eye movement pattern and a less consistent first fixation (higher entropy) when recognizing faces learned with a mask than without a mask on. The main effect of age group was not observed in EN scale or any entropy measures. The interaction between mask condition and age group was not significant in EN scale, and the normalized mask effect in EN scale did not differ between the three age groups. This suggested that the three age groups did not differ in the effect of mask use during learning. In contrast, the interaction between mask condition and age group was significant in marginal entropy of the second fixation, *F*(2, 214) = 3.12, *p* = .046, η^2_p = .028, and marginally significant in overall entropy, *F*(2, 214) = 2.46, *p* = .088, η^2_p = .022, and marginal entropy of the third fixation, *F*(2, 214) = 2.51, *p* = .084, η^2_p = .023. When using the normalized mask effect measure, the age group effect was significant in marginal entropy of the first, *F*(2, 129) = 3.52, *p* = .032, and second fixation, *F*(2, 127) = 3.35, *p* = .038, marginally significant in overall entropy, *F*(2, 129) = 2.63, *p* = .076, but not significant in marginal entropy of the third fixation. In general, the 4-6 age group had higher entropy when viewing an unmasked face that was learned with than without a mask on (Figure 3). In contrast, the 12-14 age group showed more adult-like behavior (Hsiao, Liao, et al., 2022), with no significant difference in entropy when viewing an unmasked face that was learned with or without a mask on.

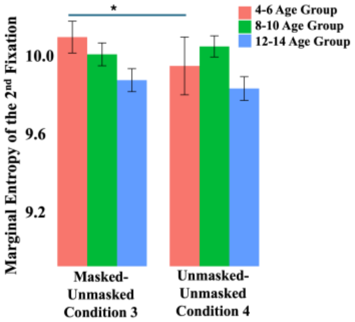


Figure 3: Marginal entropy of the 2nd fixation of the three age groups in the scenario of mask use during learning (error bars show 1 standard error of the mean, * $p < .05$).

On the effect of mask use during recognition, the main effect of mask condition was significant in EN scale, *F*(1, 213) = 162.55, *p* < .001, η^2_p = .433, and in overall entropy, *F*(1, 214) = 3.82, *p* = .052, η^2_p = .018: Participants adopted a more eyes-focused eye movement pattern and more consistent eye gaze (i.e., lower entropy) when recognizing masked than unmasked faces. No other significant effect was observed in either EN scale or any of the entropy measures, or the normalized mask effect. Thus, the effect of mask use during recognition on eye movement during recognition did not differ across the three age groups.

On the effect of mask use in the recognition task, the main effect of mask condition was significant in EN scale, *F*(1, 213) = 120.93, *p* < .001, η^2_p = .362, but not in entropy, *F*(1, 214) = .00, *p* = .986, η^2_p = .000: Participants had more eyes-focused eye movement pattern when performing the task with masked faces than unmasked faces. The main effect of age group was not significant in EN scale, *F*(2, 213) = 2.23, *p* = .110, η^2_p = .020. However, a significant age group effect was observed in overall entropy, *F*(2, 214) = 3.69, *p* = .027, η^2_p = .033, marginal entropy of the first fixation, *F*(2, 214) = 3.61, *p* = .029, η^2_p = .033, second fixation, *F*(2, 214) = 3.60, *p* = .029, η^2_p = .033, and third fixation, *F*(2, 214) = 3.31, *p* = .038, η^2_p = .030, suggesting that younger age groups had less consistent eye gaze (i.e., higher entropy). The interaction between mask condition and age group was not significant in EN scale, and also insignificant in any of the entropy measures. No significant effect was observed in the normalized mask effect measure.

Relationship Between Eye Movement Behavior Change And Performance Change Due To Mask Use

The analysis above showed that the three age groups differed in the mask effect in RT in the scenario of mask use during face recognition, where the age 12-14 group showed more adult-like behavior, spending more time recognizing masked faces than unmasked faces. We examined whether this mask effect in RT was related to the mask effect in eye movement behavior (i.e., EN scale and entropy measures). A marginal correlation between the mask effect in EN scale and the mask effect in RT was observed only in the age 12-14 group, *r*(76) = -.196, *p* =.084: a smaller increase in RT was associated with a larger increase in EN scale. None of the cognitive abilities were associated with the mask effect in RT.

The analysis above also showed that the three age groups differed in the mask effect in marginal entropy of the second fixation when recognizing faces in the scenario of mask use during face learning. We examined whether this mask effect in marginal entropy of the second fixation was related to the mask effect in performance (i.e., *d'* or RT). A correlation between the mask effect in marginal entropy of the second fixation and the mask effect in RT was observed only in the age 12-14 group, *r*(76) = .229, *p* = .047, where an increase in marginal entropy (decrease in consistency) due to mask use was associated with an increase in recognition RT.

Discussion

We examined how mask use affected face recognition performance and eye movement behavior at three different developmental stages: early childhood (4-6 years), middle childhood (8-10 years), and early adolescence (12-14 years). Following previous studies (e.g., Hsiao, Liao, et al., 2022; Tso et al., 2022; Zheng et al., 2023), we considered three different mask use scenarios: during face learning only, during face recognition only, and during both face learning and recognition, We found that mask use impaired face recognition performance in children across all age groups in all mask use scenarios, consistent with previous studies (Hsiao, Liao, et al., 2022; Stajduhar et al., 2022). By using a normalized mask effect measure to account for individual differences in overall performance level, we found no significant age group difference in the normalized mask effect in d' across all mask use scenarios, suggesting that children at different developmental stages were similarly affected by mask use in face recognition performance in *d*'. In contrast, in face recognition RT, we observed age-related differences in the normalized mask effect in the scenario of mask use during face recognition only: Children in early adolescence exhibited a more adult-like behavior, taking longer to recognize masked faces than unmasked faces, whereas children in early or middle childhood showed shorter RTs for masked faces than unmasked faces. A follow-up analysis showed that this mask effect in RT in early adolescence was marginally associated with the mask effect in eye movement pattern as measured in EN scale, with a smaller increase in RT associated with a more eyes-focused eye movement pattern due to mask use. This finding suggests that children in early adolescence may have developed a more consistent visual routine for recognizing regular, unmasked faces and thus needed more time to adjust their eye movement pattern in response to masked faces, and those who were better able to make this eye movement change had less impact on RT. Note that although adults also responded to masked faces with longer RT than unmasked faces, this mask effect in RT was not associated with eye movement pattern change due to mask use. This phenomenon may be related to a better developed visual routine for faces focusing on the eye region in adults as compared with children, although this speculation requires further examinations.

In eye movement behavior, we found that participants had a more eyes-focused eye movement pattern as assessed in EN scale in the masked than unmasked conditions during face learning and all mask use scenarios in face recognition. Nevertheless, no significant age group difference was observed in the normalized mask effects in eye movement pattern. In contrast, in eye movement consistency as measured in entropy, we found that mask use influenced the three age groups differently when recognizing faces in the scenario of mask use during face learning. More specifically, the 4-6 age group had less consistent eye movement when recognizing an unmasked face that was learned with than without a mask on. In contrast, the 12-14 age group showed more adult-like behavior (Hsiao, Liao, et al., 2022), with no significant difference in eye movement consistency when recognizing an unmasked face that was learned either with or without a mask on. This age effect in eye movement consistency was especially well observed in the marginal entropy of the second fixation. A follow-up analysis showed that this mask effect in the marginal entropy of the second fixation in this mask use scenario was associated with the normalized mask effect in RT in the 12-14 age group, with increased marginal entropy (decreased consistency) due to mask use associated with increased recognition RT. This effect demonstrated individual differences in the development of masked face processing in early adolescence, with those who showed a similar mask effect to what was observed in younger children having longer RT. Indeed, when recognizing an unmasked face that was learned with a mask on, increased eye movement entropy (decreased consistency) may signal difficulties in discovering and extracting diagnostic information that was not covered by a mask during learning for successful recognition, resulting in increased RT. A similar phenomenon has been observed in adults (Hsiao, Liao, et al., 2022): The mask effects in entropy measures were positively correlated with the mask effect in RT, suggesting that decreased consistency was associated with longer RT. Note that this association between the mask effect in entropy and mask effect in RT was not observed in the younger age groups, suggesting that they had limited ability to extract important features for recognizing an unmasked face that was learned with a mask on, a challenging mask use scenario even for adults (Hsiao, Liao, et al., 2022), resulting in increased eye movement entropy.

Our results above thus demonstrated that children at different developmental stages respond to mask use during face recognition differently. And these age differences seem to be particularly related to children's visual routine development for face recognition, and how well they can extract relevant facial information for the recognition task under different mask use scenarios. In general, at age 12-14/early adolescence, children have demonstrated adult-like responses to masked faces during face recognition. In contrast, the two younger age groups showed different mask effects in the scenarios of mask use during learning (masked-unmasked *vs.* unmasked-unmasked) and mask use during recognition (unmasked-masked *vs*. unmasked-unmasked) from the 12-14 group. Previous research has shown that adults performed particularly poorly in face recognition under these two mask use scenarios where the mask conditions between face learning and face recognition do not match (Hsiao, Liao, et al., 2022), suggesting that these two scenarios could indeed be particularly challenging to children. Thus, children at these developmental stages have different vulnerability to mask use in society from adults and may require age-specific interventions when necessary.

In summary, here we showed that although children at all developmental stages were similarly affected by mask use during face recognition in recognition performance in d' and in eye movement pattern, there were age-related differences in recognition RT and eye movement consistency in response to mask use during two challenging scenarios where the mask conditions between face learning and face recognition did not match. Specifically, in the scenario of mask use during face recognition, children aged 12-14 showed more adult-like behavior, spending longer time recognizing masked faces than unmasked faces, whereas younger children did not. In the scenario of mask use during face learning, children aged 4-6 had less consistent eye movement when recognizing an unmasked face learned with than without a mask on. In contrast, children aged 12-14 did not have this effect. These findings suggest that children in early and middle childhood have different vulnerability to mask use in society from adolescents and adults, with important implications for age-specific interventions.

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