Title: Development of ambiguity processing is explained by an inverted U-shaped curve

Short title: ambiguity processing development

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ABSTRACT

Background: Understanding the developmental trajectories for recognizing facial expressions is important for a better understanding psychopathology development. In this study, we examined the recognition of emotional and neutral facial expressions in typically developing adolescents and adults.

Methods: We used the Emotion Intensity Rating task to examine recognition of facial expressions in 93 individuals (35 adolescents (12-18 years old), 58 adults (18-45 years old) without a history of psychiatric or systemic disorders. Participants rated the intensity of emotional expression in happy, neutral, and sad faces on a scale of 1 to 9 with a score '5' assigned to neutral faces, scores between '6' (slightly happy) and '9' (very happy) assigned to happy faces, and scores between '4' (slightly sad) and '1' (very sad) assigned to sad faces. Mixed effects models examined the effects of age and emotions on recognition accuracy, reaction time (RT), and emotion intensity.

Results: Participants tended to misjudge neutral faces as sad. Recognition of happy and sad faces was similar in adolescents and adults. Adolescents were less accurate than adults for neutral face recognition ($p<0.01$). There was a significant quadratic effect of age on accuracy and RT with the most accurate and fastest performance observed in 25-35 year-olds.

Conclusion: The ability to recognize ambiguous neutral facial expressions develops during adolescence, follows an inverted U-shaped trajectory, and peaks in early adulthood. This trajectory may be associated with the prefrontal cortex maturation that provides top-down control over the heightened amygdala response to ambiguity that may be misinterpreted as emotional content.

1 INTRODUCTION

Recognition of facial emotional expressions is a key aspect of social cognition (Choi & Watanuki, 2014; Moret-Tatay et al., 2023) and develops during childhood and adolescence (Durand et al., 2007; Pfaltz et al., 2019). Aberrant recognition of facial emotional expression has been linked to various psychiatric disorders and poor socioemotional functioning (Brotman et al., 2008; Cservenka & Donahue, 2024; Foisy et al., 2007; Freeman et al., 2018; Gao et al., 2021; Leppänen, 2006; Pabst et al., 2023; Staff et al., 2022; Szanto et al., 2012). Therefore, understanding the developmental trajectories for recognizing positive, negative, and neutral facial expressions is important for a better understanding of psychopathology development.

The ability to recognize salient emotions (e.g., happy or sad faces) develops early in life (Lawrence et al., 2015; Leppänen & Nelson, 2009) and is similar across cultures (Ekman et al., 1987; Ekman & Friesen, 1971) and for adolescents and adults (Rodger et al., 2023) possibly due to attentional biases to socio-affective cues that emotional faces contain (Pabst et al., 2023). In contrast, neutral facial expressions are ambiguous (Carvajal et al., 2013; Rollins et al., 2021). It was noted that children and adolescents have difficulty identifying neutral faces as neutral and tend to assign emotional valence to these faces (Durand et al., 2007; Pfaltz et al., 2019). One reason for the non-linear development of the ability to recognize salient and neutral facial expressions in children and adolescents is that detecting ambiguity relies on top-down processes (Kaminska et al., 2020). These processes support social and emotional cognition (Vijayakumar et al., 2019), rely on amygdala and prefrontal cortex maturation (Moore et al., 2012; O'Hearn & Lynn, 2023; Scherf et al., 2013), and develop later in life (Kaminska et al., 2020).

The goal of this study was to examine the recognition of emotional and ambiguous neutral facial expressions during adolescence and adulthood in typically developing individuals without a history of psychiatric and major systemic disorders. All participants performed the Emotional Intensity Recognition task (Manelis et al., 2019) in which they were asked to judge the emotional intensity of happy, neutral, and sad facial expressions. Participants were informed that there were no correct answers and that judgments had to be made based on the participant's perception of each face. We found that these instructions make the task more sensitive to individual differences in understanding facial emotional expression because they do not require participants to look for a ground truth regarding emotional categories (e.g., "I think most people would consider this face neutral, so I should respond that it is neutral even though it seems sad to me".) Previous research showed that identifying neutral faces is less accurate not only in adolescents but also adults due to the ambiguous nature of these stimuli (Manelis et al., 2019; Somerville et al., 2004). Considering that the ability to disentangle ambiguity develops later than the processing of salient stimuli (Dodd et al., 2015; Nook et al., 2018; Wiggins et al., 2015) (Dodd et al., 2015; Lee et al., 2020; Nook et al., 2018), we hypothesize that adolescents will be less accurate than adults when recognizing neutral facial expressions and when recognizing neutral compared to emotional facial expressions (Wiggins et al., 2015).

2 METHODS

2.1 Participants

The study was approved by the University of Pittsburgh Institutional Review Board (IRB). Participants were fifty-eight adults between 18 and 45 years old (Mean(SD) age=28.9(6.4) years; 43 female; IRB number: STUDY20060265) and thirty-five adolescents between 12-17 years of age (Mean(SD) age=15.3(1.4) years;15 female; IRB number: STUDY19030360). Written informed consent was obtained from all participants older than 18 years of age. Written informed assent was obtained from all participants younger than 18 years of age and written informed consent was obtained from their caregivers. All participants were right-handed, fluent in English, and did not have a history of psychiatric disorders based on the age-appropriate psychiatric assessments: SCID-5 (First, 2015) for adults and the M.I.N.I.-KID (Sheehan et al., 2010) for adolescents.

2.2 Study procedures

All participants performed the Emotion Intensity Rating task (Manelis et al., 2019) in which they rated the intensity of emotional expression in happy, neutral, and sad faces on a scale of 1 to 9 (**Figure 1**). Participants responded by pressing the corresponding buttons on the PC keyboard. Faces believed to be neutral had to receive a score of '5'. Happy faces were scored between '6' (slightly happy faces) and '9' (very happy faces). Sad faces were scored between '4' (slightly sad faces) and '1' (very sad faces). The faces and the original ratings were taken from the Karolinska Directed Emotional Faces (KDEF) (Garrido & Prada, 2017; Goeleven et al., 2008) and NimStim (Tottenham et al., 2009) databases. These faces have previously been

tested and are empirically proven to correspond to the indicated emotions. Participants were informed that there were no correct or wrong answers and were asked to judge faces based on their perception of each face. Owing to the difference in research goals for adult and adolescent studies, the Emotion Intensity Rating tasks had a different number of trials. In the adult sample, the task included 96 trials with 32 trials each for sad, happy, and neutral faces. In the youth sample, the task included 20 trials with 10 neutral, 5 happy, and 5 sad face trials. The outcome variables were recognition accuracy, recognition reaction time (RT), and estimated intensity of emotional expressions. High emotional intensity would correspond to the scores '9' (for happy faces) and '1' (for sad faces), and low intensity would correspond to the scores '6' (for happy faces) and '4' (for sad faces).

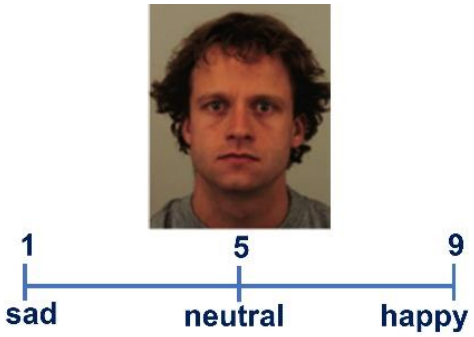

Figure 1. Emotion Intensity Rating task.

2.3 Data analysis

All statistical analyses were conducted using R (https://www.r-project.org). Mixed effects linear models ('lme4' package in R (Bates et al., 2015)) were used to examine the effects of age and facial emotional expressions on recognition accuracy, RT, and emotion intensity. These models were used to estimate contrasts and means using a 'modebased' package in R (Makowski et al., 2020) with Tukey's Honestly Significant Difference (HSD) correction for multiple comparisons. The first analysis tested our hypothesis regarding the differences in the recognition of emotional and neutral facial expressions by adolescents and adults. The second analysis examined linear and the quadratic effects of age on the ability to recognize neutral facial expressions. An additional analysis examined affective bias during the processing of neutral faces by comparing the mean intensity rating for neutral faces in each age group of participants with the score of "5" using a one-sample t-test. Significantly lower mean ratings suggest negative emotional bias, while significantly higher mean ratings suggest positive emotional bias when processing ambiguous neutral faces. The data were plotted using the 'ggpubr' and 'visreg' libraries in R.

3 RESULTS

The mixed effects analysis with emotion-by-age group interaction and sex as a covariate showed a significant emotion-by-age group interaction effect ($F(2,272)=4.66$, $p=0.01$) and a main effect of emotions ($F(2,272)=149.2$, $p<0.001$) on facial expressions recognition accuracy (**Figure 2**). Lower accuracy was observed for neutral, compared to happy ($t(182)=-15.25$, $p<0.001$) and sad ($t(182)=-14.66$, $p<0.001$), facial expressions. This effect was more pronounced in youth than in adults ($t=-3.46$, $p=0.008$).

As expected, the ratings for happy, neutral, and sad facial expressios significantly differed ($F(2,272)=2104.21$, $p<0.001$) with happy facies having highest ratings (estimated mean(SE)=7.95(0.06)), followed by neutral faces (estimated mean(SE)=4.71(0.06)), and sad faces (estimated mean(SE)=2.22(0.06)). A one-sample t-test revealed that intensity ratings for neutral faces were significantly lower than "5" in both youth ($t(34)= -5.4$, $p<0.001$) and adults ($t(57)= -7.4$, $p<0.001$) groups.

There was a main effect of the age group on RT with adults showing faster performance than youth ($F(1,90)=23.6$, $p<0.001$; $t= -4.6$, $p<0.001$). We observed no interaction effects on ratings and RT.

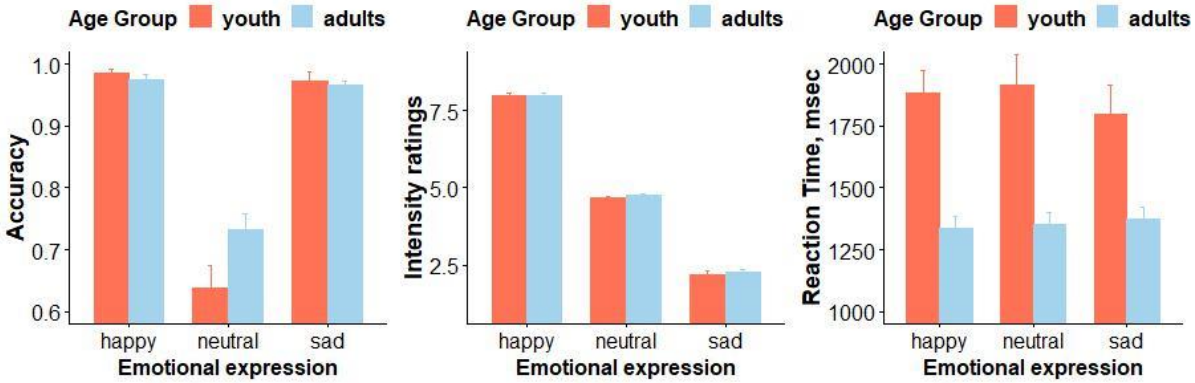

Figure 2. Estimated means for accuracy, intensity ratings, and RT in youth (13-17yo) and adult (18-45yo) samples. Standard error bars represent standard errors estimated from the mixed effects model.

Quadratic effect of age on recognition of neutral facial expressions

There was a significant negative quadratic effect of age on accuracy ($F(1,90)=10.8$, $p<0.005$; $t= -3.3$, $p<0.005$; **Figure 3A**), and a significant linear $F(1,90)=9.2$, $p<0.005$) and positive quadratic $F(1,90)=19.4$, $p<0.001$; $t=4.4$, $p<0.001$**; Figure 3B**) effects of age on RT during recognition of neutral facial expressions. The highest response accuracy and fastest RT were observed in participants who were 25-35 years old. Emotional intensity ratings for neutral faces did not depend on either linear or quadratic effects of participant's age.

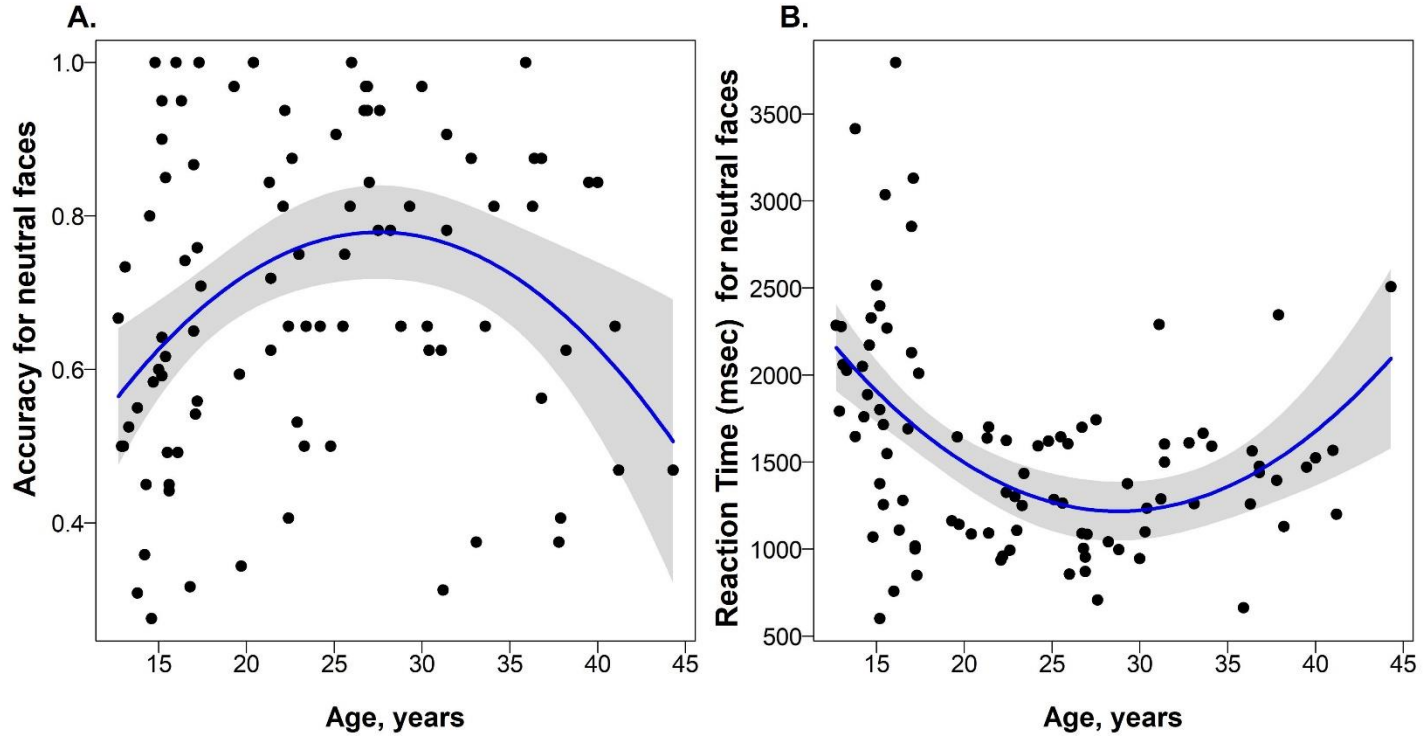

Figure 3. The effect of age on accuracy (A) and RT (B) for recognizing neutral facial expressions.

4 DISCUSSION

This study examined the recognition of facial emotional expressions in healthy adolescents and young adults. Participants accurately recognized happy and sad facial expressions independently of their age. Consistent with previous findings (Manelis et al., 2019; Somerville et al., 2004; Wiggins et al., 2015), the accuracy for neutral facial expressions was significantly lower than for happy and sad facial expressions across all participants. Both adolescents and adults tended to misjudge neutral faces as sad, thus showing negative affective bias. Overall, adolescents had lower accuracy and slower RT when recognizing neutral facial

expressions than adults. Interestingly, the relationship between participants' age and accuracy followed an inverted U-shaped curve, while the relationship between participants' age and RT followed a U-shaped curve.

Neutral facial expressions are ambiguous (Carvajal et al., 2013; Rollins et al., 2021). Ambiguous stimuli processing requires sufficient cognitive resources (Abubshait et al., 2020) to exhibit top-down control to orient social attention (Kaminska et al., 2020). Previous studies suggested that the development of cognitive control follows an inverted U-shaped trajectory (Erb et al., 2023; Li et al., 2024), which may be related to an inverted U-shaped curve in the development of the frontoparietal control network that reaches the peak between 24 and 41 years of age (Li et al., 2024). Our findings are consistent with this notion and demonstrate that the youngest and oldest participants show less accurate and slower performance and those between 25 and 35 years of age show the most accurate and fastest recognition of neutral faces.

One explanation for an inverted U-shaped developmental trajectory for neutral face recognition is that adolescents do not have sufficient resources to apply top-down cognitive control to rule out emotional signal due to under-developed emotion differentiation (Nook et al., 2018). On the other side, adolescents may have difficulty with recognizing neutral facial expressions due to increased sensitivity to emotions and social rejection (Sebastian, 2015) rather than reduced ability to process ambiguous stimuli. The latter idea is consistent with the findings of an inverted U-shaped developmental trajectory and overall heightened amygdala activation in response to emotions during adolescence (Moore et al., 2012; Pagliaccio et al., 2013). Considering that the amygdala is engaged in the coding of categorical ambiguity (Wang et al., 2017) and that amygdala activation increases can lead to interpreting neutral stimuli as emotional (Drevets, 2001), development of the ability to tell apart emotional and neutral stimuli might follow the developmental trajectory of the amygdala.

Understanding other people's facial expressions is related to social cognition and empathy and is necessary for appropriate behavioral responses in a social environment (Choi & Watanuki, 2014; Moret-Tatay et al., 2023). Aberrant recognition of facial emotional expressions and reduced empathy were linked to poor social skills (D'Hondt et al., 2014) and more severe symptoms of substance use (Rupp et al., 2017; Valmas et al., 2014), autism spectrum disorder (O'Hearn & Lynn, 2023), and depressive (Guhn et al., 2020; Manelis et al., 2019) disorders. Considering that various psychiatric disorders, including depressive and substance use disorders, develop during adolescence (Ahmed et al., 2015; Paus et al., 2008), it is important to understand how ambiguity development is related to the development of psychiatric disorders in adolescents and young adults. For example, interpreting neutral facial expressions as emotional may increase anxiety, thus leading to inappropriate emotional or behavioral responses. Previous studies showed that anxious children tend to anticipate negative emotions in ambiguous situations (Dodd et al., 2015).

Although we discuss here the potential neurobiological underpinnings of the ambiguity processing development, our study did not collect functional neuroimaging data during the Emotion Intensity recognition task. Future studies should address this limitation. Another possible limitation is the age of the face stimuli. Given that all faces belonged to adults, it is unclear how the ability to disentangle neutral from emotional faces in adolescents would change if the face stimuli were age matched. In addition, the age range of our participants was limited to 45 years. Future research should examine the processing of ambiguous emotional stimuli in older adults, especially in the relationship to developing late-life depression.

In summary, our study revealed that the ability to recognize ambiguous neutral facial expressions develops during adolescence and early adulthood and follows an inverted U-shaped trajectory, with the peak occurring between 25 and 35 years of age. This developmental trajectory may be associated with the maturation of the prefrontal cortex that provides top-down control over the heightened amygdala response to stimulus ambiguity that may be misinterpreted as emotional content. Further work is needed to understand the relationship between the ability to interpret neutral facial expressions and the development of psychiatric disorders across the lifespan.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the University of Pittsburgh (protocol numbers STUDY20060265 and STUDY19030360).

Informed Consent Statement: Informed assent was obtained from all participants under 18 years of age, and written informed consent was obtained from caregivers for adolescents and from all participants who were 18 years of age or older.

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Conflicts of Interest: The authors have no conflict of interest to declare.

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