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Mapping the Development of Visual Information Use for Facial Expression Recognition

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By

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Summary

In this thesis, I aimed to map the development of facial expression recognition from early childhood up to adulthood by identifying for the first time in the literature the quantity and quality of visual information needed to recognise the six 'basic' emotions. Using behavioural and eye tracking measures, the original contributions of this thesis include:

1. An unbiased fine-grained mapping of the continued development of facial expression recognition for the six basic emotions with the introduction of a psychophysical measure to the literature;
2. The identification of two main phases in the development of facial expression recognition, ranging from 5 to 12 years old and 13 years old to adulthood;
3. The quantity of signal and intensity information needed to recognise the six basic emotions across development;
4. The processing of signal and intensity information becomes more discriminative during development as less information is needed with age to recognise anger, disgust, surprise and sadness;
5. Novel analysis of response profiles (the sequence of responses across trials) revealed subtle but important changes in the sequence of responses along a continuum of age - profiles become more similar with age due to less random erroneous categorizations;
6. The comparison of two recognition measures across the same cohort revealing that two types of stimuli commonly used in facial emotion processing studies (expressions at full intensity vs. expressions of varying intensities) cannot be straightforwardly compared during development;

7. Novel eye movement analyses revealed the age at which perceptual strategies for the recognition of facial expressions of emotion become mature.

An initial review of the literature revealed several less studied areas of the development of facial expression recognition, which I chose to focus on for my thesis. Firstly, at the outset of this thesis there were no studies of the continued development of facial expression recognition from early childhood up to adulthood. Similarly, there were no studies which examined all six of, what are termed, the 'basic emotions' and a neutral expression within the same paradigm. Therefore, the objective of the first study was to provide a fine-grained mapping of the continued development for all six basic expressions and neutral from the age of 5 up to adulthood by introducing a novel psychophysical method to the developmental literature. The psychophysical adaptive staircase procedure provided a precise measure of recognition performance across development. Using linear regression, we then charted the developmental trajectories for recognition of each of the 6 basic emotions and neutral. This mapping of recognition across development revealed expressions that showed a steep improvement with age – disgust, neutral, and anger; expressions that showed a more gradual improvement with age – sadness, surprise; and those that remained stable from early childhood – happiness and fear; indicating that the coding for these expressions is already mature by 5 years of age. Two main phases were identified in the development of facial expression recognition as recognition thresholds were most similar between the ages of 5 to 12 and 13 to adulthood.

In the second study we aimed to take this fine-grained mapping of the development of facial expression recognition further by quantifying how much visual information is needed to recognise an expression across development by comparing two measures of visual information, signal and intensity. Again, using a psychophysical approach, this time with a repeated measures design, the quantity of signal and intensity needed to recognise sad, angry, disgust, and surprise expressions decreased with age. Therefore, the processing of both types of visual information becomes more discriminative during development as less information is needed with age to recognize these expressions. Mutual information analysis revealed that intensity and signal processing are similar only during adulthood and, therefore, expressions at full intensity (as in the signal condition) and expressions of varying intensities (as in the intensity condition) cannot be straightforwardly compared during development.

While the first two studies of this thesis addressed how much visual information is needed to recognise an expression across development, the aim of the third study was to investigate which information is used across development to recognise an expression using eye-tracking. We recorded the eye movements of children from the age of 5 up to adulthood during recognition of the six basic emotions using natural viewing and gaze-contingent conditions. Multivariate statistical analysis of the eye movement data across development revealed the age at which perceptual strategies for the recognition of facial expressions of emotion become mature. The eye movement strategies of the oldest adolescent group, 17- to 18-year-olds, were most similar to adults for all expressions. A developmental dip in strategy similarity to adults was found for each emotional expression between 11- to 14-years, and slightly earlier, 7- to 8-years, for happiness. Finally, recognition accuracy for happy, angry, and sad expressions did not differ across age groups but eye movement strategies diverged, indicating that diverse approaches are possible for reaching optimal performance.

In sum, the studies map the intricate and non-uniform trajectories of the development of facial expression recognition by comparing visual information use from early childhood up to adulthood. The studies chart not only *how well* recognition of facial expressions develops with age, but also *how* facial expression recognition is achieved throughout development by establishing whether perceptual strategies are similar across age and at what stage they can be considered mature. The studies aimed to provide the basis of an understanding of the continued development of facial expression recognition which was previously lacking from the literature. Future work aims to further this understanding by investigating how facial expression recognition develops in relation to other aspects of cognitive and emotional processing and to investigate the potential neurodevelopmental basis of the developmental dip found in fixation strategy similarity.

Résumé

Dans cette thèse, je souhaitais cartographier le développement de la reconnaissance des expressions faciales de la petite enfance à l'âge adulte en identifiant, et ceci pour la première fois dans la littérature développementale, la quantité et la qualité d'informations visuelles nécessaires pour reconnaître les six émotions « de base ». En utilisant des mesures comportementales et oculaires, les contributions originales de cette thèse incluent:

1. Une cartographie fine et impartiale du développement continu de la reconnaissance des six expressions faciales de base avec l'introduction d'une mesure psychophysique de pointe ;
2. L'identification de deux phases principales dans le développement de la reconnaissance des expressions faciales, allant de 5 à 12 ans et de 13 à l'âge adulte;
3. Une évaluation fine de la quantité d'informations (signal) et d'intensité nécessaires pour reconnaître les six émotions fondamentales du développement ;
4. Le traitement des informations relatives au signal et à l'intensité devient plus discriminant au cours du développement, car avec l'âge, moins d'informations sont nécessaires pour reconnaître la colère, le dégoût, la surprise et la tristesse.
5. Une nouvelle analyse des profils de réponse (la séquence de réponses entre les essais) a révélé des changements subtils mais importants dans la séquence de réponses sur un continuum d'âge: les profils deviennent plus similaires avec l'âge en raison de catégorisations erronées moins aléatoires;
6. La comparaison de deux mesures de reconnaissance au sein de la même cohorte, révélant que deux types de stimuli couramment utilisés dans les études sur les expressions émotionnelles (expressions à intensité maximale vs expressions d'intensités variables) ne peuvent pas être directement comparés au cours du développement;

7. De nouvelles analyses des mouvements oculaires ont révélé l'âge auquel les stratégies perceptuelles pour la reconnaissance d'expressions faciales émotionnelles deviennent matures.

Une première revue de la littérature a révélé plusieurs domaines moins étudiés du développement de la reconnaissance de l'expression faciale, sur lesquels j'ai choisi de me concentrer pour ma thèse. Tout d'abord, au début de cette thèse, aucune étude n'a été menée sur le développement continu de la reconnaissance des expressions faciales depuis la petite enfance jusqu'à l'âge adulte. De même, aucune étude n'a examiné les six expressions dites «de base» et une expression neutre dans le même paradigme. Par conséquent, l'objectif de la première étude était de fournir une cartographie fine du développement continu des six expressions de base et neutre de l'âge de 5 ans à l'âge adulte en introduisant une nouvelle méthode psychophysique dans la littérature sur le développement. La procédure psychophysique adaptatived a fourni une mesure précise de la performance de reconnaissance à travers le développement. En utilisant une régression linéaire, nous avons ensuite tracé les trajectoires de développement pour la reconnaissance de chacune des 6 émotions de base et neutres. Cette cartographie de la reconnaissance à travers le développement a révélé des expressions qui montraient une nette amélioration avec l'âge - dégoût, neutre et colère; des expressions qui montrent une amélioration graduelle avec l'âge - tristesse, surprise; et celles qui sont restés stables depuis leur plus tendre enfance - la joie et la peur; indiquant que le codage de ces expressions est déjà mature à 5 ans. Deux phases principales ont été identifiées dans le développement de la reconnaissance des expressions faciales, car les seuils de reconnaissance étaient les plus similaires entre les âges de 5 à 12 ans et de 13 ans jusqu'à l'âge adulte.

Dans la deuxième étude, nous voulions approfondir cette cartographie fine du développement de la reconnaissance des expressions faciales en quantifiant la quantité d'informations visuelles nécessaires pour reconnaître une expression au cours du développement en comparant deux mesures d'informations visuelles, le signal et l'intensité. Encore une fois, en utilisant une approche psychophysique, cette fois avec un plan de mesures répétées, la quantité de signal et l'intensité nécessaires pour reconnaître les expressions de tristesse, colère, dégoût et surprise ont diminué avec l'âge. Par conséquent, le traitement des deux types d'informations visuelles devient plus discriminant au cours du développement car moins d'informations sont nécessaires avec l'âge pour reconnaître ces expressions. L'analyse mutuelle des informations a révélé que l'intensité et le traitement du signal ne sont similaires qu'à l'âge adulte et que, par conséquent, les expressions à intensité maximale (dans la condition du signal) et les expressions d'intensité variable (dans la condition d'intensité) ne peuvent être comparées directement pendant le développement.

Alors que les deux premières études de cette thèse traitaient de la quantité d'informations visuelles nécessaires pour reconnaître une expression tout au long du développement, le but de la troisième étude était de déterminer quelle information est utilisée dans le développement pour reconnaître une expression utilisant l'eye-tracking. Nous avons enregistré les mouvements oculaires d'enfants âgés de 5 ans à l'âge adulte lors de la reconnaissance des six émotions de base en utilisant des conditions de vision naturelles et des conditions contingentes du regard. L'analyse statistique multivariée des données sur les mouvements oculaires au cours du développement a révélé l'âge auquel les stratégies perceptuelles pour la reconnaissance des expressions faciales des émotions deviennent matures. Les stratégies de mouvement oculaire du groupe d'adolescents les plus âgés, 17 à 18 ans, étaient les plus similaires aux adultes, quelle que soit leur expression. Une dépression dans le développement de la similarité stratégique avec les adultes a été trouvé pour chaque expression émotionnelle entre 11 et 14 ans et légèrement avant, entre 7 et 8 ans, pour la joie. Enfin, la précision de la reconnaissance des expressions de joie, colère et tristesse ne diffère pas d'un groupe d'âge à l'autre, mais les stratégies des mouvements oculaires divergent, ce qui indique que diverses approches sont possibles pour atteindre une performance optimale.

En résumé, les études cartographient les trajectoires complexes et non uniformes du développement de la reconnaissance des expressions faciales en comparant l'utilisation des informations visuelles depuis la petite enfance jusqu'à l'âge adulte. Les études montrent non seulement dans quelle mesure la reconnaissance des expressions faciales se développe avec l'âge, mais aussi comment cette expression est obtenue tout au long du développement en déterminant si les stratégies perceptuelles sont similaires à travers les âges et à quel stade elles peuvent être considérées comme matures. Les études visaient à fournir la base d'une compréhension du développement continu de la reconnaissance des expressions faciales, qui faisait auparavant défaut dans la littérature. Les travaux futurs visent à approfondir cette compréhension en examinant comment la reconnaissance des expressions se développe en relation avec d'autres aspects du traitement cognitif et émotionnel ce qui pourrait permettre d'éclaircir si des aspects neuro-développementaux seraient à l'origine de la dépression présente entre 7-8 et 11-14 ans lorsque l'on compare les stratégies de fixations des enfants à celles des adultes.

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Publications of the Candidate

Two of the three experimental chapters of this thesis have been published. The third is currently under review:

Rodger, H., Sokhn, N., Lao, J., Liu, Y., & Caldara, R. (under review). Developmental eye movement strategies for decoding facial expressions of emotion.

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Rodger, H., Vizioli, L., Ouyang, X., & Caldara, R. (2015). Mapping the Development of Facial Expression Recognition. *Developmental Science.* doi: 10.1111/desc.12281

Other Publications

Rodger, H., Lao, J., Stoll, C., Pascalis, O., Dye, M.W.G., & Caldara, R. (under review). The Recognition of Facial Expressions of Emotion in Deaf and Hearing Individuals.

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Wyssen, A., Lao, J., **Rodger, H.**, Humbel, N., Lennertz, J., Schuck, K., Isenschmid, B., Milos, G., Trier, S., Whinyates, K., Assion, H.-J., Ueberberg, B, Müller, J., Klauke, B., Teismann, T., Margraf, J., Juckel, G., Kossmann, C., Schneider, S., Caldara, R. & Munsch, S. (2019). Facial Emotion Recognition Abilities in Women Suffering from Eating Disorders. *Psychosomatic Medicine: Journal of Behavioral Medicine*, 81, 155-164.

Kelly, D.J., Liu, S., **Rodger, H.**, Miellet, S., Ge, L. & Caldara, R. (2011). Developing Cultural Differences in Face Processing. *Developmental Science, 14* (5), 1176-1184.

Rodger, H., Kelly, D., Blais, C., & Caldara, R. (2010). Inverting faces does not abolish cultural diversity in eye movements. *Perception 39*(11) 1491 – 1503.

Miellet, S., Zhou, X., He, L., **Rodger, H**., & Caldara, R. (2010). Investigating cultural diversity for extrafoveal information use in visual scenes. *Journal of Vision 10* (6) article 21.

I. LITERATURE REVIEW

Chapter 1

General Introduction to Facial Expression Recognition

1. General Introduction

Humans are recognised as a highly social species. Our well-being and development depend on the social relationships, groups, and structures we are surrounded by. Throughout our social exchanges, human faces provide a rich source of social information. Every day, from our first days of life, we decode the facial expressions of others. Our ability to read the social signals expressed by faces can determine how effective our social interactions are. Indeed, the ability to recognise and understand emotions can predict later social and academic performance (Denham et al., 2003; Izard, Fine, Schultz, Mostow, Ackerman et al., 2001). The ubiquitous social nature of emotional expression is apparent in wider socio-cultural contexts; from diverse cultures, we have evolved to recognise the emotional signals of distinct facial expressions. The accurate perception of emotional signals such as fear, potentially indicating an environmental threat, or of a positive emotion promoting a social reward such as bonding, is vital to the development of adaptive behaviour. While the importance of faces for social communication has been established with the identification of specialized brain networks for their perception, how we become adept at processing facial expressions of emotion in particular remains a topical question in the study of Developmental Psychology.

At the outset of this thesis, the development of facial expression recognition throughout childhood remained a surprisingly under-examined domain of research and was therefore the motivation for undertaking this thesis (Herba & Phillips, 2004; Johnston et al., 2011; Mancini, Agnoli, Baldaro, Bitti & Surcinelli, 2013; Thomas, De Bellis, Graham & LaBar, 2007). In particular, the need for studies examining the continued development of facial expression recognition from childhood through adolescence into early adulthood had been cited, as very little was known about development across the full childhood range up to adulthood (Herba & Phillips, 2004). Furthermore, the need for normative data across this age range had also been identified, not only for a greater understanding of this vital social function throughout development, but also to aid identification of atypical emotional development (Herba & Phillips, 2004). The studies in this thesis therefore attempted to fill these identified needs for further research with the following aims:

Study 1: To map for the first time the continued development of facial expression recognition in children aged 5 up to adulthood for each of the six basic emotions and a neutral expression using a novel psychophysical approach.

Study 2: To quantify intensity and signal information use for recognition of the six basic emotions from early childhood to adulthood. And to compare both intensity and signal measures to assess their functional relationship and better understand the use of different measures in developmental research.

Study 3: To study the eye movements of children from 5 years of age up to adulthood during recognition of the six basic emotions for the first time to investigate at which age perceptual strategies for emotion recognition become mature.

The studies comprising this thesis therefore all measure visual information use during the continued development of facial expression recognition, from the age of 5 years up to adulthood. This age range was targeted because of the aforementioned need for studies examining the continued development of facial expression recognition, as well as the need for studies charting the development of this important social function during childhood beyond the preschool years (Mancini, Agnoli, Baldaro, Bitti & Surcinelli, 2013; Thomas, De Bellis, Graham & LaBar, 2007). The relatively well-documented developmental course of facial expression recognition during infancy is therefore outside of the scope of this thesis.

In the succeeding chapters, I will firstly discuss theoretical questions surrounding the study of facial expression recognition; including what are facial expressions of emotion, their function and importance, the neural circuits involved in their processing, and some of the predominant theories of how we process facial expressions of emotion. After this general background to facial expression recognition, in Chapter 2 I will subsequently review the developmental literature on facial expression recognition to illustrate what is known about the development of emotion recognition in childhood. Here, I will highlight theoretical and methodological gaps in the extant literature which the experimental studies of this thesis attempt to fill. Finally, I will describe the methodological approaches chosen for the experimental studies of this thesis to investigate outstanding questions in the literature.

1.1 What is Facial Expression Recognition?

This thesis asks how facial expression recognition develops from early childhood up to adulthood. To begin with, it is therefore necessary to define what facial expressions of emotion are, and what emotion recognition is. Naturally, responses to these apparent straightforward questions have evolved over time as research methods have developed with technological advances to allow us to probe previously impenetrable phenomena, such as key areas of the brain involved in the production and processing of emotion. However, such advances do not mean that the answers to these questions are resolved. As our understanding and methods of enquiry develop, key areas of debate in the field of emotion remain topical and continue to yield further research effort. While considering the definitions put forward below, it is important to bear in mind that much of the current knowledge in this field has been furnished from human adult and animal research, leaving open further ground for unexplored developmental perspectives.

1.1.1. What are Facial Expressions of Emotion? Physical and Functional Forms.

1.1.1.1 Physical Anatomy and Taxonomy of Facial Expressions

Physically, the contraction of specific muscles in the face produces facial expressions of emotion. By using electrical stimulation, French neurologist Guillaume Duchenne (1862) originally determined that the movement of different facial muscles cause expression (Figure 1.1). Facial features briefly change form with muscle movement and this change in form can express or disguise the current experience of emotion. Each facial expression of emotion is formed by the activation of its own unique pattern of muscles. This activation may vary in intensity leading to an expression that is perceived as more or less pronounced.

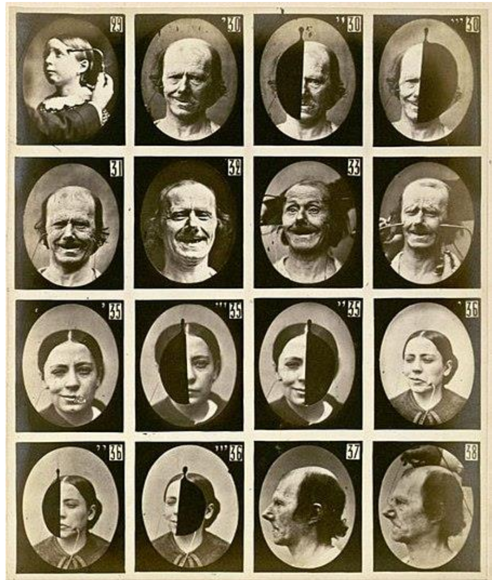

Figure 1.1. Photographs of facial expressions produced by electrical stimulation. From Duchenne's (1862) book Mécanisme de la Physionomie Humaine in which he used electric stimulation to discover the muscles responsible for different facial expressions.

One commonly used research method to understand the musculature supporting individual expressions is the Facial Action Coding System (FACS; Ekman & Friesen, 1978; Ekman, Friesen, & Hager, 2002). FACS is an anatomical taxonomy developed to measure facial muscle movements systematically. Within this system, each muscle movement is defined as an individual Action Unit (AU); there are 44 in total (see Figure 1.2 for some example AUs), and each expression is composed of the movement of a unique set of Action Units. For example, the expression of fear is produced when the Action Units illustrated in Figure 1.2 are activated. This systemised coding of facial action units therefore facilitates the reproduction and analysis of expressions in diverse research domains. FACS has been widely employed due to these features (Cohn & Ekman, 2005; Jack & Schyns, 2015).

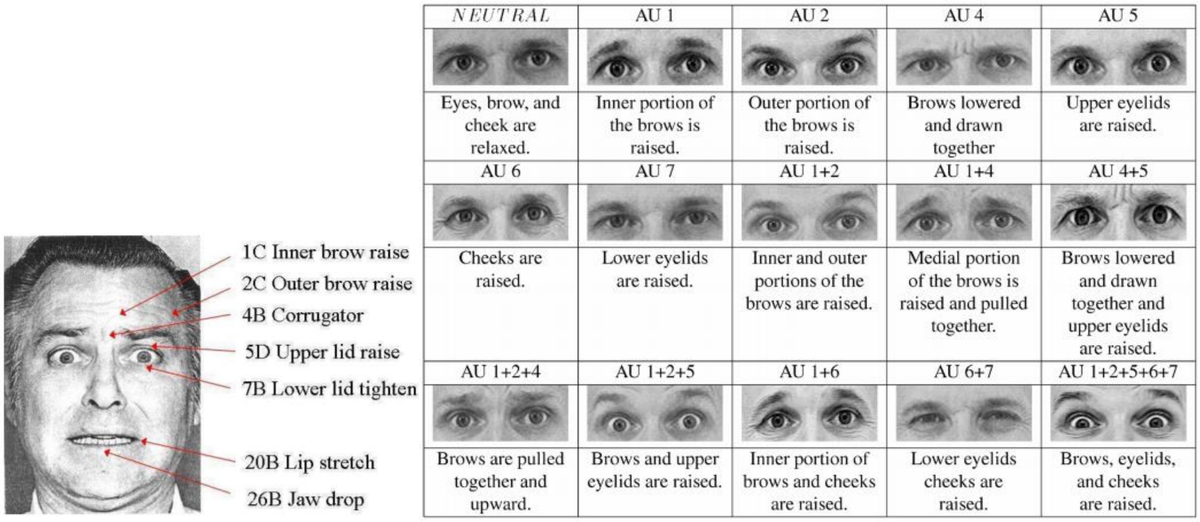

Figure 1.2. Left Panel: Action Units used in the expression of fear. Right panel: Upper Face Action Units and Combined Units. The left panel shows the Action Units used to express fear. The right panel gives examples of Upper Face Action Units and Combined Units. Adapted from Tian, Kanade, & Cohn (2001).

1.1.1.2 'Basic Emotions' and Universality

Since Ekman and Friesen's development of FACS-coded stimuli in the seventies, a large body of cross-cultural studies has found that six FACS-coded expressions: happiness, fear, anger, disgust, sadness and surprise (Figure 1.3), are consistently recognised with above chance accuracy across cultures (e.g. Biehl et al., 1997; Ekman et al., 1987; Ekman, Sorenson, Friesen, 1969; Matsumoto & Ekman, 1989). Such findings, with what is considered an objective system for mapping facial expressions, have contributed to the largely predominant view in emotion research that these six expressions represent universal "basic emotions". However, longstanding debate on the existence of basic emotions (for a recent review see Nelson & Russell, 2013) has recently been advanced by findings from a novel data-driven dynamic FACS-based Generative Face Grammar. This computer graphics platform randomly samples AUs and ascribes movement to them on 3D faces over time. Observers then categorise the dynamic expression they have perceived.

Figure 1.3. The six basic expressions of emotion. FACS-coded expressive faces from the Pictures of Facial Affect database (Ekman & Friesen,1979).

This data-driven approach has provided strong evidence that contrary to previous beliefs, FACS-coded expressive faces do not represent universally understood signals of emotion. Observers from East-Asia consistently miscategorise fear and disgust since they systematically do not look at specific action units which are necessary for the accurate categorisation of these expressions (Jack, Blais, Scheepers, Schyns, P.G., & Caldara, 2009; Jack, Caldara, & Schyns, 2012; Jack, Garrod, Yu, Caldara, & Schyns, 2012). Cultural differences in how these expressions are decoded and represented have therefore been identified. Importantly these differences reveal that the AU patterns in FACs stimuli communicate six emotions in Western cultures but not in other non-Western cultures (Jack & Schyns, 2015). Figure 1.4 gives another example of cultural differences in facial expression recognition; in how East Asian and Western Caucasian cultures differ in distinguishing disgust and anger exphressions. However, at this time, FACS-coded expressive faces remain the most widely used stimuli in psychological and neuroscientific research,

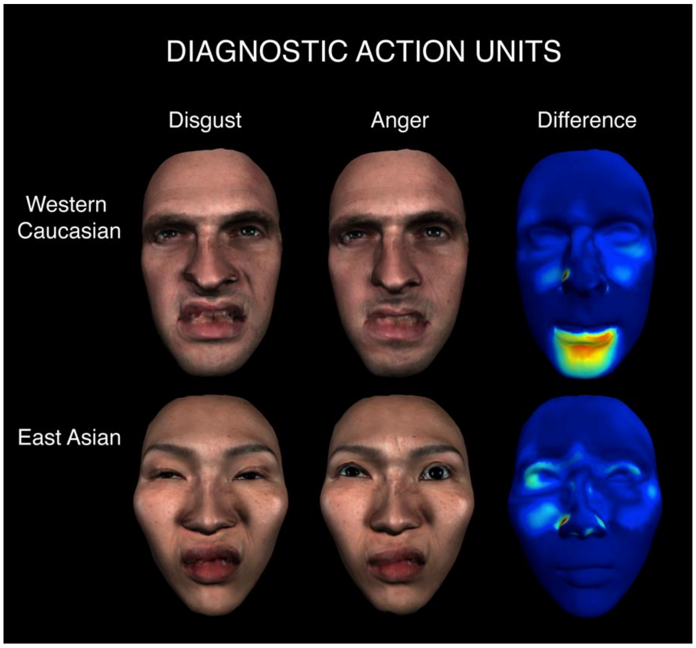

Figure 1.4. Cultural differences in diagnostic Action Units to distinguish disgust and anger. Recognition of ‘disgust’ and ‘anger’ differs in the mouth region for Western Caucasian compared to East Asians, as shown by the color-coded difference map. East Asian facial expressions of ‘disgust’ and ‘anger’ differ in the eye region. The eyes narrow for ‘disgust’ compared to the eye whites opening for ‘anger,’ again shown in the corresponding difference map (Jack and Schyns 2015).

with facial expression stimuli most commonly coming from FACS-coded databases (e.g. Japanese and Caucasian Facial Expressions of Emotion, JACFEE, Matsumoto & Ekman, 1988; The Karolinska Directed Emotional Faces, KDEF, Lundqvist, et al., 1998; The Radboud Faces Database, RaFD, Langner, et al., 2010; Pictures of Facial Affect, POFA, Ekman & Friesen, 1976; Unmasking the Face-photo set, Ekman & Friesen, 1975, and the Montreal Set of Facial Displays of Emotion, MSFDE, Beaupré, Cheung, & Hess, 2000).

As understanding of the cross-cultural nature of facial expression recognition has developed, calls have been made for classic approaches in emotion research, which have largely been driven by FACs-coded stimulus sets, to be replaced by more data-driven methods (Jack & Schyns, 2015). Importantly, such data-driven methods do not discard the use of Action Units but impress that dynamic AU patterns, which communicate emotions, should be identified using data-driven approaches that explore the permutations and combinations of dynamic AUs across different cultures to prevent potential bias in stimulus sets.

1.1.1.3. Function of Facial Expressions of Emotion

The physical manifestation of emotion on the face, as described above, is conveyed through the movement of different facial muscles. The question of why these different muscles are activated, of what function expressions serve, has long been considered from an evolutionary perspective while present-day understanding has come to recognise them as both emotional responses and tools for social communication (Adolphs, 2002; Jack & Schyns, 2015).

1. **Evolutionary Adaptations for Sensory Regulation**

   'I want, anyhow, to upset Sir C. Bell's view... that certain muscles have been given to man solely that he may reveal to other men his feelings' (F. Darwin, 1887, Vol. 2, p. 78.).

   The evolutionary origins of facial expressions have been considered since Darwin's (1872/1999) seminal works on '*The Expression of the Emotions in Man and Animals*', in which he attempted to show continuity in facial and bodily expressions of humans, nonhuman primates, and nonprimates. Over the last decade, the evolutionary perspective that facial expressions are adaptive functions which promote genetic fitness has gained further ground with several studies specifically examining the adaptive value of individual facial expressions for the first time. By mapping the facial action patterns of fear and disgust, Susskind et al., (2008) demonstrate the adaptive function of fear and disgust expressions. They reveal that the facial muscle movements of fear and disgust alter the exposure of sensory organs to the environment by either increasing or decreasing the level of exposure (Figure 1.5). For example, when we express fear, an emotion associated with sensory vigilance (Davis & Whalen, 2001; Whalen et al., 1998), the eyebrows are raised, the eyes widen to enhance the visual field size, the nostrils become flared and the mouth is open; all of which are a means to increase sensory exposure to the environment. In contrast, when disgust is expressed, sensory exposure to the environment is decreased as the eyes are narrowed, the nose is wrinkled, and the top lip raised. These convergent action tendencies therefore regulate the senses in alternate ways.

Sensory regulatory functions have also been shown for other expressions (Susskind & Anderson, 2008). Despite this evidence, cross-species evidence in line with Darwin's continuity hypothesis is necessary to further support evolutionary understanding of expressions as sensory regulators. While these finding suggest facial expressions were originally adapted for sensory regulation, present-day understanding of facial expressions is that they have functionally evolved as highly discriminable social signals (Frith, 2009; Susskind et al., 2008).

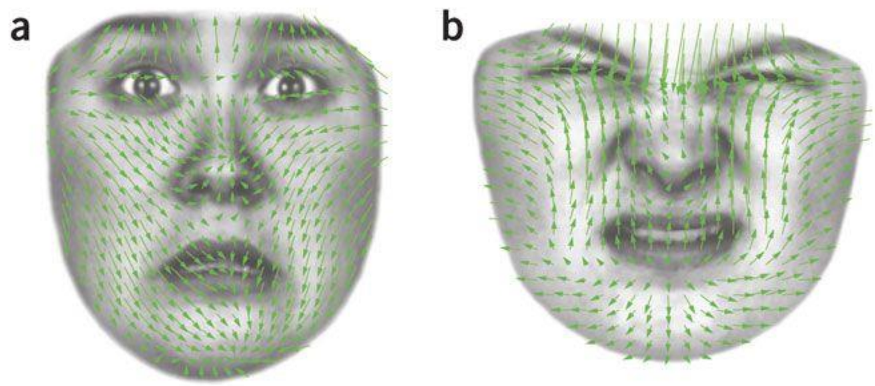

Figure 1.5. The action patterns underlying opposition in fear and disgust facial expressions. Vector flow fields were derived from the surface deformations of fear and disgust from their antiprototypes. Fear, associated with sensory vigilance, appeared to oppose that of disgust, associated with sensory rejection. These distinct expressions may therefore have been shaped by opposing underlying action tendencies related to sensory regulation. From Susskind et al. 2008.

2. Emotional Signals for Social Communication

Facial expressions of emotion are known to be important signals in social communication and are thought to have evolved in part as a method of nonverbal communication between conspecifics (Fridlund, 1994; Schmidt & Cohn, 2001). While facial expressions may originally have had behavioural advantages for the person expressing the emotion, for example sensory regulation (as described above), over time expressions came to be understood as signals by those perceiving them. Subsequently, with the awareness that their expressions were understood by others, those expressing the emotion could also control what were previously involuntary expressions. Ultimately, as both sender and receiver became aware that their expressions are socially communicative signals, expressions no longer needed to be tied to their original behavioural function and hence are now understood as emotional signals within the context of social communication (Frith, 2009).

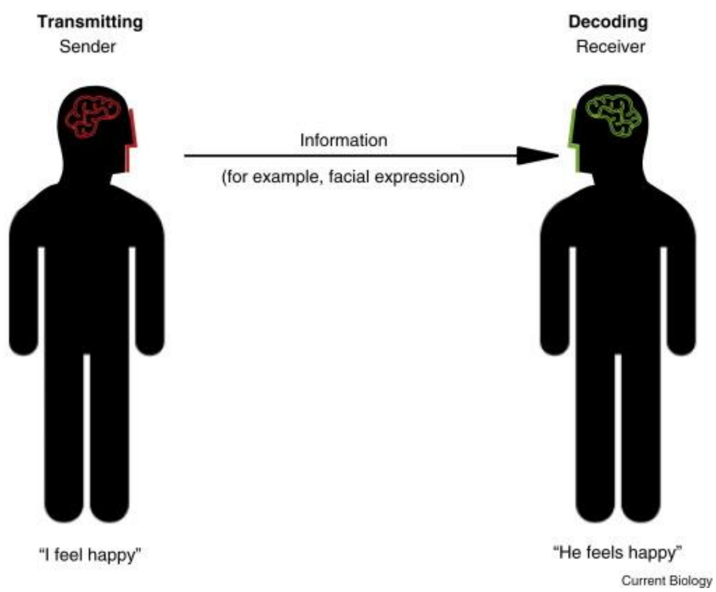

Figure 1.6. Information transmission and decoding framework. Facial expressions as a dynamical system of information transmission and decoding. During transmission the sender encodes a message (e.g. 'I feel happy') as a form of information (e.g. a facial expression, body movement, vocalisation) across a communication channel (e.g. the visual or auditory system) to the receiver. To decode this information the receiver uses prior knowledge (e.g. mental representations of categorical information) to extract relevant features and interpret the information which typically assimilates an accurate reconstruction of the message (e.g. 'he feels happy'). From Jack & Schyns, 2015.

With the demands of globalization, cultural integration, and emphasis on social communication in the digital era, the impetus to understand the face as a highly dynamic communication system has grown. Jack and Schyns (2015) describe a cross-disciplinary approach to understanding the face in this way, in their information transmission and decoding framework (Figure 1.6). Within this framework, emotion communication is achieved through the dynamic transmission and decoding of signals, which are facial expressions (and more widely, body movements and vocal intonations). During the transmission phase, the sender encodes the information he or she wishes to transmit, for example, “I feel happy”, as a signal across a communication channel (e.g. visual or auditory) to the receiver. To decode the information, the receiver uses existing knowledge (top-down information) to extract the relevant features of the signal, such as diagnostic features from the face for example, and interprets this information. For facial expressions this interpretation includes categorical perception to successfully reconstruct the message “he feels happy”. Within this framework, information can be transmitted either intentionally or unintentionally.

1.1.1.4 Involuntary versus Voluntary Expression: Basic Emotion Theory and Behavioral Ecology Functional Accounts

Previous functional explanations of facial expressions have diverged on whether expressions are intentional or unintentional. Classical accounts of emotion from Basic Emotion Theory (e.g. Ekman, 1997) hold that facial expressions are involuntary, automatic readouts of internal emotional states (Buck, 1994). By contrast, the Behavioral Ecology view of facial expressions holds that they are intentional socially-motivated communicative acts (Fridlund, 1994). Such views have also been construed as perceiver-independent (involuntary) versus perceiver-dependent (voluntary; Gendron & Barrett, 2017), whereas the information transmission and decoding framework encompasses both perspectives. Within different contexts, involuntary expressions may occur during an intense emotional reaction, or expressions can also be voluntarily modulated within social and cultural contexts.

Indeed, the neuroanatomy guiding the production of facial expressions of emotion involves both automatic and volitional components. Early studies of brain damaged patients indicated that these components are dissociable; voluntary emotional expressions could no longer be produced when the primary motor cortex was damaged, conversely damage to the insula, pons, or basal ganglia was found to impair involuntary expressions of emotion (Rinn, 1984; Hopf, Muller-Forell, & Hopf, 1992). Sub-cortical regions were therefore identified as necessary for involuntary emotional displays, whereas cortical regions were shown to be necessary for voluntary expressions of emotion (Rinn, 1984). However, subsequent findings indicate that this dichotomy is overstated as sub-cortical regions, particularly the basal ganglia, and cortical regions such as the frontal cortex, were found to modulate both involuntary and voluntary expressions of emotion in subsequent brain-damaged patient studies (Blair, 2003; Borod et al., 1990; Smith et al., 1996; Wedell, 1994). Current understanding of the neural networks involved in facial expression recognition will now be considered.

1.1.2 How do we recognise facial expressions of emotion? Multiple routes: Processes and mechanisms underlying Facial Expression Recognition

1.1.2.1 Models of Face Perception

Multiple distributed systems are understood to subserve emotion recognition in the brain, and to date the precise mechanisms involved continue to be debated (Philips, Drevets, Rauch, & Lane, 2003; Frith, 2009; Said, Haxby, & Todorov, 2011). The neural networks implicated in facial expression processing have generally been described within overarching models of general face perception. Two of the most influential face perception models, Bruce and Young's (1986) cognitive model and Haxby, Hoffman, & Gobbini's (2000) distributed neurocognitive model, assume that the processing of facial identity and facial expression involve distinct processing systems (Figure 1.7.

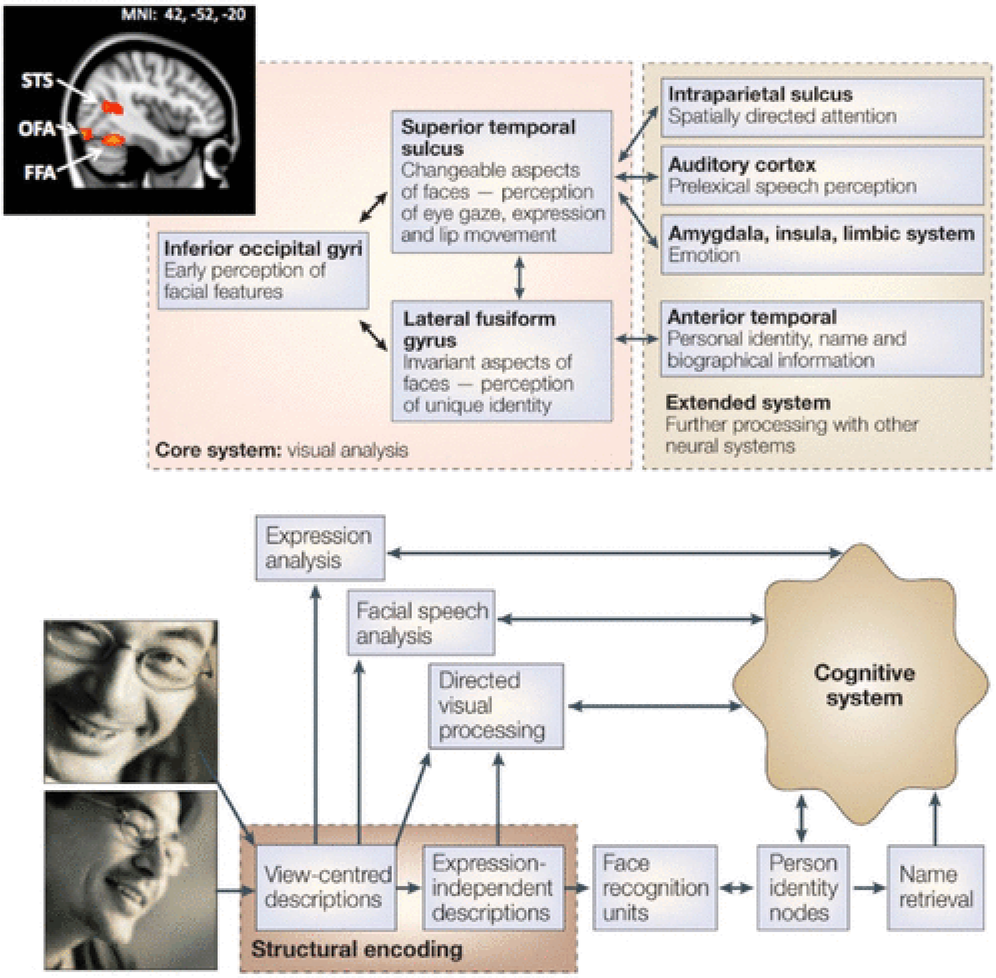

Figure 1.7. Haxby et al.'s (2000) Neurocognitive Model and Bruce & Young's (1986) Cognitive Model of Face Perception. Haxby et al.'s (2000) neurocognitive model is shown in the upper panel alongside an fMRI image illustrating the face responsive regions of the brain in their core system for visual analysis of the face: the posterior superior temporal sulcus (STS), the occipital face area (OFA) and the fusiform face area (FFA). The lower panel illustrates an adapted version of the Bruce and Young (1986) cognitive model to highlight the similarities between the two models, from Young (2018).

Bruce and Young's early cognitive model was established before many human neuroanatomical studies were available. Their proposal that identity and expression follow distinct processing streams was based on findings from prosopagnosic patients who recognize facial expressions but not identities. In their model, face processing begins with a structural encoding phase, in which either view-centred (e.g. the layout of the face) or expression-independent (e.g.

head angle) descriptions of the face occur. Subsequently, output from the structural encoding phase is input to separate processing streams, for example expression and lip movements are analysed by separate processes. Haxby et al.'s (2000) neurocognitive model integrated early cognitive and neural findings, and further developed some of the elements of Bruce and Young's model. While Haxby's model also delineates separate processing streams for expression and identity, there are differences between the models in how this is done.

Haxby and colleagues (Haxby et al., 2000; Haxby & Gobbini, 2011) distinguish between the representation of invariant features of a face, such as facial identity, and variable features such as expression, eye gaze, and lip movement recognition (Figure 1.7). By contrast, expression, eye-gaze, and lip movement analysis involve separate processes in Bruce and Young's model. Initial visual facial analysis is performed by the inferior occipital gyri in Haxby et al.'s model. Subsequently, depending on whether invariant or variant facial features have been detected, invariant features such as expression, eye-gaze, and lip movement are processed by the superior temporal sulcus (STS). Alternatively, invariant features such as identity are processed by the lateral fusiform gyrus (LFG). From the STS, emotional expression information is relayed to the amygdala, insula, and other limbic structures; these are non face-specific structures that are also involved in the experiencing of emotion (Righi & Nelson, 2013). Adolphs' (2002) model, illustrated in Figure 1.8, represents how the stages of processing involved in Bruce & Young's and Haxby's models unfold as a function of time. It depicts how the early perceptual processes described in these models move through to the processing of conceptual knowledge during the last hypothetical stage of facial expression recognition. It also includes further details of candidate systems involved in the proposed fast-early processing, detailed perception, and conceptual knowledge integration stages of recognition. Despite early agreement in both the Bruce and Young and Haxby models suggesting parallel processing routes for identity and expression, later findings caused the authors themselves to question this distinction (Calder & Young, 2005; Young & Bruce, 2011).

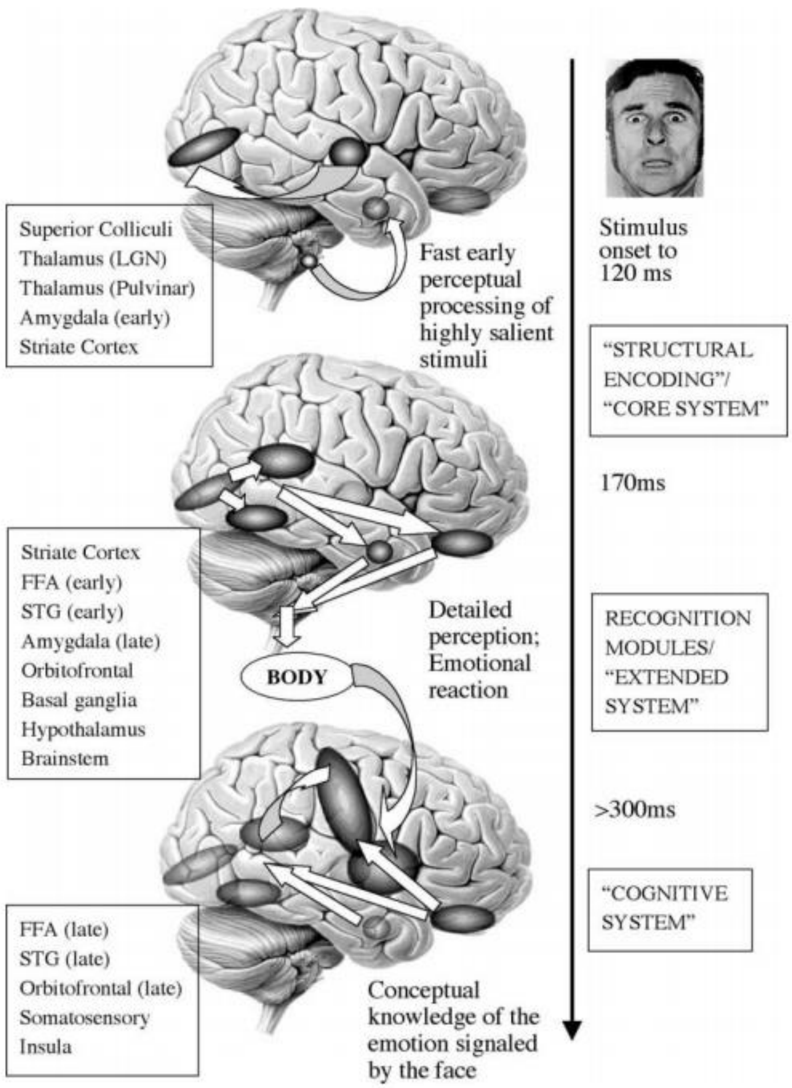

Figure 1.8. Processing of Emotional Facial Expressions as a Function of Time. The left side indicates candidate structures involved in the proposed stages of facial expression processing identified in the centre. The right side illustrates how the processes described in Bruce & Young and Haxby models unfold as a function of time (from Adolphs, 2002).

Duchaine and Yovel's *Revised Neural Framework for Face Processing* (2015) integrates more recent findings that have demonstrated the dissociation between identity and expression in the earlier Bruce & Young and Haxby et al. models is not supported. The main differences in this revised model indicate that the ventral stream still predominantly processes invariant information, for example the structure and surface properties of a face, but also contributes to facial expression processing via the FFA during expression recognition where it was previously thought not to. The dorsal stream's predominant role continues to be the representation of changing aspects of the face, including facial expression. However, it has since been found to respond more strongly to dynamic compared to static faces and is also thought to be involved in processing identity information conveyed by dynamic faces more specifically (O'Toole et al., 2002). Current thinking therefore posits a functional division between form and motion in the ventral and dorsal streams respectively (Bernstein & Yovel, 2015).

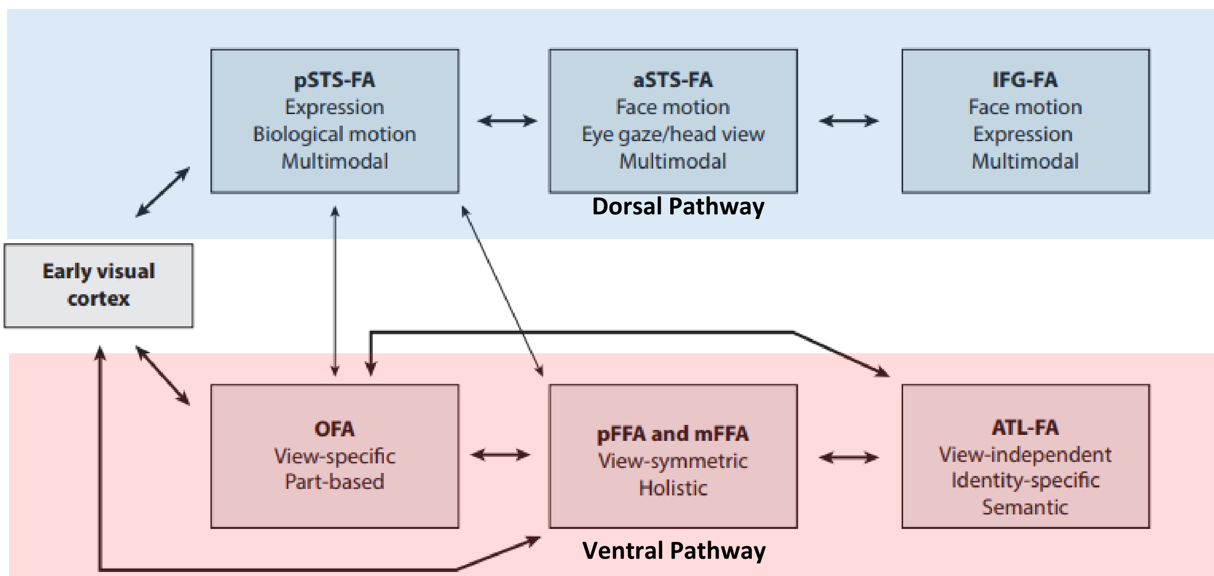

Figure 1.9. A Revised Neural Framework for Face Processing. The upper modules in blue represent the dorsal face-processing pathway and the lower modules in red the ventral face-processing pathway. Adapted from Duchaine & Yovel (2015).

1.1.2.2 Sensorimotor Simulation of Emotion.

One potential mechanism involved in the processing of expression but not identity, which is not discussed in the above models and should be included here, is sensorimotor simulation. As noted, emotional expression is a variable facial feature, which can therefore be simulated by perceivers (Calder & Young, 2005). Simulation theories of facial expression recognition hold that in order to understand others, it is necessary to reproduce their current state in ourselves. What exactly is simulated remains open to debate across the various simulation theories. I will briefly mention some of the key ideas here to describe how simulation is thought to contribute to emotion recognition and to draw links between these ideas and sensorimotor development and emotion perception. Wider discussion of the evidence and counter evidence for these ideas is outside the scope of this thesis. However, it is useful to consider how such theories relate to how conceptual understanding of the world is built during development and how this understanding contributes to facial expression recognition, as discussed later in the thesis.

Neurobiological models suggest that facial expression recognition depends on at least a subset of the same neural structures being activated as when we *express* an emotion ourselves (e.g. Adolphs, 2002; Gallese, Keysers, & Rizzolatti, 2004; Goldman & Sripada, 2005). A further suggestion is that perceiving another's emotion also involves a subset of structures that would be engaged if we were *experiencing* that emotion ourselves (Herberlein & Adolphs, 2007). This mirroring of the mind is thought to involve the mirror neuron system (e.g. Rizzolatti, Foggasi, & Gallese, 2001; Gallese, Keysers, & Rizzolatti, 2004). A mirror neuron system comprising the inferior frontal gyrus and posterior parietal cortex is thought to contribute to our understanding of the motor components of facial expressions, whereas the amygdala and insula are thought to represent a mirror neuron system contributing to the understanding of emotional experience (van der Gaag, Minderaa, & Keysers, 2007). Although many now assume that such a system exists in humans the topic continues to be debated (e.g. Kilner, 2011).

In addition to neural simulation of sensorimotor processes, sensorimotor simulation theories suggest physical embodiment is involved in emotion recognition. At the heart of simulation theories, emotions involve bodily changes that affect cognition and action, correspondingly, bodily states influence emotion and cognition (Bradley, Codispoti, Cuthbert, & Lang, 2001; Niedenthal, Winkielman, Mondillon, & Vermeulen, 2009). Facial feedback and facial mimicry are two mechanisms proposed to be involved in sensorimotor processing by such theories. The facial feedback hypothesis proposes that feedback from facial muscles when we express an emotion modulates our emotional experience (Buck, 1980). Strack, Martin, & Stepper (1988) famously demonstrated this modulation by manipulating the muscles of participants' faces with a pen held in their mouths positioned to either facilitate or inhibit smiling. Those in the facilitating smile condition rated cartoons as more humorous than their counterparts. Facial expressions were therefore shown to influence affective experience while participants were not aware of the motivation of the study. The hypothesis continues to be debated and two versions of the facial feedback hypothesis have evolved; a weak version, which posits that facial feedback can intensify or reduce our emotional experience, and a strong version, which suggests feedback itself can initiate an emotion. Relatedly, facial mimicry is the tendency for observers to display the same facial expressions as the sender (Sato, 2013). This embodiment of a perceived emotion is thought to contribute to emotion recognition as it facilitates our understanding of the sender's emotional experience. While automatic mimicry of facial expressions has been shown to occur even when people are unconsciously exposed to expressions (Dimberg, Thunberg, & Elmehed, 2000), a recent review suggests mimicry is not necessary for emotion recognition (Wood, Rychlowska, Korb, & Niedenthal, 2016).

1.1.2.3. Sensorimotor Development and Social Referencing.

The embodiment principles described by the sensorimotor simulation theories play an important role in early cognitive and social development. As the sensorimotor stage of Piaget's (1936) theory reveals, infants are essentially embodied learners; sensorimotor information drives cognitive development during this stage. Perceptual and motor interactions with the environment generate cognitive representations that are the building blocks of their knowledge about the world (Meltzoff, 1990).

Related to the building of this representation of the world is how we come to understand it through others, and facial expressions of emotion have been shown to play a critical role in this. Children will modify their behaviour according to the facial expressions of those they trust in ambiguous situations (Keltner & Haidt, 1999). Behavioural regulation in response to the perception of facial expressions is known as s*ocial referencing.* Social referencing occurs in situations of uncertainty when children refer to their parent or caregiver's facial emotion to assess whether a situation, object, or person is safe, then modify their behaviour accordingly (Klinnert, Campos, Sorce, Emde, & Svejda, 1983). The visual cliff experiment famously demonstrates social referencing as the emotion expressed by a mother determines whether her infant will cross a visual cliff (Sorce, Emde, Campos, & Klinnert, 1985).

Figure 1.10. Example of the visual cliff experiment. A mother encourages her baby to cross the deep side of the visual cliff. From Gibson and Walk (1960).

Linking sensorimotor learning and social referencing together, Glenberg (2010) emphasies how learning a new form of bodily activity influences an infant's perception of the world and their emotional and social behaviour. In a modification of the original visual cliff study, Campos et al., (2000) hypothesised that a young infant who is carried has little understanding between bodily movement and the visual information changes it perceives, such as optical flow (defined as the continuously changing ambient optic array produced by a continuously moving point of observation in Campos et al., 2000). However, as they learn to move, they understand this relationship since they experience changes in optical flow directly related to their bodily actions, e.g. movement. Infants with little locomotion tend not to show fear when crossing a visual cliff whereas experienced locomotors do show fear and do not cross the cliff. Campos et al. therefore trained infants with little self-locomotion to move themselves in a small cart by kicking the floor. With greater experience of self-locomotion, these infants then also showed fear in the visual cliff paradigm, thus demonstrating a correspondence between the newly learned bodily activity and the infants' perception and emotional response to the world (Glenberg, 2010). Sensorimotor experience and understanding emotional signals in our environment are therefore tightly bound in our representations of the world from an early age.

Chapter 2

The Development of Facial Expression Recognition during Childhood

2. The Development of Facial Expression Recognition during Childhood

The development of facial expression recognition throughout childhood remains a surprisingly under examined domain of research, despite its importance to social interaction and wellbeing (Herba & Phillips, 2004; Johnston et al., 2011; Mancini et al., 2013; Thomas et al., 2007). This identified need for further research, particularly for studies investigating the continuous development of facial expression recognition from early childhood up to adulthood (Herba et al., 2004), coupled with the importance of this skill to our social functioning and its role in the wider field of Social Cognition, were the motivations for undertaking this thesis. Given that impaired emotion processing has negative consequences on social functioning and well-being (e.g. Carton, Kessler, & Pape, 1999; Feldman, Philippot, & Custrini, 1991; Izard, Fine, Schultz, Mostow, Ackerman, et al., 2001; Nowicki & Duke, 1992), and the ability to recognize facial expressions at age 5 is predictive of later social and academic competence (Izard et al., 2001), research defining typical development is essential. For example, more closely defined typical developmental trajectories of recognition ability can aide the early identification of impairments and permit the timely initiation of necessary interventions. Similarly, emotion recognition training in typically developing children has already been shown to improve recognition performance (Pollux, Hall, & Guo, 2014), and could potentially benefit wider social processing skills. More broadly, emotion recognition forms part of a wider set of social processing skills that comprise Social Cognition. These skills include emotion processing, empathy, mental state attribution, self-processing, social hierarchy mapping, and in-group/out-group categorisation, which are necessary to understand how both ourselves and others navigate the social world (Happe & Frith, 2013). Further understanding of the development of emotion recognition could therefore also further inform research lines in the wider domain of Social Cognition.

In the following sections, I will review the literature on the development of facial expression recognition throughout childhood (from 5 years of age upwards) to provide an outline of the research to date, and to establish how the experiments defined in Chapters 3, 4, and 5 were conceived. To begin with, I will review several pertinent theoretical perspectives on the development of facial expression recognition. Subsequently, I will describe common behavioural methods used to investigate the development of facial expression recognition and their associated findings, and finally I will summarise the methodological choices of the experimental studies and thesis rationale.

2.1 Theoretical Perspectives on the Development of Facial Expression Recognition

There is no widely accepted theory of facial expression recognition, or a commonly accepted theoretical framework with which to understand how the development of emotion recognition unfolds (Herba & Phillips, 2004; McClure, 2000; Phillips et al., 2003). The under examined stages in the development of the ability to recognise expressions, as described above, likely contribute to this position. Furthermore, the interdisciplinary nature of the development of facial expression recognition, comprising physiological, cognitive, behavioural, socio-emotional and regulatory factors make it difficult to identify a unifying perspective across theoretical domains (Herba & Phillips, 2004). In the cognitive and visual perception domains, theoretical accounts of recognition ability have largely alternated between Nativist perspectives positing an innate preparedness to recognise the ‘basic emotions’ (e.g. Ekman, 1994; Izard, 1994), and empiricist accounts which highlight the role of experience in developing these abilities (e.g. Russell, 1994). More recently, Leppänen and Nelson (2006; 2009) have proposed a position that falls between these two theoretical accounts and is described below. Overall, in absence of an overarching theory, some research effort has been directed towards describing the perceptual, cognitive, and neural mechanisms involved in emotion processing, as well as advancing possible models of emotion processing during development. Below I shall discuss some of the most pertinent developmental theoretical perspectives.

2.1.1 Neural Basis of Facial Expression Recognition: Experience-Expectant and Experience-Dependent Developmental Mechanisms?

In what are still two of the most recent neurodevelopmental reviews of the literature, Leppänen and Nelson (2006; 2009) describe two possible developmental mechanisms of the neural circuitry underlying the ability to recognise facial expressions. These mechanisms incorporate both Nativist and Empiricist theoretical perspectives of biological preparedness and experience for this ability. The review largely focusses on neuroimaging findings from infant studies, which I will not describe in detail here as they are outside the scope of this thesis. It is important to cover the theoretical viewpoints of this review, however, as it describes the potential early foundations of emotion recognition processing and how these foundations may be refined throughout childhood, which are relevant to this review.

Leppänen and Nelson (2006) weigh up evidence of innate preparedness for facial expression recognition, most significantly from findings of universal recognition for some emotions (Ekman, 1999) which has led many to assume that facial expression recognition has a strong biological basis, against findings highlighting the role of experience in the development of this ability. They conclude that, given the influence of experience as demonstrated by studies showing that early social deprivation or institutionalisation can disrupt this ability (Parker, Nelson & the BEIP Core Group, 2005; Pollak, Ciccetti, Hornung & Reed, 2000; Fries & Pollak, 2004), a strong nativist account of facial expression recognition is inadequate. These findings, together with evidence from electrophysiological infant studies that cortical face-related systems are less specialised for facial information than mature systems (de Haan, Humphreys & Johnson, 2002; Halit, de Haan & Johnson, 2003) suggest that at least some of the components of the neural system subserving facial expression recognition are modified by experience. Leppänen and Johnson (2006) further conclude as studies have shown that the categorisation of facial expressions follows a similar developmental time course to the categorisation of other visual objects, it is unlikely that the development of facial expression recognition builds on perceptual mechanisms dedicated to this function alone, but instead shares a common underlying mechanism with other visual categories. Further discussion of the development of facial expression recognition as domain-specific or domain general will unfold later in this chapter.

Taking all of the findings together, Leppänen and Nelson propose that the developing brain's ability to process emotional expressions is best positioned within a neuroconstructivist framework (see Box 2.1) which emphasises the importance and interplay of both innate preparedness and experiential input. They posit two potential neural mechanisms at the foundation of the developing brain: an experience-expectant mechanism and an experience-dependent mechanism (Figure 2.2). They suggest it is possible that we have evolved to 'expect' some of the universally recognised emotions due to their presence throughout evolutionary history. Brain mechanisms may therefore have evolved that are biased towards processing emotionally salient signals from the face. The early maturation of emotion-related brain circuits, functional coupling of these circuits with cortical perceptual areas, and behavioural evidence of attentional biases for emotional compared to neutral facial expressions are cited as evidence that is compatible with a foundational experience-expectant mechanism for emotion recognition in the developing brain.

Box 2.1. Neuroconstructivism: A unifying framework for the study of cognitive development that brings together constructivism (in which development is viewed as a progressive elaboration of increasingly complex structures), cognitive neuroscience (which aims to reveal the neural mechanisms underlying behaviour), and computational modelling which details specific as opposed to descriptive specifications of information processing (Sirois et al., 2008). The framework is used to investigate how the representations underlying cognition emerge in the brain during development. Such representations are thought to occur as a result of a constructivist process involving *context-dependent* constraints that operate at all levels, from the cellular to the social environment. In this way, cognition cannot be studied independently of the brain and body. Functional brain systems are interrelated with other functional systems which are located within a body and an environment. Each of these contexts provide levels and sources of information that are incorporated into neural representations.

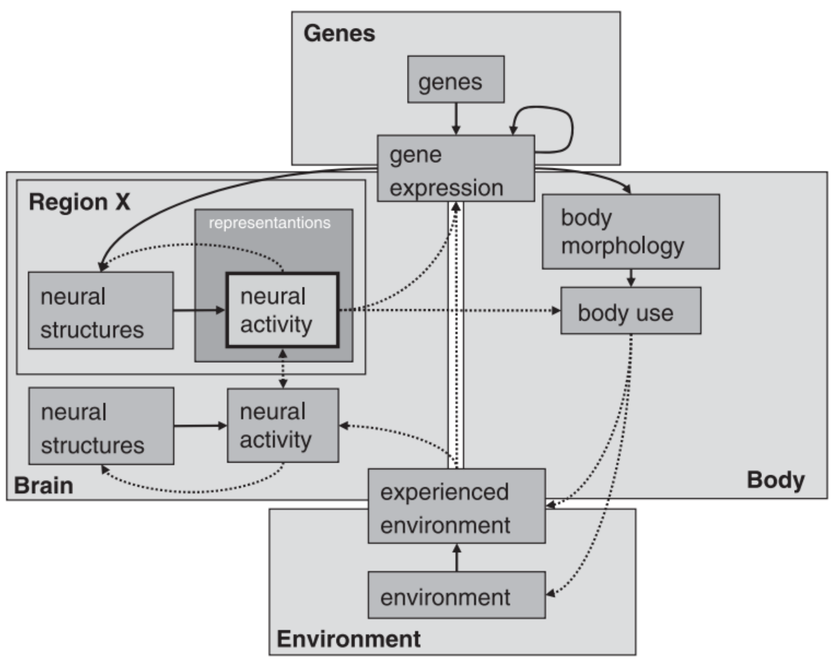

Figure 2.1. How constraints on neural development interact to shape the construction of representations in the brain. Example of multiple interacting constraints (solid lines) which shape the construction of representations (neural activation patterns) in a cortical region X. As region X is not a primary sensory area, the effects of environmental changes are mediated through other cortical regions. Representations can effect their own change (dashed lines indicate the

induction of change) through multiple loops involving genes, other brain areas, the body, and the environment (Westermann et al.,2007).

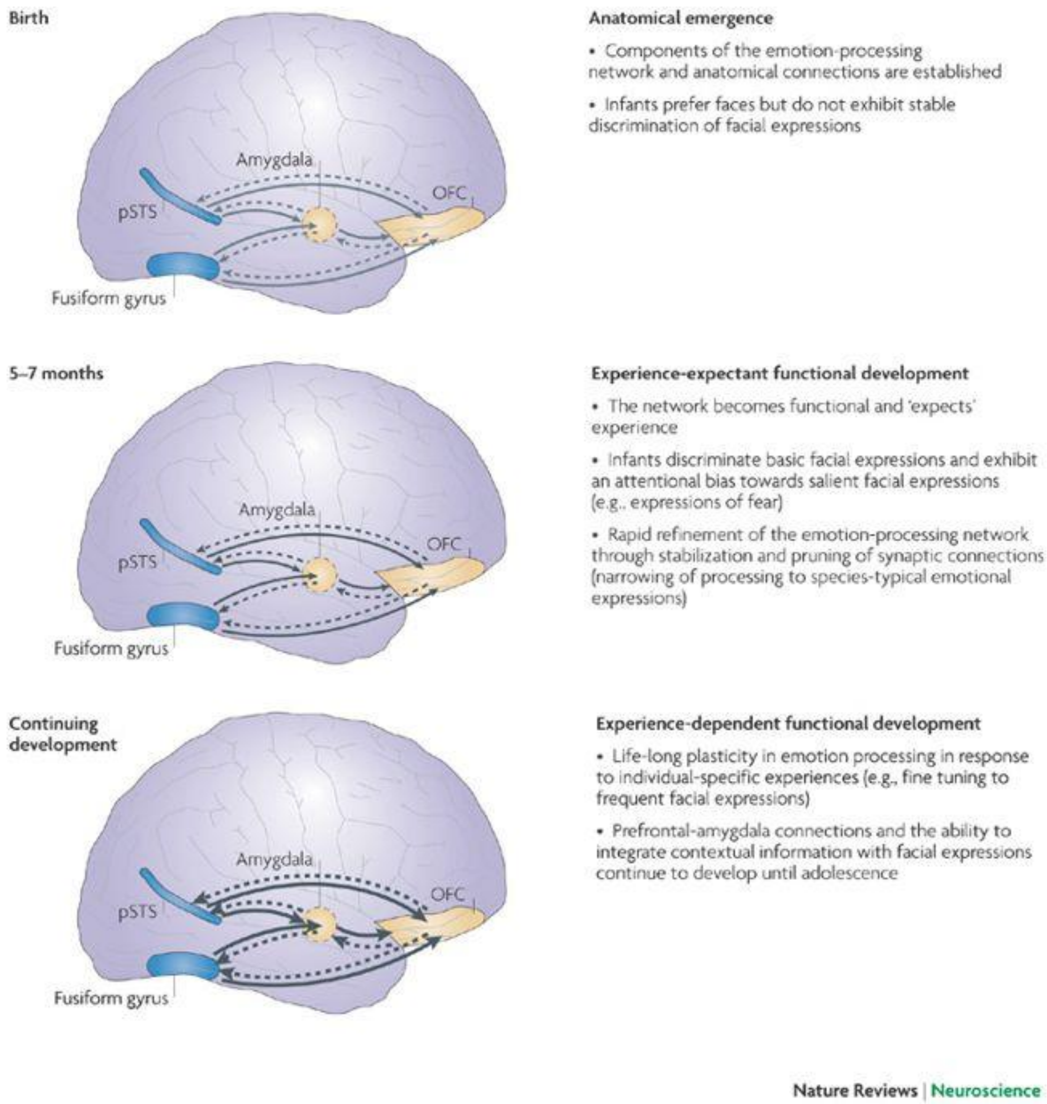

Figure 2.2. A proposed model of the development of emotion-recognition mechanisms. This model describes the basic organization of emotion recognition networks including an experience-expectant neural circuitry that emerges at 5–7 months of age and is rapidly refined by exposure to universal features of expressions during a sensitive period of development (perhaps the first few years of life). This network retains some plasticity throughout the lifespan and can be fine-tuned by individual-specific experiences (that is, experience-dependent development). Functional connectivity between emotion-processing networks and other prefrontal regulatory systems continues to develop until adolescence. Development is affected by genetic factors (for example, functional polymorphisms that affect the reactivity of relevant neural systems), environmental factors (the frequency of seeing certain emotional expressions), and their interaction (Leppänen and Nelson, 2009).

Although the early brain system is prepared to process facial expressions with an experience-expectant mechanism slightly biased towards biologically salient cues, Leppänen and Nelson suggest the circuitry is likely coarsely specified and needs exposure to species-typical emotional expressions to develop into a mature system with adult-like specificity for facial expressions. An experience-dependent mechanism is therefore posited for this function with evidence of the influence of experience on the developing system coming largely from findings that emotion-recognition abilities are disrupted in maltreated children. The development of such a mechanism may involve the strengthening of some synaptic connections and the pruning of others according to the processing of information prevalent to individual experience. In this way, they surmise it is possible that perceptual narrowing occurs, a narrowing in the range of stimuli to which the system responds that has been evidenced in the development of general face-processing skills (Pascalis, de Haan, & Nelson, 2002).

This model repositions the evidence from infant and some later childhood studies within a neuroconstructivst framework to describe a perspective that incorporates the roles of both innate preparedness and of experience on the development of emotion recognition. It thus advances previous outmoded and potentially simplified nativist versus empiricist developmental perspectives. This account corresponds with factors which have been shown to modulate the development of facial expression recognition summarised from behavioural studies, for example cultural and emotional experience (e.g. Geangu et al., 2016; Pollak et al., 2000). The authors also highlight that their perspective accords with Pollack's (2003) suggestion that the development of facial expression recognition builds on a general perceptual-cognitive mechanism that the infant uses to categorise sensory information, and through learning of the temporal synchrony of emotion-related information with experience the mechanism becomes tuned to specific patterns of signals. Leppänen and Nelson emphasise the main difference between perspectives is that they hypothesize any such general mechanism is biased towards learning from facial expressions in particular. Further similarity is also acknowledged between their views and models of facial identity processing that posit a specialisation for processing species-typical faces is developed through exposure after an initial domain-general system.

A further strength of Leppänen and Nelson’s reframing is that it stimulates several new hypotheses, including for example from the experience-expectant mechanism, the existence of sensitive periods in development in which this neural mechanism expects exposure to emotional expressions. They also suggest from the experience-dependent mechanism that since such a mechanism is not tied to a specific time point in development the brain's ongoing plasticity is inferred. Therefore, just as experience can shape perceptual biases, the theory posits that these biases can also be further modified. For example, the response bias for anger shown by maltreated children could potentially be undone. While the mechanisms described may stimulate new hypotheses, one criticism is that they would be difficult to falsify. How could the existence of sensitive periods in development which expect exposure to emotional expressions be falsified? There may be no ethical test for this but similarly falsifying one of the experience-expectant mechanism’s hypothesis that perceptual biases which have been shaped by experience can be altered would also be challenging. However, the large benefit the model brings to the developmental literature is the emphasis that facial expression recognition is dependent on many factors influencing this processing; from genes to the brain, the body, and the environment. As a whole, many of these factors of influence have been underlooked in the literature and reinforce the necessity to broaden the study of facial expression recognition by integrating these factors.

We now move to theoretical perspectives based on behavioural findings in childhood beyond infancy. As development progresses, research has focused on investigating the age at which different expressions can be recognised and the role experience plays in the development of this skill.

2.1.2 Broad to Discrete Categories? Differentiation Model of Emotion Understanding

The second theoretical perspective discussed here, Widen and Russell's (2003) *Differentiation Model* also known as *The Broad-to-Differentiated Hypothesis* (Widen, 2017), is developed from behavioural findings based on pre-schooler's emotion understanding in facial expression recognition and story-emotion labelling tasks. While the current thesis investigates the development of facial expression recognition using images of expressions alone in categorisation tasks, as opposed to more complex story telling stimuli that involve describing the cause of the emotion, Widen and Russell's model comprises one of the few developmental perspectives of how emotion understanding evolves so is therefore valuable to discuss.

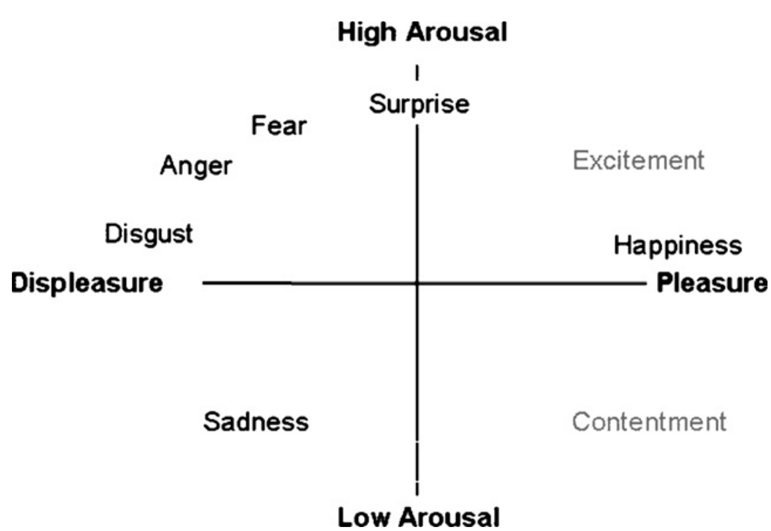

Figure 2.3. The Circumplex Model of Emotion on which the Differentiation Model was based. (From Widen & Russell, 2008b) The model shows the dimensions of valence (pleasure and displeasure) across the x-axis and the dimension of arousal (high-low) across the y-axis on which all emotions can be fitted. The six basic emotions used in the free labelling and categorisation tasks from which the Differentiation Model was developed are represented on these dimensions. The emotions printed in grey represent those used in categorisation tasks only.

The Differentiation Model describes how young children acquire emotion labels and develop emotion concepts. Widen and Russell argue that contrary to traditional discrete-category accounts of emotion understanding in which children firstly understand emotions as discrete categories with labels (e.g. angry, sad etc.) children develop emotion understanding through differentiation (Widen & Russell, 2008a). The theoretical foundation of this differentiation account stems from a dimensional model of emotion, Russell's (1980) Circumplex Model of Emotion (Figure 2.3). From the earliest age described in the model, Widen and Russell propose that 2-year-olds understand emotions in terms of the broad dimensions of valence (pleasure-displeasure) and arousal (high-low), rather than as the discrete categories that adults come to understand (Figure 2.3). Widen and Russell posit that children's understanding of emotions develops gradually from these initial broad dimensions and are slowly narrowed conceptually to discrete categories such as anger and disgust. The process of differentiation therefore involves the gradual distinction of emotion categories from the initial broad negative-positive dimensions.

Four key findings from facial expression recognition and story-emotion labelling tasks are given as evidence for the Dimensional Model (Widen & Russell, 2008b). Firstly, children's errors were systematic rather than random from the ages of 2 to 5 years and these miscategorisations were made with emotions that were most similar according to the structure of the circumplex model. Secondly, the number of emotion labels emerges in a systematic order during this age (2-5 years). Thirdly, different labels were used with different frequencies for each emotion. The most frequently used labels were the categories which emerged earliest (happiness, sadness, anger), and those found to emerge at a later age were used less frequently (fear, surprise, disgust). Finally, they argue that emotion categories narrow with age as, for example, younger children use happiness as a label for several expressions whereas 4-5-year-olds use this label for fewer expressions.

The Differentiation model is a descriptive account of how children develop understanding of emotion concepts. It offers an alternative perspective to the common discrete emotion's account of how emotion understanding may unfold during development. Evidence from brain studies is lacking from the differentiation account which could bolster the current behavioural findings supporting this account. Brain studies with 7-month-old infants have found evidence for the categorical representation of facial expressions by measuring the event-related potential (ERP) response to within-category (e.g. happy-happy) and between-category facial expressions (Leppänen, Richmond, Vogel-Farley, Moulson & Nelson, 2009). Data from this visual pairing test showed reliable discrimination for the between-category expressions only; no reliable discrimination for the within-category expressions was found. It is possible that in infancy, at the perceptual level, the representation of facial expressions is categorical and that during development as conceptual knowledge develops and contributes to the processing of facial expressions that conceptual representations of emotions are not categorical (see Figure 1.8, Adolphs' model: Processing of Emotional Facial Expressions as a Function of Time, and Brooks & Freeman, 2018; Gendron, Lindquist, Barsalou, & Barrett, 2012; Nook, Lindquist & Zaki, 2016).

The debate on whether emotions are discrete entities categorically represented or whether perception is more graded and lies on a dimensional space is deeply protracted and unlikely to be resolved soon. A complete review of the neural evidence for these contradictory views is outside this scope of this thesis. It is important, however, to underline that different accounts of the development of emotion perception and understanding during childhood and adulthood continue to exist and demonstrate that there is still lot of work required to develop a generally accepted theory of emotion recognition. I think some of the disparity is caused by the lack of definition of what is being studied. For example, a study of facial expression recognition is concerned with perception of emotion from the face as opposed to what an emotion is. So, theories of facial expression recognition need to be clearly defined in opposition to theories of emotion. The Differentiation Model is perhaps an example of this blurring of lines. As both perceptual tasks of facial expression recognition with isolated faces and emotion understanding tasks with stories in which the cause of the emotion is to be identified are mixed together in one account. It is possible that by restricting the stimuli to perceptual images uniquely, the order in which the emotion labels are acquired in the differentiation model may change. However, can perceptual and conceptual accounts of emotion truly be separated?

2.1.2.1 Emotion Perception versus Conceptual Knowledge of Emotion

Recent theoretical advances include growing evidence that a perceiver's conceptual knowledge about emotion is involved in emotion perception, even when a facial expression is presented in isolation with studies showing for example that conceptual knowledge predicts the representational structure of facial emotion perception (Gendron, Lindquist, Barsalou, & Barrett, 2012; Nook, Lindquist & Zaki, 2016). In a recent study, adult participants assessed conceptually similar and perceptually similar emotion combinations (Brooks and Freeman, 2018). Emotions that had more similarity conceptually biased the perception of these emotions as more similar, while the physical similarity of the 'basic emotion' stimuli was controlled for. Replication of this study with children would clearly provide further clarity on how perceptual and conceptual categorization of emotion occurs during development. However, current findings are in line with a neuroconstructivist view of emotion perception; even during the rapid perception of prototypical ‘basic emotions’ top-down conceptual knowledge appears to influence facial emotion perception, as has similarly been shown for contextual information (e.g. Aviezer et al., 2008; Aviezer, Dudarev, Bentin, & Hassin, 2011) and body expression (e.g. Meeren, van Heijnsbergen, & de Gelder, 2005; Van den Stock, Righart, & de Gelder, 2007). Evaluating the bias given by top-down conceptual knowledge, Brooks and Freeman (2018) suggest their results do not necessarily implicate a special role for conceptual knowledge in emotion perception, but rather show that emotion perception has domain-general characteristics of a dynamic, predictive perceptual system. Further, they suggest their findings indicate that emotion perception involves the same kind of top-down predictions that are found in the perception of objects, words, and non-emotional social categories. The domain-general versus domain-specific nature of emotion perception is another debate which continues to be addressed in both adult and developmental studies. Current thinking on this topic in the developmental literature will now be considered.

2.1.3. The Development of Facial Expression Recognition: Domain-General or Domain-Specific?

The nature of the mechanisms driving the development of facial expression recognition continue to be questioned. Do improvements in facial expression recognition reflect broad, domain-general cognitive development or domain-specific, face-selective development? Studies have failed to accord on whether the development of facial expression recognition, or more broadly, face recognition, evolves differently (and thus indicating domain-specificity) compared to other classes of stimuli (e.g. Aylward et al..2005; Carey & Diamond, 1977; Crooks & McKone, 2009; Golarai et al., 2007; Johnston et al., 2011). There is no decisive response to this question, but recent developments shed further light on this dichotomy, perhaps as suggested above, by clearer definition of exactly what is being studied. Addressing face recognition more broadly, a recent developmental study compared performance on face perception and face memory tasks, which had not previously been distinguished, in children aged 5 to 10 and adults (Weigelt et al., 2014). Testing the hypothesis that if the development of face recognition is domain-specific then performance for faces should improve faster with age compared to other stimulus categories, the authors found performance improved at the same rate for faces and other categories in a perceptual discrimination task. However, face memory performance was greater than memory for other stimulus categories suggesting domain-specific development. Therefore, distinguishing between face perception and face memory tasks isolated previous conflating results showing both domain-general and domain-specific evidence for faces.

Largely, there is consensus that performance improves across childhood and adolescence for facial expression recognition at different rates according to the expression (Herba & Phillips, 2004; Lawrence et al., 2015; Rodger et al., 2015; Rodger et al., 2018). However, few studies compare performance for facial expressions with other stimulus categories which prevents domain-specific versus domain-general conclusions from being drawn at this point in time. A study using a similar paradigm to that of Weigelt et al. could help to further distinguish the nature of the mechanisms driving development by comparing facial expression perception and memory for facial expressions.

An alternative to the domain-general or domain-specific perspectives, domain-relevance, has been proposed by one of the leading thinkers on cognitive development (Karmiloff-Smith, 2015). The domain-relevant approach was cultivated from empirical evidence of genetic and developmental disorders which suggest that adult domain-specific knowledge is emergent rather than innate. Functional specialisation is thought to emerge progressively over time though neuronal competition during development. The domain-relevant approach posits biases are present in the infant brain which are somewhat more tuned to processing certain kinds of (relevant) input but are not specific to this input. An example of such a bias would therefore be the experience-expectant mechanism proposed by Leppänen and Nelson (2009), discussed earlier in this chapter, which shows an attentional bias towards the processing of salient facial expressions from early life. Crucially, this approach argues that there is no equivalent in the infant brain for specialised functions located in the adult brain. Such a domain-specific perspective fails to take into account the developmental history of the organism. Instead, in line with neuroconstructivist approaches, neural specificity found in the adult brain is thought to be an emergent property developed over time with interactions and constraints from a self-structuring system and the environment.

2.2 Common Behavioural Methodological Approaches to the study of the Development of Facial Expression Recognition

To describe how we arrived at the methodological approaches in the experimental contribution of this thesis, I will firstly discuss some of the most common behavioural paradigms used to study the development of facial expression recognition.

2.2.1 Main Paradigms

The broad aim of behavioural studies of the development of facial expression recognition has been to chart at which age specific emotional expressions are accurately recognised. The use of different tasks, age groups, and expressions has resulted in frequently disparate findings. However, there is agreement that the developmental trajectories for recognition of different expressions are not uniform. Some expressions are consistently recognised earlier than others, while other expressions are consistently among the most difficult expressions to recognise and are only recognised accurately by older children. Some of the main approaches to measuring children's recognition of facial expressions are now described.

2.2.1.1 Matching and Labelling Paradigms

In matching tasks, the participant must select the image of an expression which corresponds to the target emotion from a choice of two or several options (Figure 2.4). Traditionally, matching tasks have been used to try to minimise verbal ability and memory confounds in studying the development of facial expression recognition. Matching tasks are thought to be a more purely perceptual type of task than labelling studies, described below, as expressions are discriminated on the basis of visual properties alone (Adolphs, 2002). Most frequently matching studies employ two-, three-, or four-alternative forced choice expression options for comparison with the target

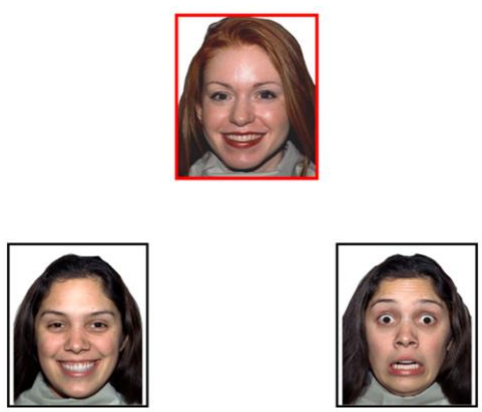

Figure 2.4. Emotion matching task (two-alternative forced-choice). The participant must choose which expression matches the target expression outlined in red.

expression and have revealed that recognition performance improves progressively between 4 and 10 years of age (e.g. Bruce et al., 2000; Mondloch et al., 2003; Vicari et al., 2000). With such tasks, a high level of performance is achieved by 10 years of age. However, slight modifications to matching tasks, such as an increase in the number of expression choices, or covering the target expression after a short interval, result in greater variations of performance (Vicari et al., 2000). Therefore, varying task demands, even for a relatively simply constructed task, alter recognition performance during development. The effect of task demands is widely acknowledged in the literature (Johnston et al., 2011; Montirosso et al., 2010; Vicari et al., 20000) and provides one of the reasons for the discrepancies found in performance across studies for different expressions. Since high levels of performance are frequently achieved by mid-childhood (e.g, Bruce et al., 2000; Harrigan, 1984; Mondloch et al., 2003; Vicari et al., 2000), matching tasks do not appear to challenge the maximum capabilities of children at this stage of development and were therefore not appropriate for our studies, which aimed to map the continuous development of facial expression recognition across childhood and adolescence, into adulthood.

Labelling tasks are a more complex type of task in comparison to matching tasks which, as described above, are closer to a purely perceptual type of task in which emotions are discriminated on the basis of visual properties alone. Labelling tasks require the child to retrieve the correct emotion label verbally for the target expression. Such tasks are therefore more suited to school-aged children with greater verbal capacities. Traditionally, labelling tasks use either forced-choice response categories or free labelling that allows for an unrestricted number of response options. In a study which compared matching and labelling tasks, as expected, recognition performance for the matching task was higher than for the labelling task in children aged 5 to 10 (Vicari et al., 2000). However, performance for each of the expressions followed a similar profile across the tasks, with the exception of sadness. The miscategorisations between categories can also be informative in this type of task as they indicate which expressions appear similar at which stage of development. As such, the comparison of miscategorisations during development to errors commonly made by adults can, in addition to accuracy scores, provide a further indicator of the maturity of facial expression processing skills. However, the analysis of miscategorisations across development remains for the time being an approach which has been understudied in the developmental literature. Recently, studies of emotional intensity, a method that has been used in a number of developmental studies, most frequently incorporate labelling tasks.

2.2.1.2 Modifying Emotional Intensity of Expressions

One common method used to obtain a more nuanced understanding of facial expression recognition during childhood is to vary the intensity of emotional expressions to identify whether more subtle expressions of emotion are recognised by older as opposed to younger children. Such results are anticipated as in daily life we most frequently perceive subtle, fleeting expressions of emotion. The intensity of the emotion is modified by creating parametric linear blends of two emotions, called a morph, as the two images are morphed together (Figure 2.5). Morphs are created by blending a percentage of an emotional expression with a different emotional expression or a neutral expression. The percentage increments for the emotion blends are determined a priori with 5, 10 or 20% increments most commonly used. The stimuli used for the morph can be either static or dynamic. As static stimuli were used in the experimental studies comprising this thesis, studies employing static stimuli are now discussed.

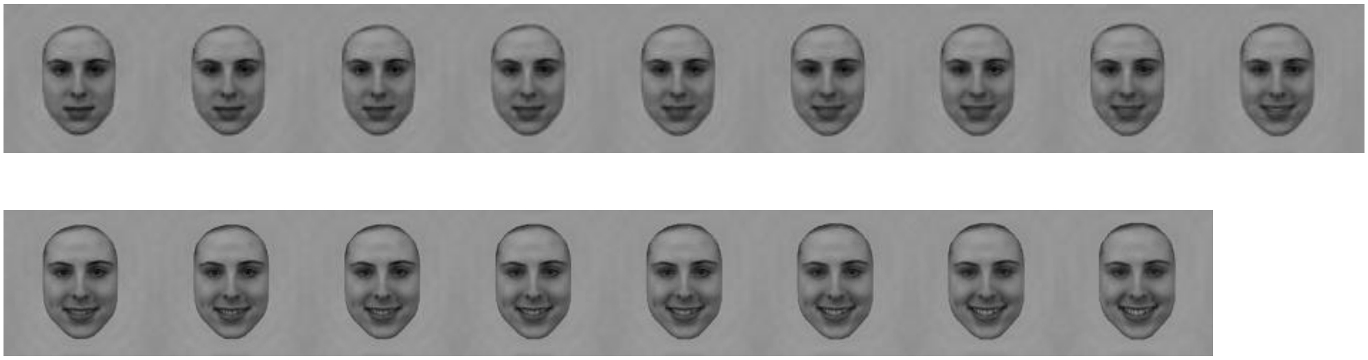

Figure 2.5. Neutral-happy emotion morphs. The expression intensity increases in 5% increments, beginning at 20% happy, 80% neutral in the top-right corner to 100% happy in the bottom-left corner.

The results have been mixed in response to the question: do older children recognize subtle expressions of emotion more easily? One of the earliest studies found no association between age and intensity of expression as predicted (Herba, Landau, Russell, Ecker & Phillips, 2006). However, it is possible that since the intensity levels used in the study were quite broad (25, 50, 75, and 100%) that differences in the mid-range could not be detected. Moreover, no adult group was included in this study, which is necessary to identify when recognition ability is closest to maturity. With the inclusion of an adult group and the use of finer intensity increments (11%), a study investigating sensitivity to fear and anger expressions revealed that only adults had significantly greater sensitivity to anger than both children and adolescents, but fear only differed significantly between adults and children (Thomas et al., 2007). It is possible with greater sensitivity, finer intensity increments, that further differences could have been detected between the age groups tested.

A variety of emotional expressions have also been included across behavioural approaches, making some cross-study comparisons difficult. At the time of the conception and data collection of the initial two studies of this thesis, only one study had tested recognition of all six basic emotions within the same paradigm (Gao & Maurer, 2010) in one of two studies which had used the finest intensity increments to-date (5%; Gao & Maurer 2009; Gao & Maurer, 2010). To investigate sensitivity to expression intensity not all six emotions were tested at once however, instead two subgroupings of emotions were tested. For all age groups, recognition accuracy for happiness reached ceiling-level performance. Between 5 and 10 years (the oldest age group tested), sensitivity to surprise, disgust, and fear improved, and sensitivity to sadness and anger continued to improve into adulthood. Several features of the paradigm make it difficult to draw definitive conclusions on sensitivity to emotion intensity in the age groups studied. Primarily, the true threshold applied here was a composite measure; a misidentification measure was calculated separately to the initial threshold measure. Furthermore, emotions could be misidentified only with emotions belonging to the same subgroup; thus, potential misidentifications across all six emotion categories were not possible. A single measure that accounts for miscategorizations could provide greater precision in the understanding of facial expression recognition. Finally, here, as with previous studies investigating sensitivity to intensity, the increments were established a priori, so the granularity of the measure can only be as fine as the predefined increments. To take advantage of these opportunities, we therefore introduced a psychophysical method to the literature in studies 1 and 2, described at the end of this chapter.

2.2.1.3 Measuring Speed of Response

The challenge, therefore, across methods has been to find appropriate tasks with sufficient sensitivity for use across development. Addressing studies that show little change in accuracy between 7 and 10 years of age, De Sonneville et al. (2002) proposed that speed of responding can provide a more sensitive measure to reveal age-related changes in facial expression processing. They found that the speed of responding greatly improved during this age range, whereas accuracy improvements were small. While speed of response revealed age differences, the task used to obtain a speed of response measure was a simple yes/no response to whether a face shows a target expression. The number of emotions that can be presented as alternative response options to the target emotion is limited because a speed of response versus length of task trade-off is expected. Information about miscategorizations across emotions similarly cannot be determined. Finding sufficient sensitivity with this paradigm for this specific age range therefore includes constraints on other performance indicators and information about facial expression recognition. Indeed, to the best of my knowledge, since this study no other study has used speed of response alone as a measure of facial expression recognition during development.

2.2.2 Use of Stimuli in Developmental Studies

Currently, developmental studies of facial expression recognition most commonly use facial expression stimuli from FACS-coded databases, which are also most commonly used in psychological and neuroscientific research with adults (e.g. Japanese and Caucasian Facial Expressions of Emotion, JACFEE, Matsumoto & Ekman, 1988; The Karolinska Directed Emotional Faces, KDEF, Lundqvist, et al., 1998; The Radboud Faces Database, RaFD, Langner, et al., 2010; Pictures of Facial Affect, POFA, Ekman & Friesen, 1976; Unmasking the Face-photo set, Ekman & Friesen, 1975, and the Montreal Set of Facial Displays of Emotion, MSFDE, Beaupré, Cheung, & Hess, 2000). Following this example in the use of normalised widely-available facial expression databases, we used the KDEF database for stimuli in our studies, with some amendments to the image properties described below. As described in the Chapter 1, the main issue that has been identified with such databases is that they potentially mask cultural differences in how emotions are represented (Jack & Schyns, 2015). The experimental studies of this thesis are not cross-cultural so this limitation does not directly affect our samples, but should be considered for future cross-cultural developmental studies. Some further potential limitations of stimuli are discussed in the final chapter.

Another consideration for the stimuli commonly used in developmental studies is the number of emotions studied. Across studies, a variety of emotional expressions from a variety of databases are included. This, in addition to the use of different tasks previously discussed, is another reason for the inconsistencies in recognition performance for specific emotions across studies. To date, no study has compared performance within the same group of children for two separate recognition tasks each comprising a different number of emotional expressions. Higher recognition performance could be expected for a simpler task containing fewer expressions. Such a study could answer the question of whether studies containing fewer emotions do find higher performance for the emotions included when compared to studies including a greater number of emotions. I chose to include all 6 basic emotions in the studies comprising this thesis firstly because at the time of conception no other studies included all six emotions and a neutral expression within the same task, and secondly because this could inform us about which expressions are most commonly confused across development and whether these confusions are similar to adult miscategorisations.

2.2.3 Response Options in Developmental Emotion Recognition Tasks

One important experimental design consideration when studying children is how the response will be recorded. The most appropriate response method will inevitably depend on the age of the children studied. I chose to study children aged 5 up to adulthood because of the distinct lack of studies of children of this age and of studies following the developmental progression of facial expression recognition up to adulthood. With children of this age, verbal responses are possible.

However, since I wanted to include all six basic emotions within the same paradigm, this number of response options was too many for young children to execute on a computer. So, children between the ages of 5 and 12 gave the response verbally and the experimenter coded the response.

The inclusion of an option for when a participant was not sure or did not know how to categorise the response was important to reduce the noise and potential response bias produced by the lack of such an option. In this way, uncertain categorisations are marginalised into this additional response category without causing a random response that biases the other response categories. As well as preventing biases in recognition accuracy performance, miscategorisations also remain unbiased. Miscategorisations therefore represent actual confusions of emotional expressions across development, with the exception of random errors of course.

Russell (1993) highlights the importance of having open response format options as the potential biases driven by forced-choices when the participant must choose one response amongst a number of named categories leave conclusions about performance unclear. Despite the possible bias led by forced-choice response designs, a more recent study compared forced-choice versus open response formats and found no difference in recognition performance for the six basic emotions between the two formats (Limbrecht-Ecklundt, et al., 2013). Similarly, accuracy rates for the six basic emotions were comparable across forced-choice and free labelling formats in another recent study (Widen, Christy, Hewett, & Russell, 2011). The potential biases originally thought to be imposed by forced-choice response formats are therefore perhaps not as severe as previously thought, however greater investigation of different response options is necessary within the developmental literature before any conclusions can be drawn.

2.3 Thesis Rationale: Introduction of Methodological Approaches to Map the Development of Visual Information Use

A review of the methods most widely used to measure the development of facial expression recognition revealed several areas of study that we wanted to target. As already described, due to a lack of research, our first aim was to measure facial expression recognition in school aged children and to map the continued development of recognition up to adulthood. To do this we required a measure that would be sensitive to the changes across the targeted range of ages. The common methods we reviewed did not provide sufficient sensitivity to reveal any potential differences across this age range. We therefore introduced a psychophysical method to the literature in studies 1 and 2 to quantify the amount of visual information required to recognise each of the basic emotions across development. The level of sensitivity achieved by this approach is beneficial to a developmental study. A precise measure of recognition can be obtained as the intensity increments for the stimuli in the psychophysical procedure are not predefined, as they have been in the methods previously reviewed. Instead, the intensity is incremented or decremented as a function of the observer's performance. By staying close to the observer's threshold with each stimulus presentation based on the previous response, adaptive staircase methods are efficient as the range of stimuli presented is reduced in this way. This efficiency allowed us to implement a paradigm including all six basic expressions and a neutral expression in a developmental study for the first time, which otherwise may have been too demanding for children as more trials would have been required. Overall, the precision of the measure permits a finer-grained representation of what is happening across development. Importantly, we also controlled low-level image properties such as contrast and luminance to minimise potential low-level confounds in the stimuli. The control of low-level image properties has been overlooked in developmental behavioural studies to date and needs greater consideration. For further details of the normalisation of image properties, the psychophysical method, and its implementation, please see the methods sections of studies 1 and 2.

In addition to quantifying how much visual information is required across development, I also wanted to investigate which visual information is used to recognise a facial expression across development. The visual system continuously processes perceptual inputs to adapt to the environment by selectively moving the eyes towards salient information. In this way, eye movements provide a functional signature of how human vision is achieved. We are particularly skilled at recognising affective information from faces (Leppänen & Nelson, 2009), and search for signals from the face to decode and integrate critical socio-emotional information which can help us to respond appropriately in different social settings. To-date, few studies have examined the perceptual strategies that are used to recognise an emotion throughout development.

Using eye tracking, we could establish whether perceptual strategies are similar across age and at what stage they can be considered mature. Eye-tracking has been a surprisingly under-utilised method in the childhood developmental studies of facial expression recognition. Indeed, as the review of eye-tracking studies in Chapter 5 reveals, there are also few studies with adults. Studies with adults have shown unique scan patterns according to the emotion observed, and the diagnostic information for each emotion is also unique (Jack, Blais, Scheepers, Schyns, & Caldara, 2009; Schurgin et al., 2014). Critically, only one study has examined the development of eye movement strategies in healthy school-aged children during facial expression recognition (Naruse et al., 2013). It was therefore important to target the lack of eye-tracking studies, particularly by investigating the continued development to determine how perceptual strategies develop. In the single eye-tracking study of school-aged children, recognition performance improved with age, however, the relationship between this improvement and changes in gaze strategies was not established. An analysis of gaze count and fixation times for the regions of interest studied (inner face area and the eyes; for a critical appraisal on the use of ROIs, see Caldara & Miellet, 2011) did not reveal any significant differences between age groups for the expressions showing improved accuracy. In study 3, we therefore aimed to establish how gaze strategies change across development, when strategies become mature, and how strategies relate to performance.

II. EXPERIMENTAL STUDIES

Chapter 3

Study 1: Mapping the Development of Facial Expression Recognition

Developmental Science

Developmental Science 18:6 (2015), pp 926–939 DOI: 10.1111/desc.12281

PAPER

Mapping the development of facial expression recognition

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Abstract

Reading the non-verbal cues from faces to infer the emotional states of others is central to our daily social interactions from very early in life. Despite the relatively well-documented ontogeny of facial expression recognition in infancy, our understanding of the development of this critical social skill throughout childhood into adulthood remains limited. To this end, using a psychophysical approach we implemented the QUEST threshold-seeking algorithm to parametrically manipulate the quantity of signals available in faces normalized for contrast and luminance displaying the six emotional expressions, plus neutral. We thus determined observers' perceptual thresholds for effective discrimination of each emotional expression from 5 years of age up to adulthood. Consistent with previous studies, happiness was most easily recognized with minimum signals (35% on average), whereas fear required the maximum signals (97% on average) across groups. Overall, recognition improved with age for all expressions except happiness and fear, for which all age groups including the youngest remained within the adult range. Uniquely, our findings characterize the recognition trajectories of the six basic emotions into three distinct groupings: expressions that show a steep improvement with age – disgust, neutral, and anger; expressions that show a more gradual improvement with age – sadness, surprise; and those that remain stable from early childhood – happiness and fear, indicating that the coding for these expressions is already mature by 5 years of age. Altogether, our data provide for the first time a fine-grained mapping of the development of facial expression recognition. This approach significantly increases our understanding of the decoding of emotions across development and offers a novel tool to measure impairments for specific facial expressions in developmental clinical populations.

Research Highlights

- Our data provide a fine-grained mapping of the development of facial expression recognition for all 6 basic emotions and a neutral expression.
- Model fitting revealed that the developmental trajectories of facial expression recognition followed 3 trends: Disgust, neutral and anger expressions showed a steep improvement across development; sadness and surprise showed a more gradual improvement; whereas recognition of happiness and fear remained stable from early childhood suggesting that the coding for these expressions is already mature by five years of age.
- Two main phases were identified in the development of facial expression recognition, ranging from 5 to 12 years old and 13 years old to adulthood.
- This approach offers a novel psychophysical tool to measure impairments for specific facial expressions in developmental clinical populations.

Abstract

Reading the non-verbal cues from faces to infer the emotional states of others is central to our daily social interactions from very early life. Despite the relatively well-documented ontogeny of facial expression recognition in infancy, our understanding of the development of this critical social skill throughout childhood into adulthood remains limited. To this aim, using a psychophysical approach we implemented the QUEST threshold-seeking algorithm to parametrically manipulate the quantity of signals available in faces normalized for contrast and luminance displaying the 6 emotional expressions, plus neutral. We thus determined observers' perceptual thresholds for effective discrimination of each emotional expression from 5 years of age up to adulthood. Consistent with previous studies, happiness was most easily recognized with minimum signals (35% on average), whereas fear required the maximum signals (97% on average) across groups. Overall, recognition improved with age for all expressions except happiness and fear, for which all age groups including the youngest remained within the adult range. Uniquely, our findings characterise the recognition trajectories of the six basic emotions into three distinct groupings: expressions that show a steep improvement with age - disgust, neutral, and anger; expressions that show a more gradual improvement with age - sadness, surprise; and those that remain stable from early childhood - happiness and fear, indicating that the coding for these expressions is already mature by 5 years of age. Altogether, our data provide for the first time a fine-grained mapping of the development of facial expression recognition. This approach significantly increases our understanding of the decoding of emotions across development and offers a novel tool to measure impairments for specific facial expressions in developmental clinical populations.

Keywords: development, facial expression recognition, psychophysics, emotional expression.

Introduction

The ability to accurately decode complex emotional cues in our social environment is a defining feature of human cognition and is essential for normative social development. How we recognise and process facial expressions of emotion throughout development to reach maturity in adulthood is a pivotal question for developmental psychologists, neuroscientists, educators, and caregivers alike, aiming to trace both typical and atypical trajectories of this important social skill. Despite the relatively well-documented developmental course of emotion recognition in infancy, it is acknowledged that our understanding of the development of this important social function throughout childhood, particularly after the preschool years, remains limited (Mancini, Agnoli, Baldaro, Ricci, & Surcinelli, 2013; Thomas, De Bellis, Graham, & LaBar, 2007). This enduring gap in the literature is surprising, especially for this stage of development as opportunities for social learning increase greatly with the onset of school (Johnston et al., 2011) and evidence suggests that the ability to recognise facial expressions at age 5 predicts later social and academic competence (Izard et al., 2001). In one of the still most recent reviews of the development of facial expression recognition (FER) during childhood and adolescence, Herba and Philips (2004) specify the need for normative data across this age range, not only for a greater understanding of this vital social function throughout development, but also to aid identification of atypical emotional development. They further stress the need for studies examining the continued development of emotional expression recognition from childhood through adolescence into early adulthood, as very little is known about development across the full childhood range up to adulthood.

Infant and childhood behavioral studies of facial expression recognition have naturally employed diverse methods according to the presence or absence of language, making comparisons across these groups difficult. Two common approaches employed during the stage of interest here, from early childhood onwards, attempt to minimize language ability confounds by using minimal verbal communication. Matching and labeling tasks require participants either to match emotional expressions from an array of expressions, or to label emotional expressions in a forced choice paradigm or freely without constraints (Mondloch, Geldart, Maurer, & Le Grand, 2003). Across such studies there is general agreement that happiness is most accurately recognized at the youngest age, while fear is consistently one of the most difficult expressions to recognize. There is less agreement concerning the trajectory of the other basic emotions following mixed reports in the literature; sadness and anger are frequently cited to be recognized most accurately and earliest subsequent to happiness, followed by surprise and disgust (Herba & Philips, 2004; Widen, 2013). Some of the discrepancies reported for developmental rates of expression recognition can be accounted for by task effects, as FER performance has been shown to be task dependent (Vicari, Reilly, Pasqualetti,Vizzotto, & Caltagirone, 2000; Montirosso, Peverelli, Frigerio, Crespi, & Borgatti, 2010; Johnston et al., 2011). For example, even within the same study very different results can be found for the same expression depending on the task employed (Vicari et al., 2000). In this instance, performance for disgust across all age groups in the labeling task was much lower than in the matching task. This difference is most likely attributed to differing language demands of the labeling versus matching task, particularly as this trend was beginning to narrow in the oldest age group (9 to 10 years) possessing greater language ability.

A third behavioral approach has more recently been employed to examine children's facial expression recognition accuracy as a function of expression intensity. The motivation for such studies is derived from the fact that we frequently see more subdued expressions of emotion in daily life; therefore do older children recognize subtle expressions of emotion more easily? Again, the results reported in the literature have been mixed. One of the earliest studies found no association between age and intensity of expression as predicted (Herba, Landau, Russell, Ecker, & Phillips, 2006). Alternatively, inclusion of an adult group in a study investigating sensitivity to fear and anger expressions only revealed that adults had significantly greater sensitivity to anger than both children and adolescents, but for fear only differed significantly from children (Thomas et al., 2007). Quantitative differences determining the stage of development when full maturity is reached for each emotional expression can therefore only be established with the inclusion of an adult group, which has not previously been adopted by all studies. A variety of emotional expressions have also been included across behavioral approaches, making some cross-study comparisons difficult. Only one study, Goa and Maurer (2010), has included all six basic emotions in a non-computerized task to investigate sensitivity to expression intensity, however during the task the expressions were divided into two subgroupings so all six emotions were not presented at once together. Similarly, across studies there has been variation in how developmental age groups are defined, with most studies comparing age groups of between 3 to 5 or more years difference, again making some cross-comparisons of studies difficult. In sum, studies controlling for the continued development of emotional expression recognition from childhood through adolescence into early adulthood remain very limited (Herba and Philips, 2004). To the best of our knowledge there is only one such developmental study investigating relatively broad age groupings of between 3 to 5 years difference, from age 7 years up to adulthood (Thomas et al., 2007). However, this study was limited to fear and anger expressions uniquely. Further, much of the research focuses on younger age groups, therefore providing only a snapshot of differences at a particular stage of development. Essentially, both empirical limitations leave the question of how the development of facial expression recognition unfolds from early childhood up to adulthood unresolved.

Targeting these prevailing gaps in the literature, the primary aim of this study was to map for the first time the continuous development of facial expression recognition in children aged 5 up to adulthood for each of the six basic emotions and a neutral expression using a psychophysical approach. To the best of our knowledge, this is the first time a psychophysical approach has been used to investigate the development of facial expression recognition. We used the QUEST adaptive staircase procedure (Watson & Pelli, 1983) to establish each participant's recognition threshold for expression discrimination in a signal detection paradigm. The QUEST procedure parametrically manipulated the quantity of face signals available in the stimulus to determine the threshold signal strength at which an expression could be categorised, with lower thresholds indicating more effective discrimination. Based on previous developmental literature, we predicted a general improvement in recognition thresholds with age, and distinct developmental trajectories for each of the expressions, with happiness being recognised most easily at the lowest threshold and fear with most difficulty at the highest threshold.

Methods

Participants: 160 individuals participated in the study. 20 adults (*M* = 21.1 years, 18 females), 60 adolescents: 20 17-18 year-olds (*M* = 17.7 years, 13 females), 20 15-16 year-olds (*M* = 15.7 years, 11 females), 20 13-14 year-olds(*M* = 13.5 years, 11 females), and 80 children: 20 11-12 year-olds (*M* = 11.5 years, 9 females), 20 x 9-10 year-olds (*M* = 9.5 years, 10 females), 20 7-8 year-olds (*M* = 7.5 years, 10 females) and 20 5-6 year-olds (*M* = 5.6 years, 10 females). Children were recruited from local schools in the Fribourg and Glasgow regions, and parental consent was obtained for all children under the age of 16. The study was approved by the Department of Psychology Ethics Committee at the University of Fribourg.

Materials: The stimuli consisted of 252 grey scale images from the KDEF (Lundqvist, Flykt, & Öhman, 1998) comprising 36 distinct identities (18 male) each displaying six facial expressions (fear, anger, disgust, happy, sad, surprise) and a neutral expression. Images were cropped around the face to remove distinctive hair styles using Adobe Photoshop, and were aligned along the eyes and mouth using Psychomorph software (Tiddeman, Burt & Perrett, 2001). The images (256 x 256 pixels) were similarly normalized for contrast and luminance using the SHINE toolbox (Willenbockel, Sadr, Fiset, Horne, Gosselin, & Tanaka, 2010) in MATLAB 7.10.0 and displayed on an 800 x 600 grey background at a distance of 50cm subtending 10^{o} x 14^{o} to simulate a natural viewing distance during social interaction (Hall, 1966). The stimuli were presented on an Acer Aspire 5742 laptop using the Psychophysics toolbox (PTB-3) with MATLAB 7.10.0 and QUEST (Watson & Pelli, 1983), a Bayesian adaptive psychometric method (described below) to produce the level of stimulus intensity for each trial. An external USB keyboard was attached to the laptop so the experimenter could key the responses on behalf of the child participants.

Procedure: Before participating, to familiarize the children with the computerized emotion recognition task, each child was shown 7 faces expressing the 6 basic emotions and a neutral expression on individually printed sheets of paper and asked to respond to the question "how do you think this person is feeling?" To facilitate the familiarization task for the younger children in particular, the first image presented was always a happy face. If children were unsure of an emotional expression in the familiarization task they were told what the emotion was. The children were then asked if they could repeat this task by looking at images on a computer, however, this time the faces would be slightly hidden or blurred so it might be more difficult to see what the person is feeling, but to please respond as well as they could. Children aged 12 and under responded verbally and the experimenter keyed the response. Children were also told if they were unsure of an expression, or could not sufficiently see the expression to make a judgement, that they could say "next" and a new face would be presented. Such responses were then coded as "don't know" by the experimenter. Adolescent and adult participants were told that they would see a series of faces expressing an emotion and to please respond as accurately as they could to which emotional expression they saw by pressing the corresponding key on the keyboard. Labels were placed on the bottom row of keys for each of the 7 expressions, and on the space bar for “don’t know” responses. Adolescent and adult participants were given as much time as they needed to familiarise themselves with the response keys before beginning the experiment and were told that accuracy not response time was important so to take as much time as needed and to look at the keys if necessary before giving their response.

The experiment began with 14 practice trials to allow participants to become familiar with viewing faces covered with random noise. The transition from practice trials to experiment proper was seamless so the participant was not aware that the initial trials were for practice only. At the beginning of each trial a fixation cross was presented for 500 ms to locate the participant’s visual attention, followed by 500 ms presentation of the face stimulus displayed at the estimated level of signal strength from the QUEST psychometric procedure (described below), directly followed by a mask of random noise (see *Figure 3.1* for an illustrated example of a trial). The emotional expression stimuli were displayed randomly and when the recognition threshold for an expression was obtained (see section below on the QUEST procedure for details), that particular expression was no longer displayed and only images of the remaining expressions were sampled. Keying a response triggered the subsequent trial, so care was required with children to ensure that they were ready for the next stimulus presentation before the response was entered. The number of trials for each participant varied as a function of the QUEST procedure (again described below), so for the youngest children the experiment was paused at roughly mid-way and continued after a break.

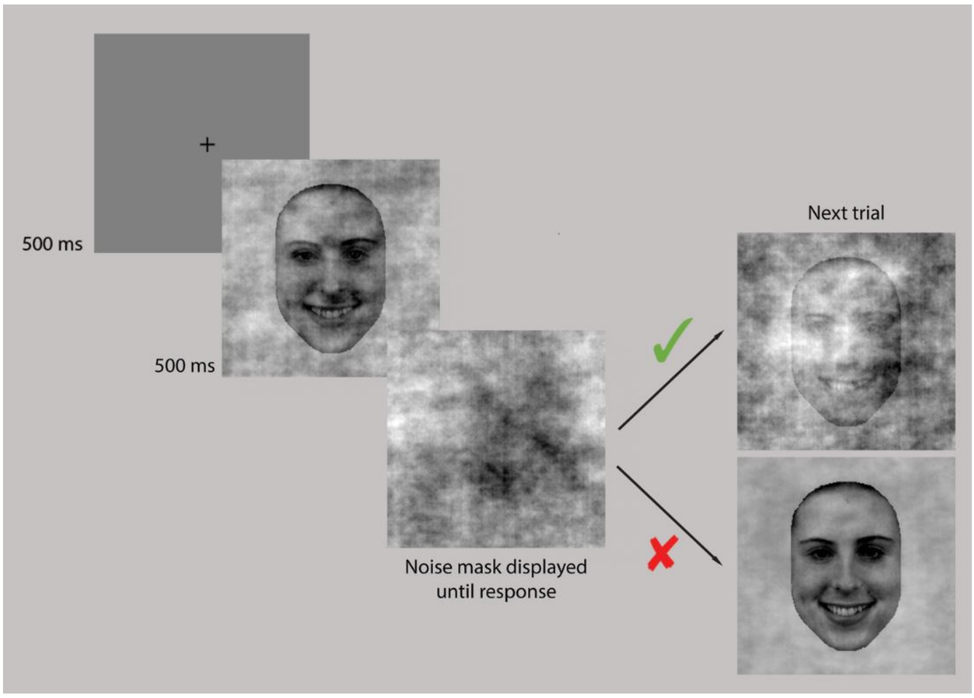

Figure 3.1 Example trial. Each trial began with a fixation cross presented for 500 milliseconds, followed by 500 millisecond presentation of a randomly selected face expressing one of 6 emotional expressions (happiness, surprise, fear, anger, disgust, sadness) or a neutral expression (randomly sampled from the 252 available images) at a signal strength estimated by the QUEST procedure, followed by a random noise mask which remained on the screen until the user provided a response and the next trial was initiated. All images were normalized for contrast and luminance.

The QUEST Bayesian adaptive psychometric procedure:

QUEST is a psychometric function that uses an adaptive staircase procedure to establish an observer's threshold sensitivity to some physical measure of a stimulus, most commonly stimulus strength (Watson & Pelli). The threshold obtained by the procedure therefore provides a measure of how effectively an observer can discriminate a stimulus. Adaptive staircase procedures obtain the threshold by adapting the sequence of stimulus presentations according to the observer's previous responses. Adaptive staircase methods can therefore be seen as more efficient in determining the observer's perceptual threshold for stimulus detection since the range of stimuli presented is reduced by staying close to the observer's threshold by accounting for their previous responses.

We adopted QUEST for this efficiency as it allowed us to implement a paradigm including all 7 expressions at once for the first time in a developmental study. The QUEST threshold seeking algorithm was implemented in MATLAB 7.10.0 with the Psychophysics Toolbox (PTB-3), to parametrically determine an observer's perceptual threshold for discriminating each of the 6 emotional expressions and a neutral expression. Adopting a signal-detection approach, QUEST was used to parametrically adapt the signal strength of the greyscale facial expression images presented to the participant by adding a mask of random noise to the image according to the current signal strength parameter determined by the function based on the participant's previous performance. If the expression was accurately or inaccurately discriminated on a given trial, then the subsequent signal strength estimate was decreased or increased. The final threshold estimate is determined as the signal strength where the expression is predicted to be discriminated on 75% of trials. In this way equal performance is maintained across observers. 3 QUEST procedures were implemented each with different initial stimulus strengths (60%, 40%, and 20%) to prevent possible bias in the final estimate towards the direction of the initial value. The threshold for detecting an expression was therefore the mean of the final estimates from each of the three procedures. The QUEST procedure terminates for an expression after 3 consecutive correct or incorrect trials in which the signal strength standard deviations are less than 0.025. The threshold is then calculated as the mean stimulus strength of these trials.

Data Analyses

Two-way Mixed Model ANOVA

To investigate the effect of age on emotion recognition thresholds, we performed a mixed model repeated measures ANOVA with emotional expression (7) as the within subjects factor, and age group (8) as the between subjects factor.

The threshold estimated by QUEST is the best indicator of performance using an adaptive staircase procedure. The number of trials might not be indicative of performance with this type of procedure, as a short number of trials can be indicative of either a well-recognized expression or a poorly recognized expression that terminated quickly due to consistent inaccurate categorization. Conversely, a long sequence of trials can be indicative of a mixed performance, which has alternated between correct and incorrect responses. For this reason we will not examine the number of trials here.

Generalized Linear Model Regression Analyses with bootstrap procedure

In order to characterise the decrease or increase in the amount of information required to accurately categorise an expression across development, we fitted general linear models (GLMs) across age groups independently per emotional expression. For each expression, we sampled with replacement the participants' mean recognition thresholds independently per group. We then computed the trimmed mean (30%) across 20 randomly chosen participants (with replacement), and repeated this procedure 1000 times, leading to 1000 (samples) x 7 (emotions) x 8 (age groups) threshold scores. We then used GLM to fit a line across the 8 age groups independently per emotion and sample, thus obtaining 7 x 1000 fitted linear models. We took the first derivative of each fitted line (which is equivalent to the beta obtained by fitting a GLM with an intercept) resulting in 1000 derivative values. Each derivative thus indicates the rate of decrease/increase in the amount of information required to categorise an emotional expression across age groups. To test whether the increase/decrease across age groups in the amount of information required to categorization an expression was significantly different between emotional expressions we computed 95% confidence intervals (btCI) on the differences (across all pairs of emotions) for our 1000 bootstrapped derivatives. For a given comparison, btCIs non-overlapping with zero indicate that the rate of decrease across development is significantly different.

Similarity Matrix and Multidimensional Scaling Analyses

To further characterize the relationship between age and expression recognition we computed a similarity matrix by correlating the average recognition threshold for all expressions across groups. We computed the mean across participants independently per age group and emotional expression, leading to 8 vectors (1 per group) of 7 emotional thresholds. We then iteratively Pearson correlated these vectors across all groups to obtain our similarity matrix. Each value within this matrix thus indicates the similarity of response profiles between 2 age groups. To clarify which age groups showed closest similarity in response profiles (i.e., calculated by correlating the vector of the mean recognition thresholds for all expressions across two age groups) during development we conducted multidimensional scaling analysis with a metric stress criterion. This produced an unsupervised arrangement (i.e. without presupposing categorical structure) of the age groups according to their response similarity (Torgerson, 1958; Shepard, 1980; Edelman, 1998). Thus age groups placed close together elicited similar response patterns.

Results

Mean expression recognition thresholds across development

The mean age group recognition thresholds for each expression category are shown in Figure 3.2, which provides a visual re-representation of the thresholds required for expression categorisation across age groups. Overall, the mean recognition thresholds improve with age between the youngest and oldest age groups. As predicted, the happy expression had the lowest perceptual threshold across all age groups. This expression could be discriminated at very low signal levels from the youngest age group. Conversely, all age groups showed the highest perceptual threshold for fear. Almost a full strength signal was required by all age groups to categorise this expression. Between the highest and lowest thresholds there was variation across age groups in the ranking of the thresholds for the remaining expressions. Figure 3.3 also illustrates the mean age group thresholds, line-plotted per expression.

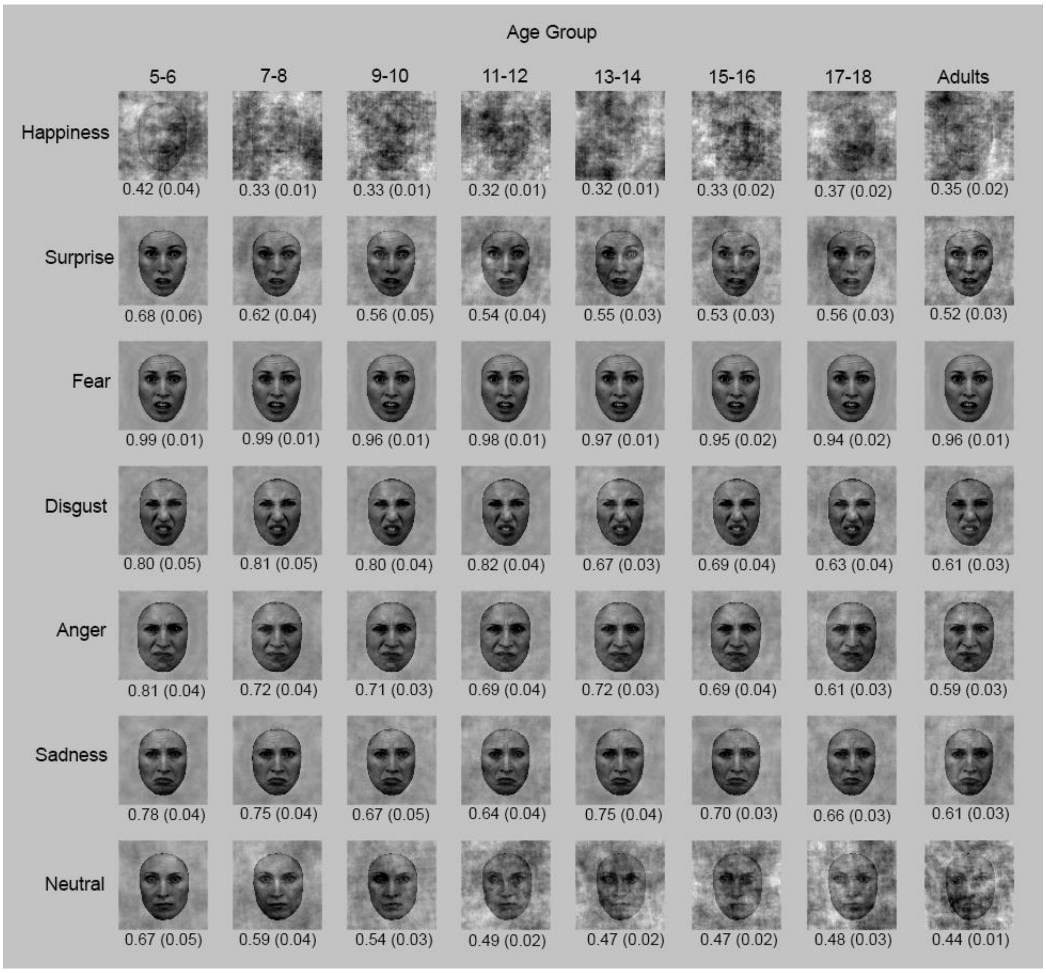

Figure 3.2 Mean recognition thresholds across development. Mean recognition thresholds for each expression category per age group. Numbers in parenthesis report the ± standard errors of the mean.

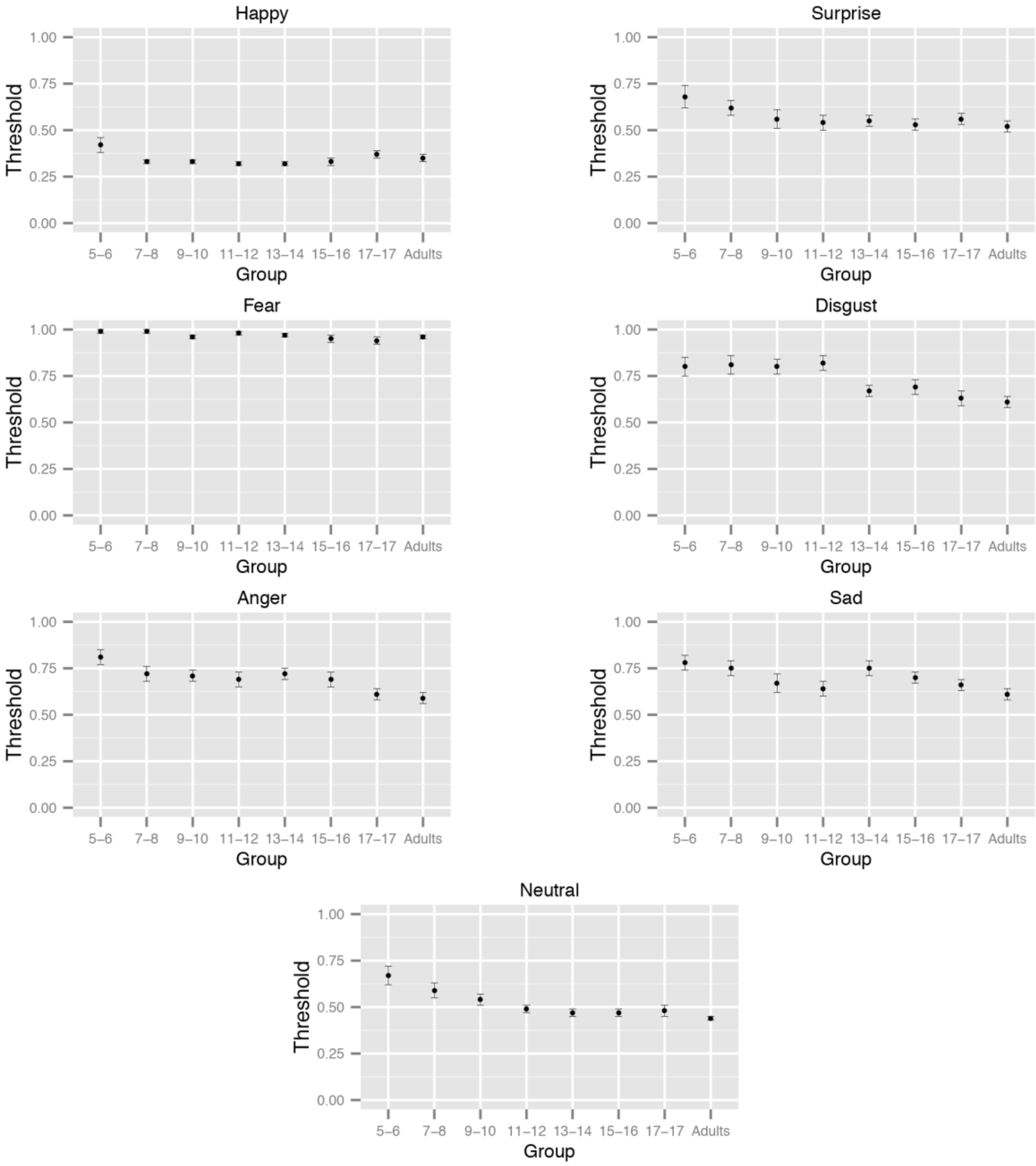

Figure 3.3 Age group mean recognition thresholds plotted per facial expression of emotion. Error bars report the ± standard errors of the means.

ANOVA Recognition thresholds by Age group

The mixed model repeated measures ANOVA examining the effects of age (8 age groups) and emotional expression revealed significant main effects for both age, *F*(7, 152) = 11.4, *p*=.000, and emotional expression, *F*(4.46, 678.09) = 303.34, *p*=.006. The interaction between age group and emotional expression was also significant, *F*(42, 152) = 3.76, *p*=.000, with

Greenhouse-Geisser corrections applied to the within-subjects factor.

Generalized Linear Model Regression Analyses with bootstrap procedure

The General Linear Model regression analyses (Figure 3.4) revealed a general improvement across development in facial expression recognition for all expressions except fear and happiness. The slope declines from the fitted models illustrate the level of decrease in recognition thresholds with age, and thus the decrease in the amount of information required to categorise an expression. Each emotional expression showed a unique trajectory across development and these trajectories could be more broadly categorised into three groups: expressions that showed a steep improvement in recognition with age up to adulthood - disgust, neutral, and anger; expressions with a more gradual improvement across development - sadness, surprise; and expressions that remained stable from age 5 up to adulthood – happiness and fear. The disgust expression showed the steepest improvement in recognition with age, closely followed by neutral. Alternatively, happiness and fear showed no significant improvement across age with slope derivatives remaining close to zero.

Figure 3.5a illustrates the boxplots of the means of the 1000 bootstrapped derivatives for each expression. Mean derivatives closest to zero indicate no rate of change in recognition thresholds across age groups. Recognition thresholds for fear and happiness with mean derivatives close to zero therefore did not improve across development. The disgust, neutral and anger expressions with mean derivatives furthest from zero therefore showed the steepest rate of improvement in recognition thresholds across development. The mean derivatives for sadness and surprise fall between the no rate of change fear and happiness expressions and the expressions showing the steepest rate of improvement across development, disgust, neutral and anger.

Figure 3.5b shows the 95% confidence intervals (btCI) on the differences across all pairs of emotions for the 1000 bootstrapped derivatives. High and low CIs non-overlapping with of zero indicate significant differences between the mean slopes of a given pair of derivatives. 95% btCIs show that the rate of decrease across development for both fear and happiness differed significantly from all other expressions.

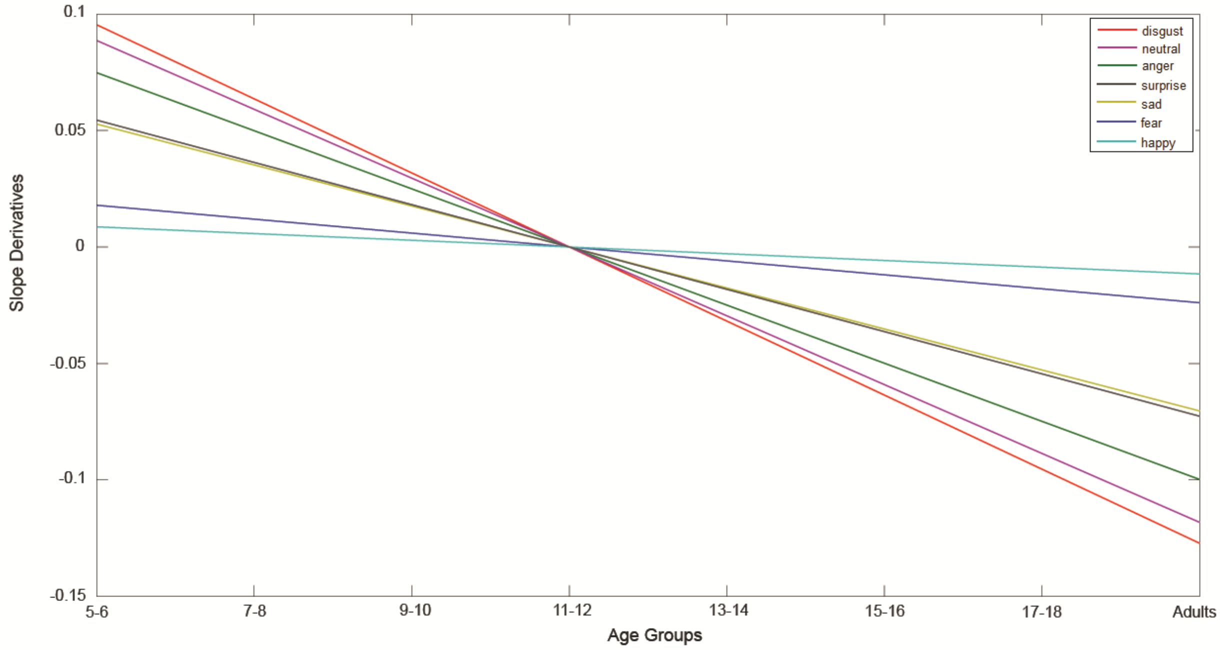

Figure 3.4 Linear Models: recognition thresholds across development. Slope decline of the fitted General Linear Model indicates the level of decrease in recognition thresholds with age. The derivatives were centred on the 11-12 age group for visualisation purposes. Disgust, neutral, and anger expressions show the greatest level of improvement in recognition with age. Recognition for sadness and surprise improves more gradually with age whereas happiness and fear remain stable.

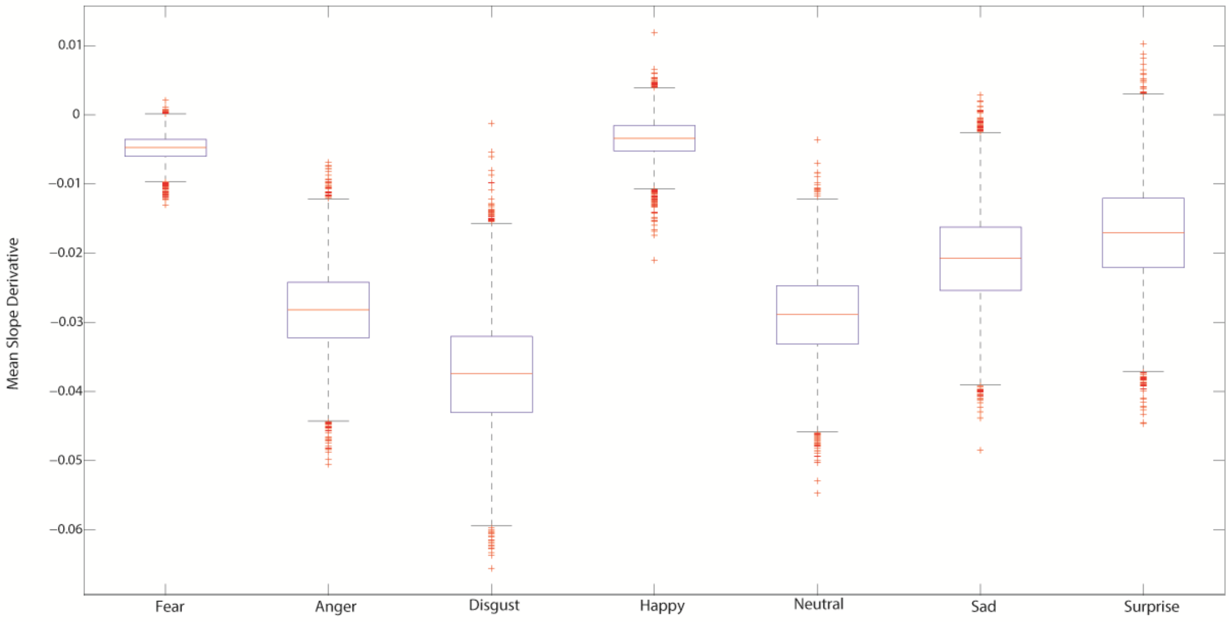

Figure 3.5a. Boxplot of the derivatives from the bootstrap populations. Boxplots of the derivatives from the bootstrap populations of the lines fitted across age groups independently per expression recognition threshold. The central mark reports the median of the distribution, the edges of the box are the 25th and 75th percentiles (i.e., interquartile range - iqr), the whiskers extend to a maximum of 1.5 times the length of the iqrs. Values falling 1.5 times outside the iqr are considered outliers and plotted as red crosses ('+'). Smaller values indicate greater slope decline and therefore greater improvement in recognition with age.

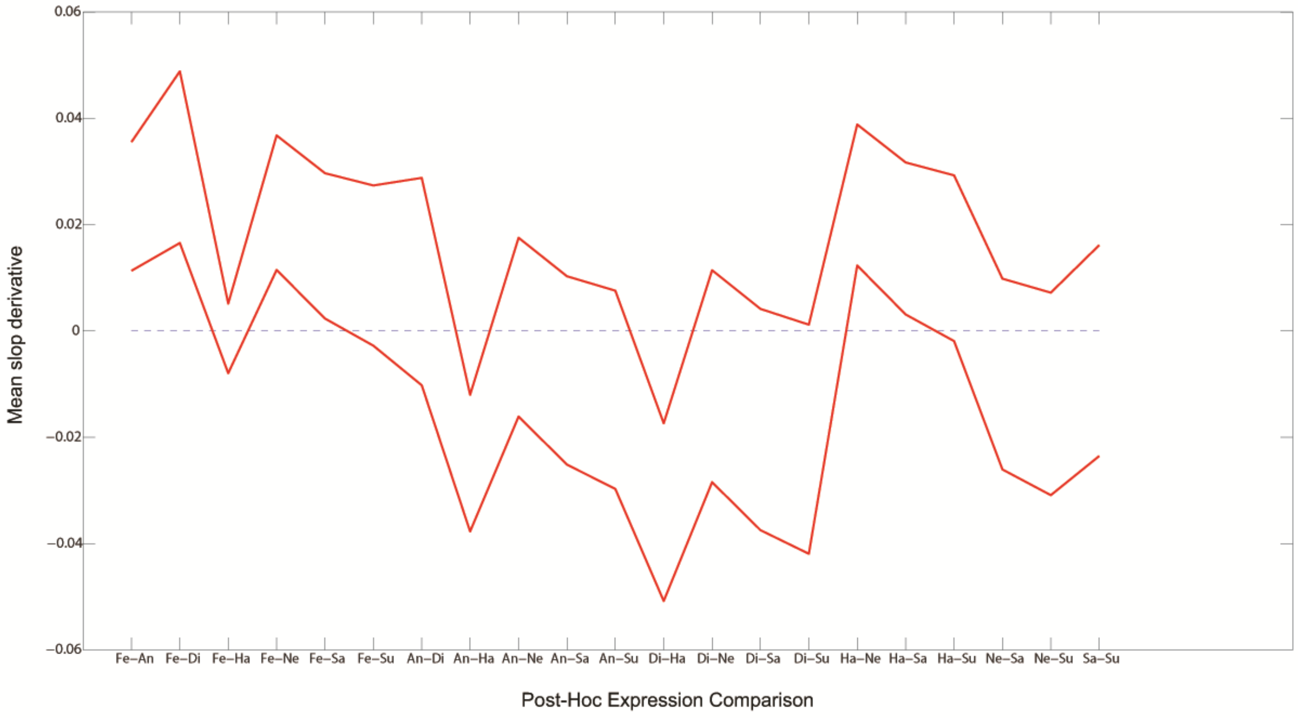

Figure 3.5b. 95% bootstrapped confidence intervals of the mean slope derivatives for all possible expression comparisons. The upper and lower red lines depict the high and low 95% bootstrap confidence intervals (CIs) respectively. High and low CIs that both fall on either side of zero, represented by the dashed line, indicate significant differences between mean slope derivatives across two conditions. Both fear and happiness differ significantly from all the other facial expressions of emotion.

Similarity of emotion recognition thresholds across development

The correlation of group means for all 7 expressions between age groups is illustrated with a similarity matrix in Figure 3.6a. Recognition thresholds were most similar between age groups closest in proximity. More broadly, the youngest age groups up to age 12 correlated well, as did the older age groups from age 13 up to adulthood. The multidimensional scaling analysis (Figure 3.6b) verified which age groups across development showed the most similar response profiles in overall mean recognition scores; the mean squared distances of age groups 5 to 12 clustered together showing similar overall response patterns, as did the age groups from 13 up to adulthood, suggesting there are two main phases during development in the recognition of facial expressions of emotion.

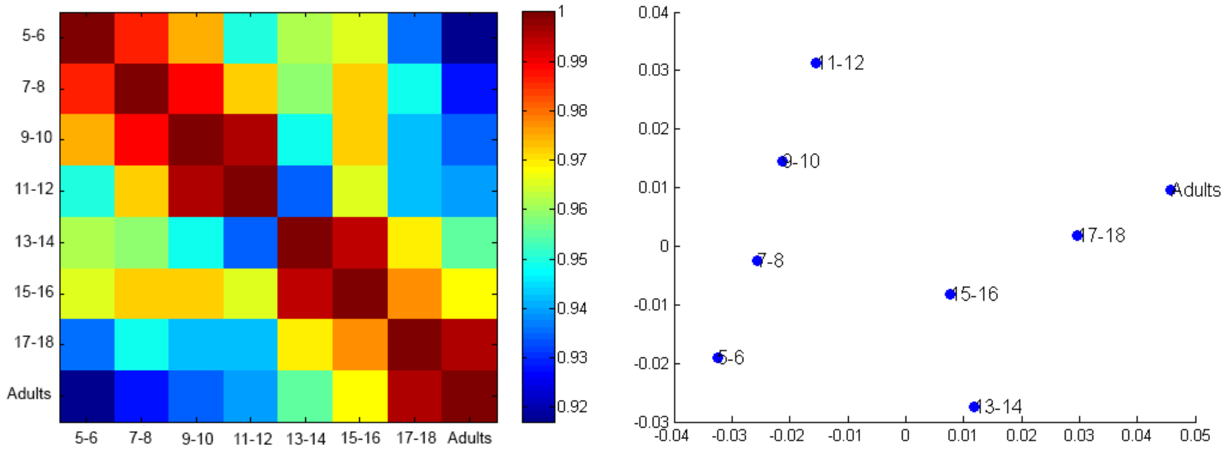

Figure 3.6 Similarity matrix of recognition thresholds by age group. (a) Similarity matrix (i.e. matrix of correlated pair values) of the mean group threshold profiles, for all 6 expressions plus neutral. Dark red indicates high similarity, and the values on the diagonal are of 1.
(b) Multidimensional Scaling Analysis: Euclidean distances of overall mean group thresholds.

Response biases for emotion categories:

Finally, to examine response biases we calculated confusion matrices for each expression and age group (Figure 3.7). For all age groups, fear was the most commonly confounded expression, as shown in the top right hand corner of the confusion matrices for each age group. Fear had the highest confusion rate with surprise, reaching up to 40% in the 11-12 age group. The confusion rate for fear with disgust also increased between the ages of 15-18 but remained lower than that of fear and surprise. The second most commonly confounded expressions were disgust and anger, reaching 30% for 7-8 year olds and to a lesser extent disgust with sadness, reaching 21% for 9-10 year olds. Lastly, sadness was most frequently confounded with the neutral expression across all age groups, with rates resting between 15-20%.

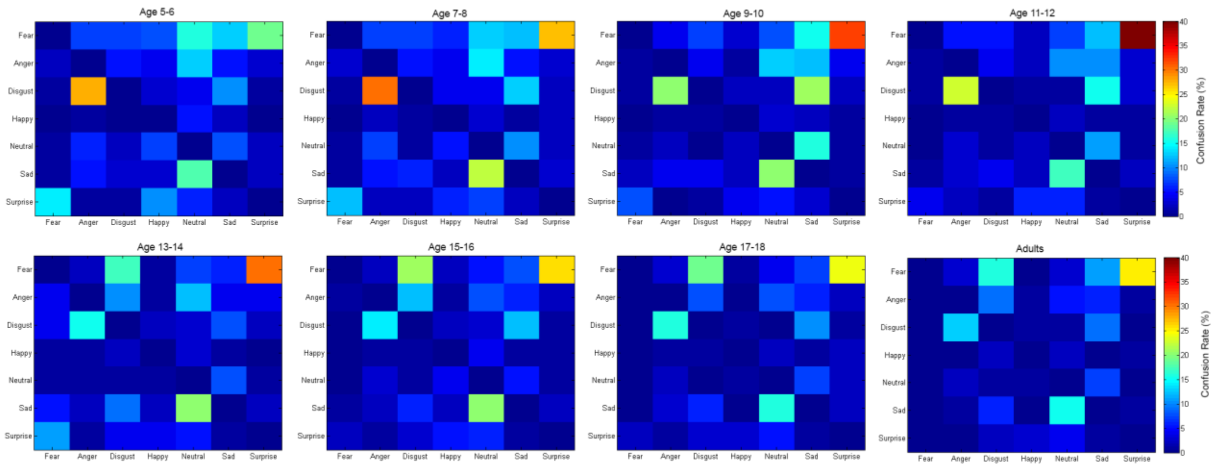

Figure 3.7. Facial Expressions of Emotion Categorisation Errors - Confusion matrices. Response biases for expression categorisation across age groups (%).

Discussion

Our results provide a fine-grained mapping of the development of facial expression recognition for all six basic emotions and a neutral expression throughout childhood into adulthood. Using a novel psychophysical approach that maintains equal performance across observers and facial expressions of emotions, we parametrically manipulated the quantity of face signals available to determine an observer's perceptual threshold for each of the six basic emotions and a neutral expression. By controlling for low-level properties such as contrast and luminance, we precisely estimated the quantity of signal necessary to achieve effective recognition for all basic facial expressions of emotion for the first time with young children up to adulthood. The precision and novelty of this approach therefore offer new insight to the understanding of how the development of facial expression recognition unfolds across development.

Overall, recognition accuracy improved with age for all expressions except fear and happiness, for which all age groups including the youngest remained within the adult range. Across development, happiness was the easiest expression to recognise as it was correctly categorized with minimum signals, whereas fear was the most difficult requiring maximum signals. This result confirms the particular status of both facial expressions of emotion, suggesting that the coding for these expressions is already mature at 5 years old. While fear and happiness were the most difficult and easiest expressions to recognise, the developmental profile of each expression was unique. Unique developmental trajectories for the recognition of individual facial expressions of emotion have been reported in the literature previously and our results further evidence this uniqueness (Boyatzis, Chazan & Ting, 1993; Vicari et al., 2000; Herba & Philips, 2004). Exclusively, our findings characterise the unique trajectories in recognition of the six basic emotions into three distinct groupings: expressions that show a steep improvement in accuracy with age up to adulthood - disgust, neutral, and anger; expressions with a more gradual improvement across development - sadness, surprise; and expressions that remain stable from age 5 up to adulthood – happiness and fear. Two main stages in the development of facial expression recognition were also identified. In the first stage, between the ages of 5 and 12 years, recognition thresholds across expressions followed a similar response profile and developed progressively. The second stage of development began with the onset of adolescence and continued up to adulthood as recognition thresholds across expressions during this stage also showed similar response profiles. It is worth noting that such response patterns were related to similar mean recognition thresholds for all the expressions (see Figure 3.2), ruling out the possibility that the high-correlation values were a result of significantly lower overall thresholds between two age groups. Within the second stage described here, our data do not clearly distinguish whether there is an additional period during early adolescence where the overall threshold diverges from the oldest three age groups. Further studies including more measures are necessary to clarify this pattern during early adolescence. Altogether, our data show that the recognition of facial expressions of emotion does not follow a unique monotonic dynamic throughout development.

Emotional expressions with a steep improvement in recognition across development: Disgust, Neutral, Anger,

Within the first grouping of expressions showing a steep improvement in performance with age, anger has similarly been found to show a sharp increase during development in several other studies (Montirosso et al., 2010; Gao & Maurer, 2010; Thomas et al., 2007; Vicari et al., 2000), although its comparative trajectory with all seven expressions at once has not been identified previously as we show here. In studies examining recognition performance as a function of expression intensity, somewhat closer to the psychophysical methodology employed here, all have shown a sharper increase in recognition of anger but not disgust with the exception of Herba et al. (2006) who report steeper improvements for both disgust and fear but not anger. Thomas et al. showed a marked increase in sensitivity to anger from adolescence to adulthood, but examined only fear and anger expressions. While the study did not investigate the neural underpinnings of this result directly, Thomas et al. suggest that later development in the recognition of anger fits with neurological evidence as the PFC continues to develop throughout adolescence, with the orbitofrontal cortex in particular being implicated in anger recognition (Murphy, Nimmo-Smith, & Lawrence, 2003). In addition to neurobiological accounts for later maturation of anger recognition, the effect of experience has also been evidenced as children growing up in hostile environments show higher accuracy for anger than typically developing children (Pollack & Sinha, 2002). More broadly, cultural differences have been shown in the expectations of facial expression signals and how these signals are decoded in adult populations, so socio-cultural experience also impacts recognition of expressions (Jack, Caldara, & Schyns, 2012; Jack, Blais, Scheepers, Schyns, & Caldara, 2009). Here, younger children showed comparatively more difficulty in recognising anger than the expressions showing more gradual trajectories, and were more likely to confound anger with a neutral expression as opposed to disgust as the four oldest age groups did. Anger recognition did not reach adult like performance until the oldest adolescent age group which, coupled with low miscategorisation rates across age, suggests the late maturation of anger recognition could reflect accumulated exposure to this expression which is frequently masked in various social contexts (Underwood, Coie, & Herbsman, 1992).

Previously reported trajectories for disgust recognition have been mixed. Most recently, an emotional intensity study found accuracy for disgust remained at a similar level in children between the ages of 5 to 10 years; however disgust was tested alongside surprise and fear expressions only, so it is possible its distinctness from these other expressions could have contributed to the stable performance (Goa &Maurer, 2010). An emotion intensity study using dynamic stimuli similarly did not find an age-related improvement for disgust between preschool and adolescence, but found that anger improved consistently from school age to late adolescence as we report (Montirosso et al., 2010). Conversely, an earlier study reports a steep developmental improvement on a labelling task for disgust in children aged 5 to 10, but a ceiling effect for disgust on a matching task using the same stimuli (Vicari et al., 2000). Since the visuo-spatial configuration of disgust is very distinctive, the authors suggest the steeper developmental improvement in the labelling task occurs because of greater lexico-semantic abilities in older children. However, when tested directly a more recent study found verbal ability does not significantly impact FER whereas labelling ability does (Herba et al., 2008). We do not attribute the steep improvement in disgust found here to greater labelling ability in older children since we accepted responses from younger children such as ‘he doesn’t like it’ or more simply a ‘yuck’ noise as accurate labels of disgust. Considering the more stable performance in disgust recognition found in the emotion intensity studies described above, methodological differences possibly account for this. Notably, the threshold obtained by this paradigm was a measure that was adapted from the observer’s previous response accuracy.

Previous studies have established intensity measurement increments a priori rather than on a trial-by-trial basis, and these increments have tended to be large so can lack the sufficient sensitivity to identify developmental differences in emotion processing where an adaptive measure permits greater sensitivity. Moreover, it is important to distinguish that while both paradigms use techniques to parametrically reduce the strength of the original expression to establish an observer's recognition sensitivity, one provides a measure of the intensity at which an expression can be recognised, while the other identifies the quantity of information required for accurate expression recognition.

Lastly, neutral, the final expression of the steep increase with age category, was not included in any of the emotional intensity studies previously discussed here as a distinct emotion category since intensity increments are defined by morphing neutral and emotional expressions together. In general, neutral expressions have been under-investigated in behavioural studies so very little is known about how neutral expressions are perceived during childhood. An early review states that children have difficulty recognising neutral expressions, and to our knowledge no recent behavioural studies have addressed the development of this expression specifically (Gross &Ballif, 1991). Our finding of a steep increase in improvement between the youngest and oldest age groups accords with this reported early difficulty and could be explained by a general bias to attend more to emotive faces throughout our social experiences (Leppanen & Nelson, 2009).

Emotional expressions with a gradual improvement in recognition across development: Sadness and Surprise

Sadness showed a gradual improvement in recognition across development and followed a similar trajectory to surprise. Generally, corresponding with our findings, children have been shown to perform well in recognising sadness (Herba & Philips, 2004; Widen, 2013). Several studies have shown that children aged 5 to 6 years do not perform as well as older children or adults, which accords with the slower developmental trajectory reported here (Vicari et al., 2000; Gao & Maurer, 2010; Montirosso et al., 2010), and this trend has been more frequently shown in studies of emotion intensity, with the exception of Gao and Maurer (2009) who found that children as young as 5 can recognise expressions of sadness as accurately as adults. Previous studies have shown that sadness is frequently confounded with fear, disgust, or neutral expressions, but have not tested all 7 expressions together at once so confusion rates varied according to which expressions sadness was categorised alongside. We show that sadness was most frequently confounded with neutral expressions across all age groups. To establish whether this miscategorisation is simply due to closer similarity in the facial configurations of these two expressions, further studies are needed to determine information use that leads to both accurate and inaccurate categorisation across development, as a reduction in miscategorisation with age is also shown here.

Surprise similarly showed a more gradual improvement in recognition accuracy across development. Of the emotion intensity studies that we have focussed on because of their closer similarity to the psychophysical method adopted here, similarly to the neutral expression, development in the recognition of surprise is not well documented. Inconsistency across the range of expressions tested at this stage of development was one of the motivations for conducting this study with all 6 basic emotions and a neutral expression. More generally, other methodologies have shown that surprise is recognized at a later stage of development than other expressions (Herba & Philips, 2004; Widen, 2012), however we found that when all expressions are compared together, the developmental trajectory for surprise is more gradual, with younger children performing well in recognition of surprise but at the same time showing higher confusion of surprise with fear than older age groups.

Emotional expressions that remained stable from early childhood: Happiness and Fear

Robust recognition of happiness from an early age was demonstrated by this paradigm as even with a very rapid presentation time of 500 milliseconds in comparison to previous developmental studies, and distortion of the emotional expression with a random noise mask, performance for happiness was highest and remained similar across age groups. Other studies have similarly found that children as young as five can recognise a happy expression as well as adults, and that happiness is the first expression to be accurately recognized (Gao & Maurer, 2009; Herba & Philips, 2004; Gross & Ballif, 1991). As mentioned above, of the emotional intensity studies cited here, Herba et al. (2006) found a steeper developmental trajectory in the recognition of fear than we report but the majority of studies showed findings consistent with a more gradual improvement (Thomas et al., 2007; Gao & Maurer, 2009; Gao & Maurer, 2010). However, previous emotional intensity studies have shown higher performance in recognition of fear at lower levels of intensity than we report, where almost maximum signals were required across development to categorize fear. While intensity and signal strength provide distinct measures, the high signal strength required here can be explained by the high variance in miscategorization rates for fear across development which prevented lower threshold rates from being achieved. Such variance could not be achieved in previous studies as they have not included all 7 expressions simultaneously. Fear was most consistently miscategorized as surprise at the highest rate across development of between 22 to 37%, and variability in miscategorizations was much greater compared to other expressions as confusions were found with all other expressions except happiness across age groups. The high confusion rate for fear and high variability of these confusions indicates that below a full signal level information was insufficient to categorise fear.

Fear as the most difficult or one of the most difficult expressions to accurately recognise with static images is consistently reported in both the developmental behavioural literature (Gross & Ballif, 1991; Herba et al., 2004; Widen, 2013) and the literature on adults (Rapcsak et al., 2000; Calder et al., 2003); however this difficulty is frequently juxtaposed with the evolutionary argument that accurate recognition of fear is critical to our survival in comprehending environmental threats. Fear is perhaps the strongest multisensory expression, for instance, people may shout when expressing fear. Consequently, our results and previous results showing difficulty in the categorization of fear suggest that this expression requires additional information to be effectively recognized, when presented as a static image in conjunction with several expressions. Additional cues from other modalities, and body posture or context, may enable more consistent recognition (Aviezer et al., 2008). Overall, our data show that fear and happiness share a special status in the framework of facial expression recognition as the coding for these expressions is already mature by 5 years of age.

Lastly, whether the perceptual mechanisms governing facial expression recognition are holistic or feature based, or whether each type of processing plays a differential role according to particular facial expressions is still debated in the adult literature (Beaudry, Roy-Charland, Perron, Cormier, & Tapp, 2014). Although this question is out with the scope of our study, it should be acknowledged that if holistic processing was affected by the use of noise to control for the quantity of signal, then all expressions were equally affected by this manipulation. Therefore, this potential impairment to holistic processing does not straightforwardly account for the differences in recognition thresholds across expressions and age groups. Our results and previous work (Jack et al., 2009) would instead favour a feature based processing account for facial expression recognition. However future developmental studies are necessary to directly address this issue, with paradigms controlling for facial feature information and metrics.

Conclusions

Our data provide a fine-grained mapping of the development of facial expression recognition for the six basic emotions and a neutral expression in children aged 5 up to adulthood. The novel psychophysical approach offers new insight to the understanding of how facial expression recognition unfolds, firstly by characterising the developmental trajectories of expression recognition into three distinct groupings: expressions that show a steep improvement in accuracy with age up to adulthood - disgust, neutral, and anger; expressions with a more gradual improvement across development - sadness, surprise; and expressions that remain stable from age 5 up to adulthood – happiness and fear; and secondly by identifying two main stages in the development of facial expression recognition ranging from age 5 to 12 and 13 up to adulthood. These insights have implications for caregivers and educators working daily with young children, particularly for expressions showing a steep improvement with age such as anger, as we show here that in early childhood anger is not easily recognised. Lastly the fine-grained scale of this approach in mapping the development of FER provides a benchmark for thresholds in typically developing children and offers a novel tool to measure impairments to individual facial expressions in developmental clinical populations, such as children with Autism Spectrum Disorders or social behavioural disorders.

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Chapter 4

Study 2: Quantifying Facial Expression Signal and Intensity Use During Development

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Quantifying facial expression signal and intensity use during development

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A B S T R A C T

Behavioral studies investigating facial expression recognition during development have applied various methods to establish by which age emotional expressions can be recognized. Most commonly, these methods employ static images of expressions at their highest intensity (apex) or morphed expressions of different intensities, but they have not previously been compared. Our aim was to (a) quantify the intensity and signal use for recognition of six emotional expressions from early childhood to adulthood and (b) compare both measures and assess their functional relationship to better understand the use of different measures across development. Using a psychophysical approach, we isolated the quantity of *signal* necessary to recognize an emotional expression at full intensity and the quantity of expression *intensity* (using neutral expression image morphs of varying intensities) necessary for each observer to recognize the six basic emotions while maintaining performance at 75%. Both measures revealed that fear and happiness were the most difficult and easiest expressions to recognize across age groups, respectively, a pattern already stable during early childhood. The quantity of signal and intensity needed to recognize sad, angry, disgust, and surprise expressions decreased with age. Using a Bayesian update procedure, we then reconstructed the response profiles for both measures. This analysis revealed that intensity and signal processing are similar *only* during adulthood and, therefore, cannot be straightforwardly compared during development. Altogether, our findings offer novel methodological and theoretical insights and tools for the investigation of the developing affective system.

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Research Highlights

- We studied the development of facial expression recognition from 5 up to adulthood.
- Discrimination of *signal* and *intensity* of facial expressions increases with age.
- Recognition of *fear* and *happy* expressions is stable from the age of 5.
- Facial expression *signal* and *intensity* information use converges in adulthood.
- Full intensity expressions are not comparable to varied intensities at early age.

Abstract

Behavioural studies investigating facial expression recognition during development have applied various methods to establish by which age emotional expressions can be recognized. Most commonly these methods employ static images of expressions at their highest intensity (apex) or morphed expressions of different intensities, but have not previously been compared. Our aim was (1) to quantify the intensity and signal use for recognition of 6 emotional expressions from early childhood up to adulthood, and (2) to compare both measures and assess their functional relationship to better understand the use of different measures across development. Using a psychophysical approach, we isolated the quantity of *signal* necessary to recognize an emotional expression at full intensity, and the quantity of expression *intensity* (using neutral-expression image morphs of varying intensities) necessary for each observer to recognize the 6 basic emotions while maintaining performance at 75%. Both measures revealed that fear and happiness were the most difficult and easiest expressions to recognize across age groups, a pattern already stable in early childhood. The quantity of signal and intensity needed to recognise sad, angry, disgust, and surprise expressions decreased with age. Using a Bayesian update procedure, we then reconstructed the response profiles for both measures. This analysis revealed that intensity and signal processing are similar *only* in adulthood and therefore cannot be straightforwardly compared during development. Altogether our findings offer novel methodological and theoretical insights and tools for the investigation of the developing affective system.

Introduction

Perceiving the emotions of others is fundamental to our daily interactions from birth, and by adulthood most have developed the capacity to read the emotional cues of others effortlessly. How we become proficient in reading the emotional cues of others is a critical developmental question, as it is well recognised that impaired emotion processing has negative consequences on social functioning and well-being at all stages of development (e.g. Carton, Kessler, & Pape,1999; Feldman, Philippot, & Custrini, 1991; Izard, Fine, Schultz, Mostow, Ackerman, *et al.*, 2001; Nowicki & Duke, 1992). Much research has focused on how we recognize emotion from facial expressions, as they are one of the most prevalent cues that communicate our internal affective states.

Different behavioural paradigms have been adopted to understand how our ability to process facial expressions of emotion develops by measuring changes in recognition performance across the lifespan. The broad aim of developmental studies of facial expression recognition (FER) is therefore to chart at which age specific emotions can be accurately recognised. In doing so, trajectories representing typical development can be identified and, consequently, early identification of impairments in emotion processing is possible. However, the application of different methods, varied developmental age groups, and subsets of facial expressions tested, do not provide a uniform picture of how this ability unfolds during childhood, and makes comparisons across studies and age groups difficult (Herba & Philips, 2004). For example, to date, much of the developmental research on facial expression recognition has targeted infancy and pre-schoolers (Mancini, Agnoli, Baldaro, Bitti, & Surcinelli, 2013; Thomas, De Bellis, Graham, & LaBar, 2007) and few studies address the continued development of facial expression recognition throughout childhood and adolescence up to adulthood (Herba & Philips, 2004; Rodger, Vizioli, Ouyag, & Caldara, 2015). No study has directly compared FER tasks that use emotional expressions of full intensity with those which use morphed expressions of varying emotional intensities.

To address these discrepancies in the literature, our study focused on the continued development of facial expression recognition from school-age children of 5 years of age up to adulthood. In a previous study, we mapped the development of recognition of 6 facial expressions of emotion and a neutral expression using a novel psychophysical approach (Rodger et al., 2015). Here, we compare two distinct measures of facial expression recognition using a psychophysical approach to study the continued development of emotion recognition throughout childhood and adolescence. This approach gives a precise measure of recognition performance across development as the quantity of signal (random image noise blended with emotional facial expression images), or intensity (neutral to facial expression image morphs) are parametrically manipulated. The signal condition is comparable to conventional FER categorization tasks which use expressions with 100% phase signals, whereas the intensity condition is similar to tasks using parametric morph designs with expressions of different intensities (however, the intensity increments have been predetermined in studies up until now). The methodological novelty of our psychophysical approach consists in increasing the sensitivity for both tasks, by determining an unbiased fine-grained threshold for the effective categorization of facial expressions with a response-driven approach. The theoretical novelty lies in our investigation of whether such commonly used paradigms in the literature relate to the same categorization processes across development, or not, as they have up until now been considered interchangeable. To the best of our knowledge, a straightforward relationship between these two measures across development has always been assumed, but has never been tested empirically.

Common behavioural methods in the study of the development of Facial Expression Recognition

The most common behavioural methods to investigate facial expression recognition in childhood include matching and labelling tasks, and studies of expression intensity. Each method has its strengths and aims to uncover specific features of emotion processing at a given stage of development. Comparison of these common methods can reveal what is consistently found for facial expression recognition during a developmental stage, and where methodological gaps or inconsistencies exist. After reviewing these common methods, we describe the novel psychophysical approach we applied to investigate the development of facial expression recognition.

Matching and Labelling Tasks. Facial expression matching tasks have been employed most frequently in developmental studies of the previous decade. Matching tasks require the child to match one image of an expression to another image of an expression, or to one image among several. Studies using matching tasks with 2, 3, or 4-alternative forced-choices to the target expression have found that recognition performance progressively improves between the ages of 4 and 10 (e.g. Bruce, Campbell, Doherty-Sneddon, Import, Langton, et al., 2000; Mondloch, Geldart, Maurer, & Le Grand, 200; Vicari, Snitzer Reilly, Pasqualetti, Vizzotto, & Caltagirone, 2000). Such tasks also show converging high-level performance by 10 years of age. Using a 2-alternative forced-choice matching task, accuracy had reached almost 100% by 10 years of age in a study which consequently classified this type of task as 'easy' amongst the face-processing tasks investigated (Bruce et al., 2000). Similarly, with a 3-alternative forced-choice matching task, by 10 years of age performance was equivalent to that of adults (Mondloch et al., 2003). While a high level of performance in matching tasks is therefore possible by 10 years of age, slight modification of this type of task to a simple pointing exercise between pairs of expressions for the target expression led to ceiling level performance by 6 years of age (Bruce et al., 2000). An increase in the number of expression choices, with a 4-alternative forced-choice matching task, similarly showed that by the age of 10 performance was high across the expression categories tested (Vicari, et al., 2000). Again, modification of this task showed different performance outcomes. When the target expression was covered after 5 seconds, thereby placing greater demands on memory, performance consequently dipped in this age group (Vicari et al., 2000). Therefore, even for relatively simple tasks, varying task demands alter recognition performance during development, as is acknowledged in the literature (Johnston, Kaufman, Bajic, Sercombe, Michie et al., 2011; Montirosso, Peverelli, Frigerio, Crespi, & Borgatti, 2010; Vicari et al., 2000). The more recent challenge has, therefore, been to find appropriate tasks with sufficient sensitivity for use across development.

Conventionally, matching paradigms have been used to attempt to minimize verbal ability and memory confounds. However, as illustrated above, across the variety of matching paradigms that have employed tasks of increasing or decreasing complexity, high levels of performance have been shown by mid-to-late childhood, indicating that this type of task does not challenge the maximum capabilities of children at this stage of development. Addressing studies that show little change in accuracy between 7 and 10 years of age, De Sonneville et al. (2002), proposed that speed of responding can provide a more sensitive measure to reveal age related changes in facial expression processing. They found that the speed of responding greatly improved during this age range while accuracy improvements were small. However, the task used to obtain a speed of response measure was a simple yes/no response to whether a face shows the target expression. Although this paradigm could reveal developmental changes where accuracy measures could not there are also several constraints. As only yes/no response options are possible accuracy must be significantly greater than the 50% chance level, and the number of emotions that can be presented is limited as a speed of response versus length of task trade-off is expected. Information about miscategorisations across emotions similarly cannot be determined.

Alternatively, labelling tasks, another commonly employed method, allow an unrestricted number of response options and analysis of miscategorisations. In a labelling task, the child must select the correct emotion label for the expression presented from several label options. These tasks have traditionally used either forced-choice response categories or free labelling which allows for an unrestricted number of response options and the analysis of miscategorisations. Here, we focus on school-aged children and the use of labelling in intensity studies similar to the method applied here, but would like to note the body of work using labelling tasks with younger children by Widen and Russell, as it comprises one of the few developmental perspectives of how emotion understanding evolves.

In a series of studies using the labelling of both images of facial expressions and emotion stories, Widen and Russell developed the Differentiation Model of emotion understanding (Widen & Russell, 2003). The model describes how children initially understand emotions in terms of the broad dimensions of valence (pleasure-displeasure) and arousal (high-low), rather than as the discrete categories that adults come to understand. Gradually understanding of these initial broad dimensions is slowly narrowed conceptually to discrete categories such as anger and disgust. As this model is developed from the use of different types of labelling tasks including conceptual stories, it is possible that by restricting the stimuli to perceptual images uniquely, the order in which these labels are acquired may change. Moreover, the type of miscategorisations in a perceptual study may also inform how emotion labels are acquired. Basic visual stimuli are used in the present study, and similarly in other studies of emotion intensity, which have mainly employed labelling tasks. We now focus on intensity studies as intensity comprises one of the measures here. The verbal ability required for labelling tasks limits their use to school-aged and some pre-school age groups of children.

In comparing matching and labelling tasks, it is evident that the balance between sensitivity in the measure and complexity of the task is challenging to assimilate for the accurate assessment of recognition performance across different developmental age groups.

Expression Intensity Studies. To obtain a more nuanced understanding of the development of facial expression recognition, one approach in more recent behavioural studies has been to vary the intensity of expressions to establish whether older children can recognise more subtle expressions of emotion in comparison to younger children. Such results are anticipated since in daily life we more frequently perceive subtle expressions of emotion. Expression intensity is modified by creating parametric linear blends of emotions called morphs. Typically, morphs are created by blending a percentage of an emotional expression with a percentage of a neutral expression, or another emotional expression. While studies employing this method remain few in the developmental literature, the percentage increments to index intensities across studies vary, with 5 or 10% increments most commonly used. Similarly, the morph stimuli used can be static or dynamic.

The results obtained from studies using static morphs have varied, most likely as a consequence of the various levels of intensity increments used, and the various age groups and emotions studied. Our study focuses on typically developing children, but previous original findings have effectively illustrated the usefulness of the morphing technique by showing the effect of emotional experience on emotional recognition (Pollak & Kistler, 2002), with physically abused children showing greater sensitivity to anger. An early study to use morphs with typically developing children investigated the correspondence between recognition performance and emotion intensity in three age groups, between 4 to 15 years, and four levels of emotional intensity (25%, 50%, 75%, and 100%), but found no association between age and level of intensity as predicted (Herba, Landau, Russell, Ecker, & Phillips, 2006). Moreover, comparison between intensity levels and emotion categories in the explicit emotion matching task that was used revealed only significant differences between the lowest and highest intensities, suggesting that the increments were too broad to capture differences in the mid-range.

In a study of sensitivity to emotion intensity for fear and anger expressions, again across three distinct age groups (child, adolescent, and adult,) but with finer increments of intensity at 11%, participants had to judge whether the face stimuli expressed a neutral versus angry, or neutral versus fearful expression (Thomas et al., 2007). Sensitivity to emotion intensity was measured by comparing the d´ average and d´ slope across the three age groups, and revealed significant differences only between adults and children for fear, and again between adults and both children and adolescents for anger. Interpreting the results, the authors suggest there was a marked increase in sensitivity to anger from adolescence to adulthood, whereas sensitivity to fear showed a more gradual incline with age. However, the relatively broad age categories and intensity increments used in this study may have prevented differences from being revealed across the child and adolescent groups.

Finally, two more recent studies investigated sensitivity to emotion intensity using three child age groups from 5 to 10 years of age, of two to three-year intervals, with the finest intensity measures to date, 20 levels of 5% increments for each expression studied (Gao & Maurer, 2009; Gao & Maurer, 2010). The studies also included a broader range of expressions and analysed miscategorisations. Applying the same methodology, both studies investigated children's responsiveness to emotional intensity by calculating a threshold for accurate discrimination of each emotion; happiness, sadness, and fear in the first study, followed by all 6 basic emotions in the second study. Thresholds were defined as the intensity level at which 50% of the time the expressive face was recognised as a neutral expression and 50% of the time as an expressive face. Importantly this could mean any expression from the emotional expression categories available and not necessarily the correct one, as a second measure for misidentification of expression was also recorded. Unlike the previous studies discussed here, the task was not computerized. Instead, children were asked to physically categorize photographs of emotional expressions of varying intensities.

Gao and Maurer (2009) found different developmental patterns for each of the three emotions investigated. The youngest children matched adult sensitivity for both measures of threshold intensity and misidentification of happiness. For sadness, even the oldest children, aged 10, were prone to confusing this emotion with fear, and for the fear expression children did not reach adult-like thresholds until 10 years of age. Gao and Maurer (2010) expanded the number of emotion categories to include all six basic emotions, which were then subdivided into two groupings based on previous findings of the confusability of emotion categories. Therefore, participants completed the recognition task in two blocks, each with distinct emotion categories and not with all six emotions at once. For all age groups, recognition accuracy for happiness reached ceiling-level performance. Between 5 and 10 years, sensitivity to surprise, disgust and fear improved, and sensitivity to sadness and anger continued to improve into adulthood.

While this was the first study to include a broader range of emotion categories, several features of this paradigm make it difficult to draw definitive conclusions on sensitivity to emotion intensity in the age groups studied. Primarily, the true threshold applied here was a composite measure; a misidentification measure was calculated separately to the initial threshold measure. Further, emotions could only be misidentified with emotions belonging in the same subgroup, thus potential misidentifications across all six emotion categories were not possible. A single measure that accounts for miscategorisations could provide greater precision in the understating of FER. Finally, here, as with previous studies investigating sensitivity to intensity, the increments were established a priori, so the granularity of the measure can only be as fine as the predefined increments.

A Psychophysical Approach. Here, we investigated the continued development of facial expression recognition for all 6 of the basic emotions from early childhood (5 years of age) up to adulthood. We introduced a novel psychophysical method using the QUEST threshold seeking algorithm (Watson & Pelli, 1983) to obtain a sensitive measure of FER performance across the age groups studied. This algorithm identifies an individual's recognition threshold for an expression with a sensitivity of 1% for intensity measures, or less for signal measures. The threshold is adapted online during the execution of the experiment. The algorithm therefore permits greater sensitivity in the measure of recognition performance, and intensity increments do not need to be defined a priori as with other methods. Our aim was to (1) obtain a precise measure of the quantity of visual information needed to recognise an expression across development, and (2) compare two measures of visual information use, *signal* versus *intensity* thresholds, using an experimental design in which each participant is tested under all experimental conditions, to better understand the use of different measures in assessing recognition performance across development. We predicted recognition performance would improve with age for both measures, and that this improvement would be distinct for each expression. Based on previous findings, we predicted happiness would be the easiest expression to recognise across age groups, and fear would be among the most difficult (Herba & Philips, 2004; Rodger et al., 2015). The QUEST algorithm was used to identify the recognition thresholds for both the signal and intensity measures, however we had no prediction whether one measure would yield higher or lower thresholds, or whether those measures would be significantly related to one another, as no study has previously compared these distinct measures.

Method

Participants

In total, 159 individuals participated in both the signal and intensity conditions. As described below, participants were analysed on a continuum of age in years. For simplicity, we list the participants by age group:

The adult participant group consisted of 19 adults (*M* = 24.2 years, *SD* = 1.8, 10 females). Sixty adolescents participated in the experiment: 20 17-18 year-olds (*M* = 17.9 years, *SD* = 0.65,17 females), 20 15-16 year-olds (*M* = 16 years, *SD* = 0.73, 12 females), 20 13-14 year-olds (*M* = 14 years, *SD* = 0.5, 12 females), and 80 children participated: 20 11-12 year-olds (*M* = 11.9 years, *SD* = 0.5, 8 females), 20 9-10 year-olds (*M* = 9.9 years, *SD* = 0.59, 9 females), 20 7-8 year-olds (*M* = 7.9 years, *SD* = 0.61, 13 females) and 20 5-6 year-olds (*M* = 5.9 years, *SD* = 0.56, 13 females). Children were recruited from local schools in the Fribourg area and parental consent was obtained for all children under the age of 16. The study was approved by the Department of Psychology Ethics Committee at the University of Fribourg.

Materials

For the signal condition, the stimuli consisted of 252 grey scale images (256 x 256 pixels) from the Karolinska Directed Emotional Faces (KDEF) database (Lundqvist, Flykt, & Öhman, 1998) comprising 36 distinct identities (18 female) each displaying six facial expressions (fear, anger, disgust, happy, sad, surprise) and a neutral expression. For the intensity condition, we used 8 identities (4 female) expressing each of the 6 basic emotions from the KDEF (Lundqvist et al., 1998) image database. Abrosoft FantaMorph software was used to create morphs of 100 increments for each identity and emotional expression, ranging from a 1% morph of a neutral face and an expressive face up to a 100% expressive face. The total number of images used was therefore 4800 (8 identities x 6 expressions x 100 increments).

Example stimuli of different expression intensities and signal strengths are shown in Figure 1. Participants only viewed images at the intensities calculated by the

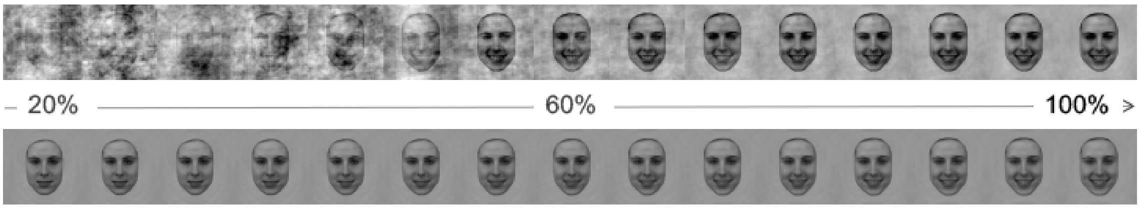

Figure 4.1 Example stimuli from the signal and intensity conditions. In this image, the stimuli are shown in increasing 5% increments, starting at 20% signal or intensity.

QUEST procedure. All images were cropped around the face to remove distinctive hair styles using Adobe Photoshop, and were aligned along the eyes and mouth using Psychomorph software (Tiddeman, Burt & Perrett, 2001). Images were also normalized for contrast and luminance using the SHINE toolbox (Willenbockel, Sadr, Fiset, Horne, Gosselin, & Tanaka, 2010) in MATLAB 7.10.0 and displayed on an 800 x 600 grey background at a distance of 50cm subtending 10° x 14° to simulate a natural viewing distance during social interaction (Hall, 1966). The stimuli were presented on an Acer Aspire 5742 laptop using the Psychophysics toolbox (PTB-3) with MATLAB 7.10.0 and QUEST (Watson & Pelli, 1983), a Bayesian adaptive psychometric method (described below) to estimate the level of stimuli strength (signal or intensity) for each trial. An external USB keyboard was attached to the laptop so the experimenter could key the responses on behalf of the child participants.

Procedure

To familiarize the children with the computerized emotion recognition task, each child was shown 6 faces expressing the 6 basic emotions on individually printed sheets of paper and asked to respond to the question "how do you think this person is feeling?" To facilitate the familiarization task for the younger children in particular, the first image presented was always a happy face. If children were unsure of an emotional expression in the familiarization task they were told what the emotion was. Children were then asked if they could repeat this task by looking at similar images on a computer screen. For the signal condition, children were told that this time the faces would be slightly hidden or blurred so it might be more difficult to see what the person is feeling, but to please respond as well as they could. As there were 6 expressions to choose from labelled on 6 computer keys, children aged 12 and under responded verbally and the experimenter keyed the response on their behalf. Children were also told if they were unsure of an expression, or could not sufficiently see the expression to make a judgement, that they could say “next” and a new face would be presented. Such responses were then coded as “don’t know” by the experimenter. Adolescent and adult participants were similarly asked to respond as accurately as they could to how the person in the picture was feeling by pressing the corresponding emotion key labelled on the keyboard. Labels were placed on the bottom row of keys for each of the 6 expressions, and on the space bar for “don’t know or uncertain” responses. Adolescent and adult participants were given as much time as they needed to familiarise themselves with the response keys before beginning the experiment and were told that accuracy not response time was important, so to take as much time as needed and to look at the keys if necessary before giving their response.

The experiment began with 6 practice trials to allow participants to become familiar with the computerised task. The transition from practice trials to experiment proper was seamless so the participant was not aware that the initial trials were for practice only. At the beginning of each trial a fixation cross was presented for 500 ms to locate the participant’s visual attention, followed by 500 ms presentation of the face stimulus displayed at the signal strength or intensity estimate from the QUEST psychometric procedure (described below), directly followed by a mask of random noise (see Figure *2* for an illustrated example of a trial). The emotional expression stimuli were displayed randomly and when the recognition threshold for an expression was obtained (see section below on the QUEST procedure for details), that particular expression was no longer displayed and only images of the remaining expressions were sampled. Keying a response triggered the subsequent trial, so care was required with children to ensure that they were ready for the next stimulus presentation before the response was entered. The number of trials for each participant varied as a function of the QUEST procedure (again described below), so for the youngest children the experiment was paused at roughly mid-way and continued after a short break.

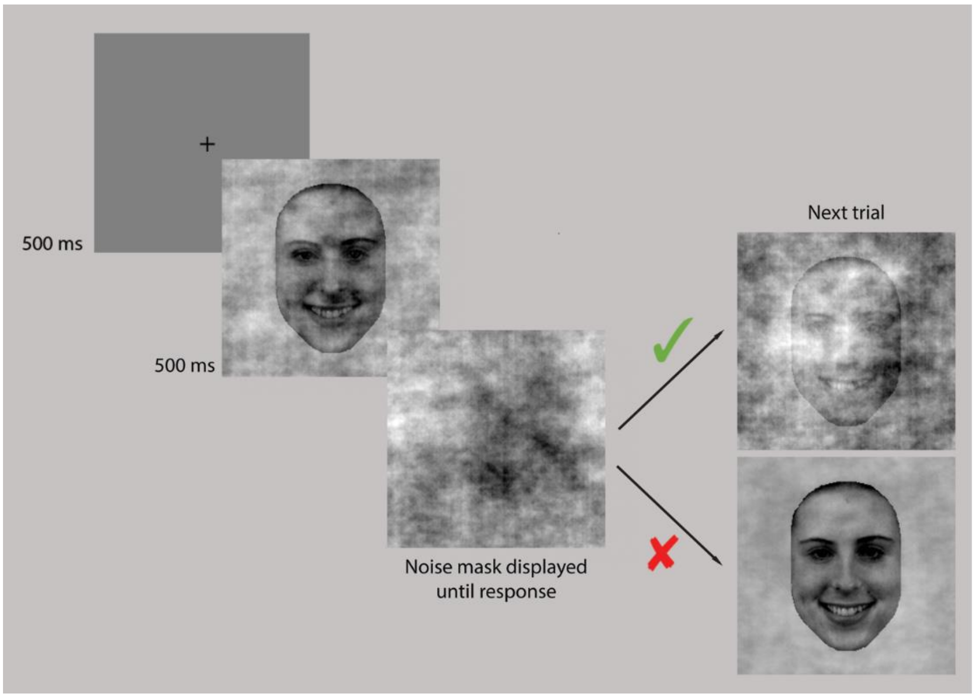

Figure 4.2 Example trial from the signal condition. At the beginning of each trial a fixation cross was presented for 500 ms to locate the participant's visual attention, followed by 500 ms presentation of the face stimulus displayed at the signal strength or intensity estimate from the QUEST psychometric procedure, directly followed by a mask of random noise until a response was made. Depending on accuracy, the next trial was followed by a face containing more (in case of an erroneous response) or less (in case of an accurate response) signal.

The QUEST Bayesian adaptive psychometric procedure

The QUEST procedure as implemented by Rodger et al. (2015) was used. QUEST is a psychometric function that uses an adaptive staircase procedure to establish an observer's threshold sensitivity to some physical measure of a stimulus, most commonly stimulus strength (Watson & Pelli, 1983). The threshold obtained by the QUEST procedure therefore provides a measure of how effectively an observer can discriminate a stimulus. Here we investigated threshold sensitivity for signal and intensity of expression in 2 separate conditions across developmental age groups. Adaptive staircase procedures obtain the threshold by adapting the sequence of stimulus presentations according to the observer's previous responses. For example, the stimulus strength becomes weaker or stronger according to the user's history of correct and incorrect responses to a particular stimulus category. Adaptive staircase methods can therefore be more efficient in determining the observer's perceptual threshold for stimulus detection since the range of stimuli presented is reduced by staying close to the observer's threshold by accounting for their previous responses.

We adopted QUEST for this efficiency as it allowed us to implement a paradigm including all 6 expressions at once in a developmental study. The QUEST threshold seeking algorithm was implemented in MATLAB 7.10.0 with the Psychophysics Toolbox (PTB-3), to parametrically determine an observer's perceptual threshold for discriminating each of the 6 emotional expressions. Adopting a signal-detection approach, QUEST was used to parametrically adapt the signal strength of the greyscale facial expression images presented to the participant by adding a mask of random noise to the image corresponding to the current signal strength parameter determined by the function based on the participant's previous performance. If the expression was accurately or inaccurately discriminated on a given trial, then the subsequent signal strength estimate was decreased or increased. Similarly, the intensity of the expression was adapted using neutral-expression image morphs from 0% expression (a neutral face) to 100% expression. The final threshold estimate is determined as the intensity or signal strength where the expression is predicted to be discriminated on 75% of trials. In this way, equal performance is maintained across observers. The 75% performance threshold was chosen as it has been conventionally been applied in adult face identity and facial expression recognition studies (e.g., Gosselin & Schyns, 2001; Schyns, Bonnar, & Gosselin, 2002; Smith, Gosselin, Cottrell, & Schyns, 2005). For the signal condition, 3 QUEST procedures were implemented each with different initial stimulus strengths (60%, 40%, and 20%) to prevent possible bias in the final estimate towards the direction of the initial value. For the intensity condition, one QUEST procedure was implemented with an initial expression intensity of 30%. This intensity was selected since by nature 50% intensity denotes an image morph of 50% expression and 50% neutral expression, so the initial value should be below this level of morph. The QUEST procedure terminates for an expression after 3 consecutive correct or incorrect trials in which the intensity or signal strength standard deviations are less than 0.025.

Data Analyses

Threshold detection. The participant's recognition threshold for each task is identified as the level of information (intensity or signal) needed to maintain performance at 75%, as quantified by the QUEST procedure. For each expression and participant, the QUEST procedure assumes that the response (in terms of accuracy rate) and the presented signal or intensity follows a psychometric function. Throughout the experiment, this psychometric function is updated and refined for each trial until the end of the experiment. The final threshold estimate is the level of information at which the participant is predicted to maintain 75% performance for expression recognition. This estimate is obtained by computing the mean of the Quest posterior probability density function (pdf) using the *QuestMean* function from theQuest toolbox (King-Smith et al., 1994; Pelli, 1987), which uses a Weibull psychometric function. In the signal task where multiple QUEST procedures were employed, we computed the average of the threshold estimations as our final estimation for each participant. In our previous paper, we used the intensity of the last trial from the QUEST procedure as the threshold estimation (Rodger et al., 2015). However, since some participants cannot achieve 75% accurate identification even when signal or intensity is at the maximum (100%), the previous calculation returns a ceiling value of 1 (which is equal to 100% signal or intensity). This occurs almost exclusively for fear recognition (see the supplementary figure in Rodger et al., 2015). Instead, here, for the intensity and signal conditions, the threshold estimate now returns values of above 1, e.g. 1.112. As the expression has failed to be categorized at full strength, by using the precise estimate instead the threshold is no longer constrained by its physical limitation, a value of 1, so a more continuous measure is possible which gives greater sensitivity to detect potential developmental differences, even for expressions that are difficult to recognise across age groups.

Signal and intensity recognition thresholds as a linear function of age per emotional expression. To quantify the relationship between age and emotion recognition performance, we fitted General Linear Models (GLM) with age as predictor for each task and expression independently (Rodger et al., 2015). We then compared the regression coefficients between the two tasks for each expression to infer the effect of age (Figure 4). GLMs were fitted using the *fitlm* function in Matlab with the default robust option using a bisquare weight function to eliminate the effect of outliers. Hypothesis testing on the model coefficients were corrected for multiple comparisons using a Bonferroni correction.

Response profile analysis. While the QUEST procedure is efficient in estimating a desired threshold, the returned estimation is a summary statistic that is only sufficient under strong assumptions (e.g., the underlying posterior pdf is parameterized only using the mean). In other words, the uncertainty of the estimation is usually discarded. To fully account for all the information encoded in the response during the QUEST procedure, we applied a Dirichlet-multinomial model to recover the response profile for each participant. This procedure is conceptually described in Figure 5.

For each participant, we first extracted the raw response vector and the corresponding intensity/signal level for one expression in one task (Step 1 in Figure 5). We then projected each element in the response vector and its corresponding intensity/signal level into a sparse matrix (Step 2 in Figure 5). To recover the full response profile from the sparse raw response matrix, we applied a Dirichlet-multinomial model for each intensity/signal level, a probabilistic model widely used to model categorical responses. Here, we assume that at each intensity/signal level the participant's response to a random stimulus follows a multinomial distribution: $X \sim Multinomial\ (response,\ p)$. The *response* is all six tested expressions plus neutral and the *I don't know response*; p is an 8-element vector (summed to 1) coded for the probability of each response. Moreover, p follows a Dirichlet distribution $p \sim Dirichlet\ (\alpha)$, where α is the concentration parameter of the Dirichlet distribution. To recover the response profile matrix, we started from the lowest intensity/signal level (0%) with a uniform prior for the Dirichlet distribution: a vector of 1s as α. We applied the Bayes Theorem to get the posterior of α, then used the posterior of α as the new prior for the next intensity/signal level (Step 3 in Figure 5). The Bayesian update procedure is repeated until the highest intensity/signal level (100%) is reached. In this way, the dense matrix representation of the response profile (final output in Figure 5) is recovered. In the resulting response profile, the value is the concentration parameter α of the Dirichlet distribution, in which a higher value relates to a higher concentration in the response probability *p* in the Multinomial distribution.

Specifically, we performed the Bayesian update for each intensity/signal step using PyMC3 with 10000 Metropolis-Hastings sampling. Instead of sampling from a Dirichlet distribution with the concentration parameter α, we sampled from α_i ~ Gamma (α_i, 1), and normalized the sum of [$\alpha_{1,\ldots,}$ α_k] to 1 to get the parameter *p* for the multinomial distribution. This formulation allowed us to obtain the posterior of the concentration parameter α for the update at the next intensity/signal level.

It is worth noting that the Bayesian update procedure applied here is conceptually similar to fitting a psychometric function independently for each row in the raw response matrix in Figure 5. However, applying a Dirichlet-multinomial model is more accurate and does not require any collapse of conditions in the computation.

The response profiles for each expression per task across all participants are shown in Figure 6. To further explore the relationship between the intensity and signal task for each participant, we computed the mutual information between the response profiles (using the algorithm in Kinney and Atwal, 2014). Importantly, we only included the responses of the six target expressions (i.e., excluding the rows coded for the neutral expression and *I don't know* response) so that the two tasks were consistent. Robust regression is fitted between the mutual information and age, similarly to as described above, to quantify the effect of age.

Results

Mean expression thresholds across development

Signal: The mean age recognition thresholds and their 95% bootstrapped confidence intervals for each of the expression categories are plotted in Figure 3. As predicted, happiness was the easiest expression to recognise across age groups as it was recognised with the lowest mean thresholds across age groups. In contrast, fear was the most difficult expression to recognise across age groups with the highest mean thresholds across groups; even at full signal strength participants generally do not reach the target accuracy (75%) for the fear expression, which resulted in threshold estimations of greater than 1 by the QUEST algorithm. Across age groups, the rank order of mean expression thresholds between the highest and lowest mean thresholds varied. The mean number of trials for the signal condition was 216.74 (SD= 49.96).

Intensity: The mean recognition thresholds and their 95% bootstrapped confidence intervals for each expression and age group are plotted in Figure 3. Similarly to the signal condition, happiness and fear were the easiest and most difficult expressions to categorise across age groups, with the lowest mean thresholds for happiness and the highest for fear. Again, as for the signal measure, the majority of participants do not reach the target accuracy (75%) even at full intensity for the categorization of the fear expression. The ranking of mean thresholds between the highest and lowest intensity thresholds again varied across age groups, with no set pattern established across age groups for the remaining expressions. The mean number of trials for the intensity task was 78.06 (SD=14.15).

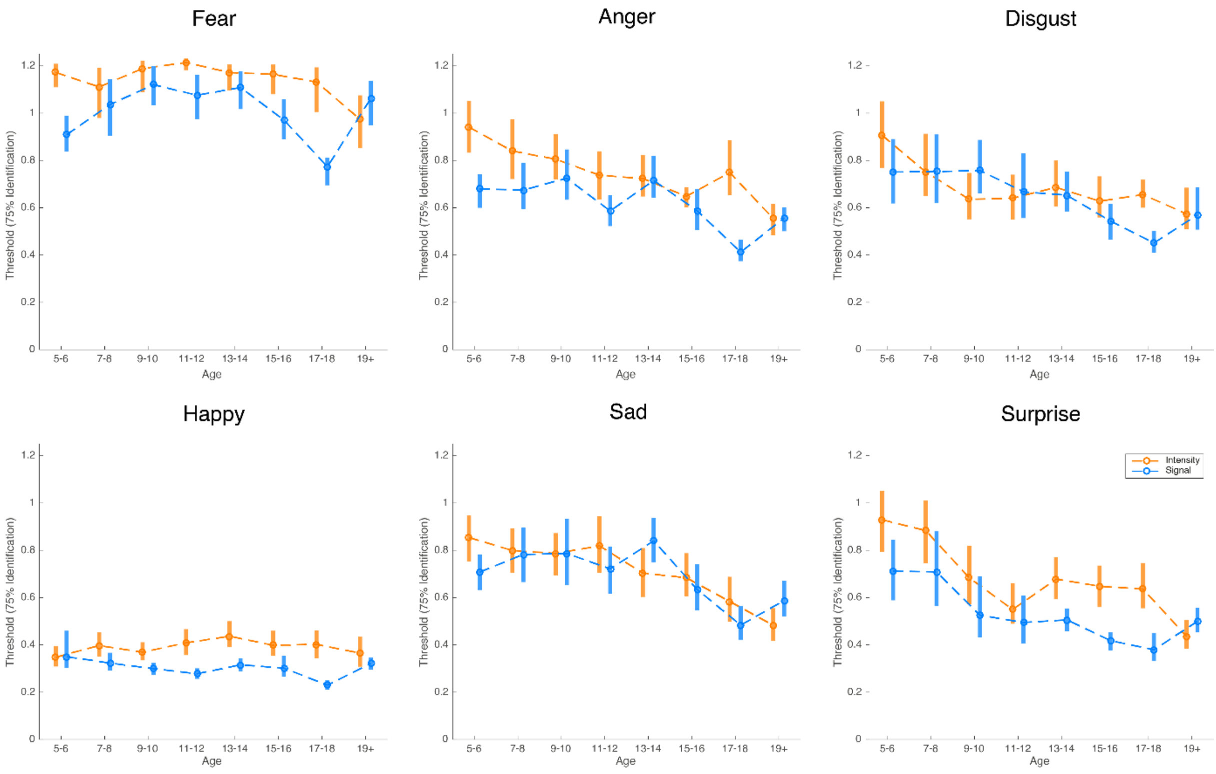

Figure 4.3 Age group mean recognition thresholds plotted per facial expression of emotion. Orange lines indicate the intensity task, blue lines the signal task. Error bars report the 95% confidence intervals.

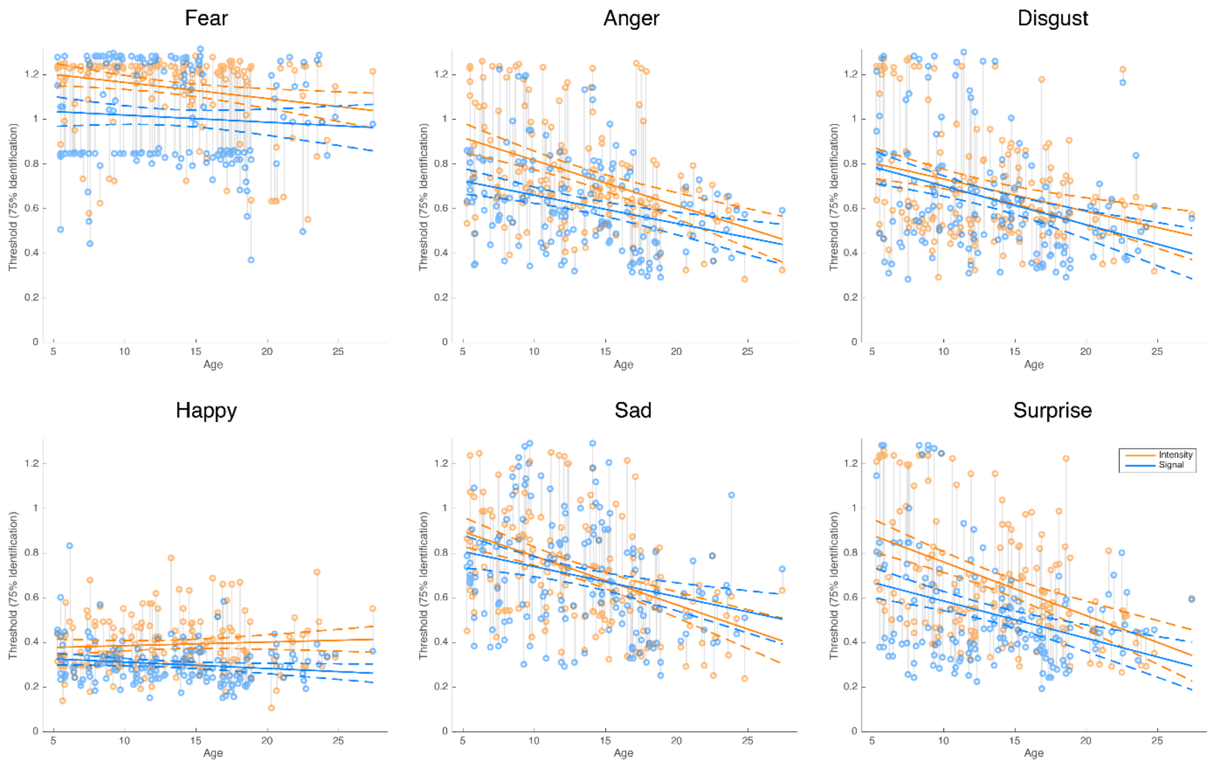

Figure 4.4 Individual recognition thresholds plotted as a function of age (x-axis) per facial expression of emotion. Orange dots indicate the intensity task, blue dots the signal task. Data from the same participant is linked with a grey line. Longer lines indicate that the thresholds for signal and intensity are not similar, and therefore further apart. Short lines indicate that the thresholds for this individual are similar. Line plots show the results of the linear regression between threshold and age, dotted lines show the 95% confidence intervals.

Signal and intensity recognition thresholds as a linear function of age per emotional expression

Figure 4 shows the change in information use across age for each emotional expression. Each individual's threshold for signal and intensity was plotted, with age along the x-axis. The fitted regression lines for intensity and signal are shown in red and blue respectively; the dotted line indicates the 95% Confidence interval. Overall, a significant decrease in thresholds across age was found for both the signal and intensity measures for four of the six expressions: anger (Intensity: -.02 [-.0271, -.0135], $t(157) = -5.87$; Signal: -.013 [-.0186, -.00674], $t(157) = -4.21$; square bracket shows 95% Confidence interval, $p < .05$ *Bonferroni corrected*), disgust

(Intensity: -.015 [-.0217, -.00732], *t*(157) = -3.99; Signal: -.017 [-.0249, -.00981], *t*(157) = -4.55), sadness (Intensity: -.022 [-.0286, -.0151], *t*(157) = -6.36; Signal: -.014 [-.0209, -.00614], *t*(157) = -3.61), and surprise (Intensity: -.024 [-.0316, -.0164], *t*(157) = -6.22; Signal: -.017 [-.0238, -.0096], *t*(157) = -465). Older participants were able to recognise an emotional expression with less information, at lower levels of signal or intensity, than younger participants.

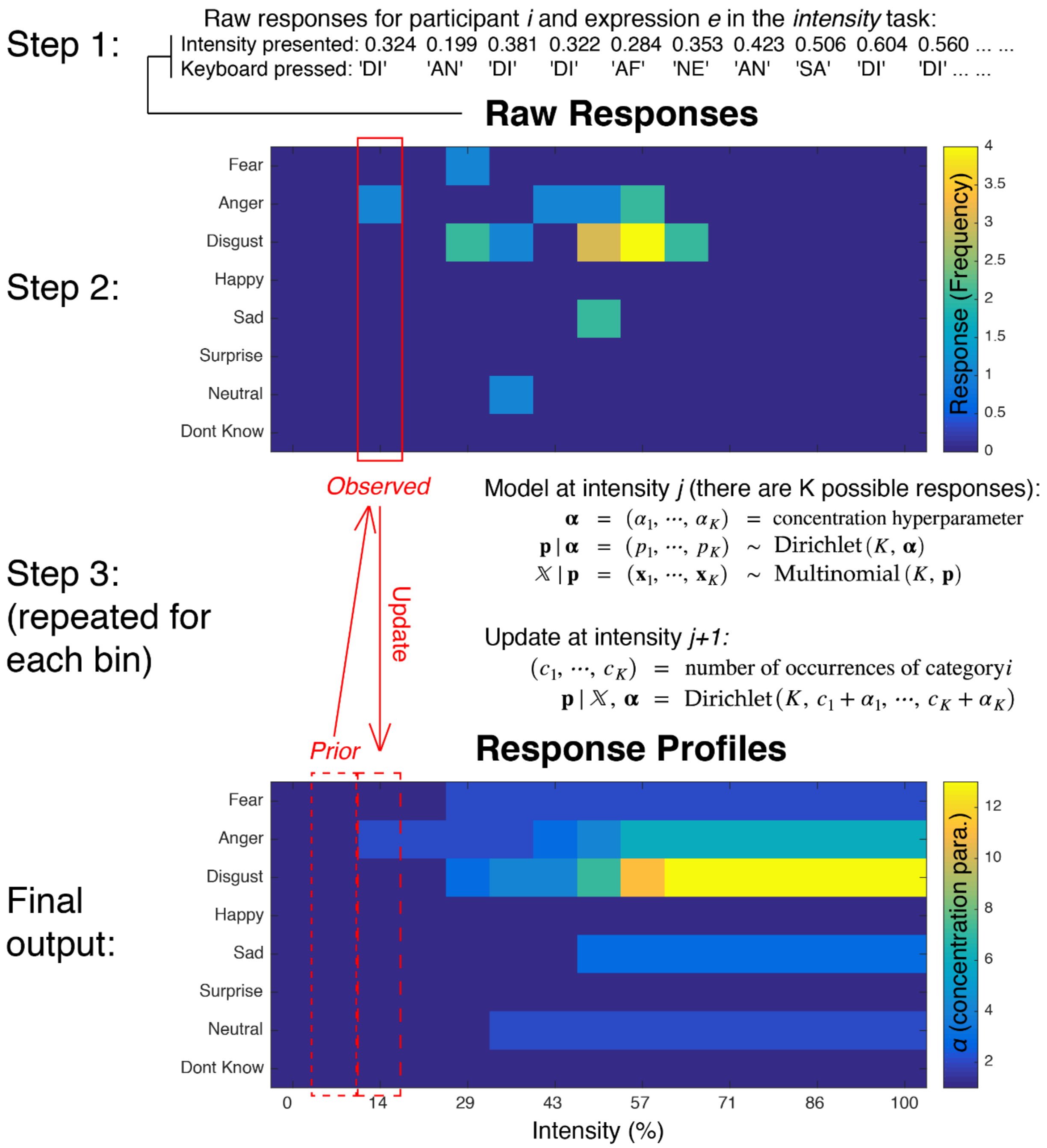

Figure 4.5 Response profile analysis for a single participant for one expression (disgust) during the intensity task. The procedure starts with the raw response and intensity level (step 1), projects them into 2 dimensions (intensity levels by categorized expressions, step 2), and applies the Bayesian update to recover the full response profile (step 3 and 4). This procedure is repeated for all expressions in both tasks, independently for each participant.

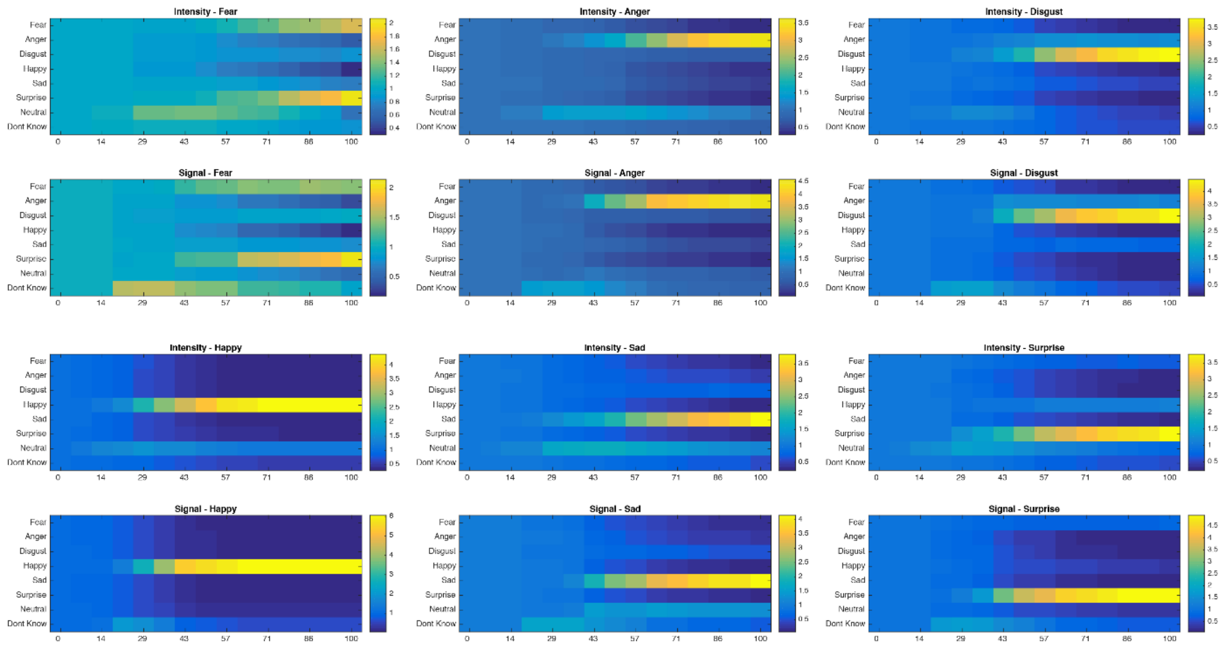

Figure 4.6 Average response profiles across groups for the intensity and signal tasks and each facial expression of emotion. Each subplot shows the average response profile for one expression in one task. The rows represent the different responses from participants (6 basic expressions + neutral + don't know response), whereas the columns represent the signal or intensity level presented by QUEST. The value of the color maps are the concentration parameter α of the Dirichlet distribution (see the main text and figure 5 for more details). A high value indicates higher probability *and* greater confidence in choosing that response.

Response profile analysis

As shown in Figure 6, there are substantial differences between the response profiles of the two tasks for most of the expressions. To establish how similar the signal and intensity measures were across development, we performed a mutual information analysis on the response profiles of both measures for each participant (Figure 7). Each plotted point therefore represents the similarity in the response profiles of the two measures for one participant. Overall, there was an upwards trend for the response profiles to become more similar with age, as four of the six emotions showed a significant increase in similarity with age: anger (regression coefficient: β = .014 [.0036, .0243], $t(157)$ = 2.67, p = .0083), disgust (β = .018 [.0073, .0286], $t(157)$ = 3.33, p = .0011), sadness (β = .012 [.0025, .0219], $t(157)$ = 2.48, p = .0143), and surprise (β = .024 [.0013, .0361], $t(157)$ = 4.06, p = 7.73e-5). Moreover, a robust

GLM between mean mutual information across expression and age showed a significant positive correlation: $\beta = .0103$ [.006, .0145], $t(157) = 4.74$, $p = 4.75e\text{-}6$. As the response profiles become more similar with age, erroneous responses therefore become less random in comparison with younger participants.

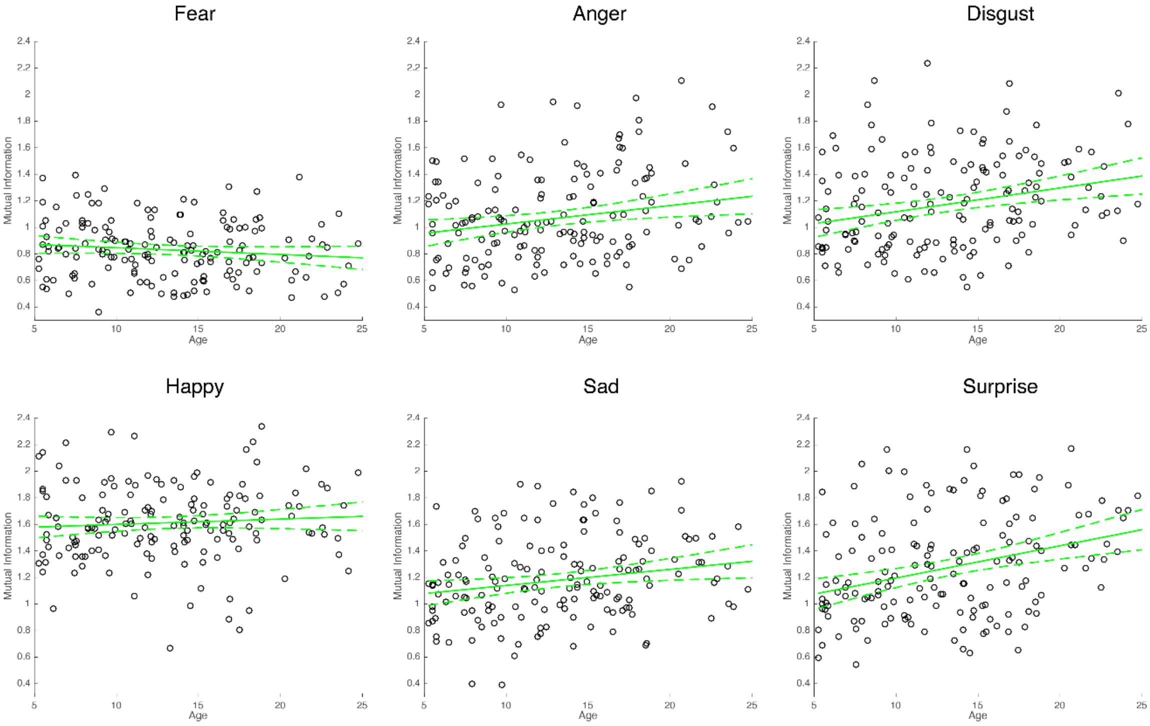

Figure 4.7 Mutual information (MI) between the intensity and signal tasks for each participant per expression. Higher MI indicates higher similarity in the response profile between the two tasks. Line plots show the linear regression between MI and age, dotted lines show the 95% confidence region of the regression.

Discussion

Using a psychophysical approach and an experimental design in which all participants completed both experimental conditions, we aimed to: (1) isolate the quantity of *signal* and of *intensity* (using neutral-expression image morphs) necessary to recognise 6 prototypical facial expressions of emotion in children from age 5 up to adulthood while maintaining performance at 75%, and (2) compare these measures to better understand the use and sensitivity of different measures in assessing recognition performance across development. To achieve these aims, we used a data-driven methodological approach by analysing recognition performance on a *continuum* of age; a novel approach that overcomes the delimitation and use of arbitrary age boundaries.

The results of the first objective revealed that, as expected, the quantity of signal and of intensity needed to recognise the majority of expressions reduced with age, for sad, angry, disgust and surprise expressions respectively. Therefore, the processing of both types of visual information becomes more discriminative during development as less information is needed with age to recognise these expressions. However, recognition improvement across development was not uniform for these expressions, as has also been shown in previous studies (Boyatzis, Chazan, & Ting, 1993; Gao & Maurer, 2010; Herba & Phillips, 2004; Lawrence, Campbell, & Skuse, 2015; Mancini, Agnoli, Baldaro, Bitti, & Surcinelli, 2013; Rodger et al., 2015; Vicari et al., 2000). For fear and happy expressions, age did not have a major impact on the quantity of signal and of intensity use. Therefore, recognition performance for fear and happy expressions was relatively stable from the age of 5 years. For both measures, fear and happiness were the most difficult and easiest expressions to recognise across age groups. Earlier studies have similarly shown that happy expressions have the highest recognition performance and that this remains stable from an early age (Gao & Maurer, 2009; Gao & Maurer, 2010; Gross & Ballif, 1991; Herba & Phillips, 2004; Mancini et al., 2013). However, one recent study showed that despite the youngest age group tested (6-year-olds) showing 92% recognition accuracy for happy expressions there was a small but significant improvement in accuracy with age (Lawrence et al., 2015). Stability in accuracy levels for fear recognition from an early age was similarly found in an earlier study measuring signal recognition thresholds uniquely (Rodger et al., 2015). Overall, the recognition thresholds for both measures showed a similar trend in improvement or stability across expressions and in the ease and difficulty of happy and fear recognition respectively.

Although similar developmental trajectories for recognition of these expressions have been revealed in other studies, the reasons behind such particular patterns of trajectories remain widely speculated. Studies that have tested different developmental cohorts have shown the effect experience has on emotion recognition. For example, a cross-cultural eye-tracking study testing Caucasian and Asian infants recently revealed information sampling biases in infants as young as 7-months-old when they discriminate facial expressions of emotion (Geangu et al., 2016; for a review see Caldara, 2017). Early culture-specific experience can therefore affect which visual information we sample from the environment. The authors speculate that within the cultural environment, it is possible that parental practices most prevalently affect young infants. For example, Asian mothers have been found to be less emotionally expressive and use more non-direct body contact compared to Western mothers (Kisilevsky et al., 1998), which could affect infants' attentional strategies towards the culturally-specific emotionally salient features of the face and body.

Similarly, by testing different developmental cohorts, children who have been exposed to physical abuse and those who have not, Pollak's work has notably demonstrated the effect of emotional experience on emotion recognition (e.g. Pollak, Cicchetti, Hornung, & Reed, 2000; Pollack & Kistler, 2002; Pollak, Messner, Kistler, & Cohn, 2009; Pollak & Sinha 2002). Children who had suffered physical abuse were consistently found to recognise anger more rapidly, or with less physical cues than non-abused children. As the children studied had similar sociodemographic and family backgrounds, except for the experience of physical abuse, the explanation of this heightened sensitivity for anger recognition alone suggests that affective experience can influence perceptual representations of emotions.

As described above, developmental studies of facial expression recognition have repeatedly shown that happy is the most easy and earliest expression to be recognised. This facility with happiness could be partially explained in typically-developing children by our frequent exposure to smiling faces in early childhood, combined with happiness' visual distinctiveness from other expressions (e.g. Calvo & Marrero, 2009; Kohler et al., 2004). Expressions of fear, by contrast, although critical to our survival, are not commonly experienced frequently during daily life. Although experience alone may not account for poor recognition rates of fear in adult and developmental studies (e.g. Gross & Ballif, 1991; Herba & Phillips, 2004; Widen, 2013; Rapcsak, Galper, Comer, Reminger, Nielsen et al., 2000; Calder, Keane, Manly, Sprengelmeyer, Scott et al., 2003), it is a possible contributory factor. The low rates of fear recognition from both signal and intensity measures in our study suggest that for optimal recognition additional information is required, perhaps from several modalities. Experiential factors impacting the recognition of sadness have also been show in studies of depressed adults (e.g. Arteche et al., 2011; Gollan et al., 2010; Gur et al., 1992; Kluczniok et al., 2016). Precisely because measuring an individual's prior experience of emotional expressions empirically is difficult, measuring different cohorts to inform how cultural and social experiences affect our capacity to recognise emotions is valuable. Future cross-cultural, clinical and developmental studies with diverse cohorts could adopt the paradigm here to establish possible differences in sensitivity to signal and intensity information, and further determine if any differences found are related to experiential factors.

Comparison of response profiles for signal and intensity measures

To establish how comparable the signal and intensity measures were across development and better understand the use and sensitivity of different measures in assessing recognition performance across development, we compared the measures using a novel data driven analysis. We used mutual information analysis to establish how similar the response profiles of the signal and intensity measures were for each individual on a *continuum* of age. The analysis of age in years on a continuous rather than a categorical scale is a data-driven non-biased approach which permits a finer level of analysis to provide a more precise picture of how the development of facial expression recognition unfolds. The mutual information analysis showed that the response profiles of the signal and intensity measures became more similar with age for the sad, angry, disgust, and surprise expressions. Again, for fear and happy expressions no significant change across development was evident. Similarity in the response profiles of the sad, angry, disgust, and surprise expressions was only evident in the oldest aged participants. Therefore, the response profiles for emotional expressions of full intensity in the signal condition did not correspond with the profiles obtained from expressions of varying intensity in the morph condition throughout the majority of development.

The mutual information analysis therefore established that two types of stimuli commonly used in facial emotion processing studies (expressions at full intensity versus expressions of varying intensities) cannot be straightforwardly compared during development. This critical point is another explanatory factor, alongside differences in age groups, expressions and tasks, for the differences in recognition trajectories found throughout the developmental literature described in the introduction.

Importantly, as the response profiles for sad, angry, disgust, and surprise expressions became more similar with age, erroneous responses therefore become less random. This suggests that representations of emotional expressions are more robust in the oldest participants tested, as they produced systematic confusions, for example fear for surprise. Novel analysis of the overall response profiles for the expression recognition tasks, rather than the more standard practice of analysing the final response values *per se*, therefore revealed subtle but important changes in the sequence of responses along the continuum of age.

The presence of more robust expression representations in adulthood aligns with Widen and Russell's Differentiation Model of emotion (Widen, 2013; Widen & Russell, 2008; Widen & Russell, 2003) that emotion concepts are acquired gradually throughout development, beginning with a broad concept including any emotion of the same valence, and hence the potential for greater confusion, with concepts gradually narrowing and becoming more discrete with age. Only visual information was available in the present study, without any social or contextual information to aid accurate categorisation. It is thus plausible that the randomness in the categorisation errors of younger children might arise from their lack of sufficiently robust visual representations of an emotion, despite already having a concept of the emotion. A potential mechanism for this refining of emotion categories and greater robustness in their perceptual representations is provided by Leppänen and Nelson (2009). In their review of how the developing brain becomes tuned to the social signals of emotional expressions, they describe an experience-dependent mechanism that is necessary for the development of a mature system. They propose that our perceptual representations of facial expressions are initially coarsely specified, and only develop into a mature system with adult-like specificity through exposure to species-typical emotional expressions. The experience-dependent nature of facial expression processing has been shown by the disruption caused to typical development by species atypical parenting and social deprivation (e.g. Pollak & Kistler, 2002). In contrast, typical development, as shown here, results in a mature system with more highly specified categorical representations of expressions that are also prone to more systematic errors. Future studies can apply these methods to further investigate sensitivity to specific emotions and discrepancies in response confusions across the lifespan, as well as in diverse clinical groups.

Future studies should also investigate some of the limitations of the current study. This cross-sectional study has revealed specific developmental trajectories and response profiles for expression recognition using signal and intensity information. A longitudinal design with neural measures could further establish how processing of signal and intensity information evolves with age. For example, whether neural populations processing the two types of information overlap with age as sensitivity for decoding both types of information becomes more similar. It is also worth noting that there is large variability for the mutual information estimation between the response profiles from the two tasks. While our data show a significant association between age and the estimated mutual information, it is important to consider the practical significance of the observed effect. Indeed, the coefficient estimation values from the regression model are generally between .01 to .025, which is not a large change compared to the intercept (with an estimate of roughly 1 bit). However, no studies have compared the change of multivariate response patterns in a behavioural task using mutual information, thus it is difficult to straightforwardly interpret the current changes of information use. Further studies are necessary to quantify the practical significance of the effects observed here. Similarly, adult face stimuli uniquely were studied. The question of whether there is an own-age advantage for emotion recognition is still debated (Griffiths, Penton-Voak, Jarrold, & Munafò, 2015; Hills, 2012; Wiese, Komes, & Schweinberger, 2013). It is possible that with own-age stimuli, children may recognise emotional expressions alternatively, and show different developmental trajectories for recognition than is found with adult faces. Finally, since faces are not the only signal used in the natural environment for effective emotional communication, future studies are needed to further evaluate how contextual and other social cues contribute to the processing of emotional expressions across development. To determine, for example, the effect of non-facial emotional cues on recognition when face signals or intensity is modified as it is here.

Conclusions

These findings have important theoretical and methodological implications for developmental, lifespan, emotion, and face processing research. Firstly, findings from facial expression recognition studies with different age cohorts using emotional expressions of full intensity, as in the signal condition here, cannot be straightforwardly compared to findings using varied expression intensities. Throughout development the response profiles for recognition of expressions at full intensity were not comparable to those of varied intensities. Secondly, by examining individual responses along an age continuum, as opposed to the mean responses of age group categories, a finer level of analysis is possible that can provide a more precise picture of differences occurring during development. Here, this revealed a gradual reduction in information use for recognition of four of the six expressions tested, and for the same expressions, a gradual increase in the similarity of response profiles with age. Thirdly, by analysing the response profiles (i.e. the sequence of responses across trials), rather than the fixed end point measure of recognition score, a richer explanation of what is occurring is possible, as we compare the overall distribution of responses. For example, this approach revealed that the response profiles become more similar with age due to less random erroneous categorisations. This broader analysis can therefore provide insight into the underlying processing of visual information; as the categorisation errors become less random with age this suggests that the expression representation becomes more robust. Potentially, therefore, the neural populations processing the two types of information - signal and intensity - overlap with age as sensitivity for decoding both types of information becomes more similar. Altogether, our data provide novel methodological and theoretical insights on the developing affective system.

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Chapter 5

Study 3: Developmental Eye Movement Strategies for Decoding Facial Expressions of Emotion

Developmental eye movement strategies for decoding facial expressions of emotion

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Research Highlights

- Novel eye movement analyses reveals at which stage of development perceptual strategies for the recognition of facial expressions of emotion become mature.
- The eye movement strategies of the oldest adolescent group, 17- to 18-year-olds, were most similar to young adults for all expressions.
- A developmental dip in strategy similarity to adults was found for each emotional expression from 11- to 14-years, and 7- to 8-years for happiness.
- For happy, angry, and sad, performance did not differ across age groups but eye movement strategies diverged, indicating diverse approaches for reaching optimal performance.

Abstract

In our daily lives, we routinely look at the faces of others to try to understand how someone is feeling. Few studies have examined the perceptual strategies that are used to recognise facial expressions of emotion and none have attempted to isolate 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. 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: 13- to 14-years for sadness recognition, 11- to 12-years for fear, anger, surprise, and disgust, and 7- to 8-years for happiness. For happy, angry, and sad performance did not differ significantly across age groups, but strategies diverged. Therefore, a unique strategy was not a prerequisite for optimal recognition performance for these expressions. Our data provide novel insights on the developmental trajectories underlying facial expression recognition, a critical ability for adaptive social relations.

Key words: Facial Expression Recognition, Eye movements, Emotions, Development, Face Scanning, Eye tracking

Introduction

In our daily lives, we repeatedly look at the faces of others to understand, consciously or unconsciously, how someone is feeling. We search for signals from the face to decode and integrate critical socio-emotional information which can help us to respond appropriately in different social settings. This important social skill, the recognition of emotion from the face, emerges in early infancy and develops over time from our first social experiences. Indeed, the process of recognition implies a before, to recognise something we must have seen it before. And 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 recognised. Largely, behavioural, 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 recognise an emotion throughout development. 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 used to recognise an emotion across development. Comparing the visual scan paths with behavioural performance across development can establish which perceptual strategies are effective, which information is needed to recognise an emotion, and at which stage of development perceptual strategies become mature.

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 categorise 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, Blais, Scheepers, Schyns, & Caldara, 2009; Schurgin et al., 2014). For example, to recognise disgust fixations are most densely populated towards 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) from their seminal research on human emotion.

The scan patterns outlined above describe the typical fixations of adult Western Caucasians. Several studies have recently revealed group differences across cultures in the facial information processed to recognise several of the classically studied emotions of fear, anger, disgust, happiness, sadness, and surprise (Jack et al., 2009; Jack, Garrod, Yu, Caldara & Schyns, 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 to 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, similarly 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 to healthy controls has been linked to a lack of attention to the eye region during the processing of fear expressions (Adolphs, Tranel, Damasio, & Damasio, 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 towards understanding the development of general face processing abilities. Behavioural 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, Woodson, Greenberg, & Cohen, 1982; Geangu et al., 2016; Serrano, Iglesias, & Loeches, 1992). The first study to examine the scan patterns of infants using several different emotional expressions within the same paradigm revealed that infants' scanning behaviour varies according to the expression observed (Hunnius, de Wit, Vrins, & von Hofsten, 2011). Following on from an earlier event-related potential study, which established an enhancement in 3-month-old infants' attention towards fearful versus neutral faces (Hoehl & Striano, 2010), Hunnius, de Wit, Vrins and von Hofsten (2011) investigated scanning behaviour towards threat-related versus non-threat-related emotional expressions. Overall, scanning behaviour in both infants at 4 and 7 months and adults towards 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 a general avoidant reaction towards threatening facial expressions is therefore present from early life (e.g. see Bayet, Quinn, Laboissière, Caldara, Lee, & Pascalis, 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 behaviour 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 infants were slower to disengage attention from fearful faces (Peltola, Leppanen, Vogel-Farley, Hietanen, & Nelson, 2009). However, similarly to Hunnius et al., 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, Eriksson, Schmitow, Laeng, and Stenberg (2012) found scan patterns did differ according to the expression viewed, the familiarity of the face, and the infant's experience of parental leave; whether the infant had primarily been at home with their mother or with both parents. Therefore, with the limited number of infant eye tracking studies available, and some equivocal results, more studies are necessary to draw any firm conclusions about scanning behaviour in infants when processing emotional expressions. A tendency towards differential scan patterns for different emotions has been shown, as well as an early preference to fixate the eye region.

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, but 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 behaviour in nine-year-old children and adults (Pollux, Hall & Guo, 2014). As predicted, training-related improvements in recognition of all three expressions for the nine-year-old child group were shown to correspond with changes in gaze-strategy, with more fixations being directed towards the eyes for all expressions after training, resulting in a more adult-like strategy. No gaze instructions were given during the training sessions which suggests 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. (2014) studied 3 groups of school-aged children (6 to 8 years, 8 to 10 years, and 10 to 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 or happy expressions) between the youngest and older age groups. However, how these behavioural improvements related to changes in gaze strategies was not established, as 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 ROIs, 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 4 of the expressions compared to the middle and older age groups. No adult group was included to approximate the maturity of the different age groups' gaze strategy. Therefore, further investigation is needed to establish how gaze strategies change across development, when strategies become mature, and how strategies relate to performance.

Finally, while 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 group. To measure attentional biases during emotion recognition, the children explored blurred images of faces with a mouse-controlled window of 2 x 2 º which renders clear the part of the face revealed by the window (the Moving Window Technique). An overall attentional bias towards the left eye of the face emerged in the oldest 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 for each emotion is necessary to determine how these changes relate to improvements in recognition accuracy.

As described, there are a very limited number of studies examining the perceptual strategies used to achieve emotion recognition across childhood, and none have included all of the basic expressions, an adult control group, and a measure of information use. We therefore 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, as natural viewing conditions cannot provide conclusive results on information use since a visual fixation does not correspond to the location of attention (see Caldara, Zhou, & Miellet, 2010; Miellet, He, Zhou, Lao, & Caldara, 2012; Miellet, Vizioli, He, Zhou, & Caldara, 2013). We thus recorded the natural and gaze-contingent eye movements of eight different developmental groups from the age of five 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, Miellet, Pernet, Sokhn, & Caldara, 2017), to map the ocular strategy used by each age group to recognise 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, and map the fixation strategy. By not having to define 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 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 strategy can therefore be deemed superior. We expected that the adult group would have the highest accuracy levels across emotion categories and that their ocular strategy is therefore the most effective. Similarly, we expected that the youngest age group of children would have the lowest levels of recognition accuracy and therefore the least efficient gaze strategy. Between the youngest and oldest groups of children, we aimed to establish at which age the perceptual strategies become most similar to that of the adult group to determine if strategies reach maturity before adulthood.

Method

Participants

128 participants of 8 different age groups took part in the study. 64 children comprising 4 age groups: 16 5- to 6-year-olds (*M* = 6 years 3 months, 7 females), 16 7- to 8-year-olds (*M* = 8 years 1 month, 11 females), 16 9- to 10-year-olds (*M* = 10 years 1 months, 9 females), 16 11- to 12-year-olds (*M* = 11 years 11 months, 10 females); 48 adolescents: 16 13- to 14-year-olds (*M* = 14 years 1 month, 12 females), 16 15- to 16-year-olds (*M* = 15 years 9 months, 14 females), 16 17- to 18-year-olds (*M* = 18 years 5 months, 10 females), and 16 adults (*M* = 22 years 8 months, 8 females). Children were recruited from local schools, and parental consent was obtained for all children under the age of 16 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

60 grey scale images (706 x 706 pixels) were used from the KDEF (Lundqvist, Flykt, & Öhman, 1998) database, 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 hair styles using Adobe Photoshop, and aligned along the eyes and mouth using Psychomorph software (Tiddeman, Burt & Perrett, 2001). The images were normalized for contrast and luminance using the SHINE toolbox (Willenbockel, Sadr, Fiset, Horne, Gosselin, & Tanaka, 2010) with MATLAB 7.10.0 and displayed on a 1920 x 1080 grey background, subtending 14.2^{o} x 14.2^{o} 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 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 2K eye tracker at a sampling rate of 1000Hz, an average gaze position error of 0.25^{o}, a spatial resolution of 0.01^{o}, 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, 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 centre of the screen that served as a drift correction of the gaze estimate. If the drift correction was greater than 1^{o} 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 randomised across participants. 60 expressions were randomly viewed in each condition (6 basic expressions from 10 distinct identities, 5 male, 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) which 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^{o} every 25 milliseconds) as the observer fixates an area of the stimulus. Each time the participant fixates the stimulus, the gaze-contingent Spotlight renders this area of the stimulus clear. The area outside of the spotlight is an average non-discernible face template, composed of all of the stimuli used in the experiment, to allow participants to plan saccades naturally during face viewing. To begin with, the Spotlight is a Gaussian aperture of 2^{o}, representing foveal vision. It expands at a rate of 1^{o} per 25 ms at each novel fixation point the participant makes, without expansion limit constraints. In this way, the quality and the 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 been found in Miellet et al. (2013). Here, the expanding spotlight reveals the quantity and quality of information used across development to recognise 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 characterise gaze-strategy changes across the developmental age groups.

Procedure

To familiarize the children with the computerized emotion recognition task, each child was shown 6 faces expressing the 6 basic emotions on individually printed sheets of paper and asked to respond to the question “how do you think this person is feeling?” To facilitate the familiarization task for the younger 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 protocol was the same for the adolescent and adult participants, except no familiarisation 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 centre of the screen before each expression. Children under 12 years of age responded verbally to the expression stimuli and the experimenter keyed the response. Participants above 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 7 labels (fear, anger, disgust, happiness, sadness, surprise, and don’t know) presented on the screen after the stimulus. Children were also told if they were unsure of an expression that 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

Behavioural performance was measured by the number of correctly recognised 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 ^{o}; a saccade acceleration threshold of 4000 ^{o} /s^{2}; and the merging of fixations that were close spatially and temporally (<50ms, <0.3 ^{o}). For each participant, the number of fixations and fixation durations were calculated for each trial. The *i*Map 4 toolbox was then used to compute statistical fixation distribution maps for each of the eight age groups in the study. The *i*Map 4 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 *i*Map produces with heat spots showing the most densely fixated regions for each condition. The spatial mapping of fixations across age groups and emotion categories is then statistically analysed using Linear Mixed Modelling to identify significant differences in fixation strategies across groups. Full details of the statistical analysis and processing stream used in *i*Map 4 can be found in Lao, Miellet, Pernet, Sokhn, & Caldara (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 (i.e. the Mahalanobis distance) of the fixation maps between one age group and the adult group for each expression.

We then plotted the changes in similarity (Figure 5.4), to further quantify how the mean fixation pattern evolves across age and when it approaches an optimal adult-like pattern.

Results

Behavioural Results

The mean recognition scores for the natural viewing and spotlight conditions are shown in Tables 1 and 2. For both conditions, across all age groups, participants were most accurate in recognising happy expressions and least accurate in recognising 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 for surprise; both differences were non-significant, $p > 0.05$.

For the natural viewing condition, a mixed model ANOVA revealed a significant main effect of emotional expression, $F(3.42, 410) = 205$, $p = 0.00$ (Greenhouse-Geisser correction), a main effect of age group, $F(7, 383) = 16.25$, $p = 0.00$, and a significant interaction between emotional expression and age group $F(23.93, 1985) = 4.49$, $p = 0.00$. The Bonferroni Post Hoc Comparisons for the expression by age group interaction are reported in Table 5.3. The interaction was mainly driven by the Adult and 17- to 18-year-old age 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 of the other age groups.

For the spotlight condition, the results of a mixed model ANOVA showed significant main effects of emotional expression, $F(3.38, 405.7) = 177$, $p = 0.00$ (Greenhouse-Geisser correction), and age group $F(7, 454) = 10.17$, $p = 0.00$; and a significant interaction between age group and emotional expression $F(23.93, 1985) = 4.49$, $p = 0.00$. The significant interaction was driven by the adults having a significant higher level of accuracy than the youngest four age groups for fear recognition, and than age groups 5-6 and 9-10 for disgust and sadness recognition. Finally, the youngest age group had poorer recognition for sadness than most of the older age groups; 11-12, 13-14, 15-16 and adults.

Table 5.1

Mean Accuracy Natural Viewing Condition. The Standard Error of the Mean is reported in parentheses.

	Mean Recognition Accuracy (%)					
Age Group	**Fear**	**Anger**	**Disgust**	**Happy**	**Sad**	**Surprise**
5-6	17.5 (5)	73.8 (4.8)	43.8 (9.9)	99.4 (0.6)	80.6 (2.3)	38.1 (9.4)
7-8	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	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	14.4 (3.4)	81.3 (2)	80.0 (3.3)	99.4 (0.6)	80.6 (3.3)	88.8 (2.6)
13-14	25.6 (4.6)	76.3 (4.3)	75.6 (5)	98.8 (0.8)	76.3 (4.5)	80.0 (3.9)
15-16	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	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)

Table 5.2

Mean Accuracy Spotlight Condition. The Standard Error of the Mean is reported in parentheses.

Age Group	Mean Recognition Accuracy (%)					
	Fear	**Anger**	**Disgust**	**Happy**	**Sad**	**Surprise**
5-6	24.4 (5.8)	72.5 (5.2)	53.8 (10)	99.4 (0.6)	76.3 (6.2)	53.1 (9.1)
7-8	16.9 (5.4)	76.9 (3)	67.5 (7.8)	97.5 (1.9)	84.4 (3.9)	71.9 (7.4)
9-10	24.4 (5.8)	70.0 (3.2)	56.3 (8.9)	98.1 (1)	67.5 (7.8)	69.4 (5.2)

11-12	22.5 (4.6)	77.5 (3.9)	82.5 (5.1)	99.4 (0.6)	76.9 (4)	86.3 (3.5)
13-14	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	36.9 (5.4)	75.0 (3.4)	65.0 (5.3)	97.5 (1.4)	75.0 (4.1)	86.3 (3)
17-18	36.3 (4.5)	77.5 (2.8)	78.8 (4)	98.1 (1.3)	81.9 (3.8)	76.3 (4.5)
Adults	48.8 (6.3)	80.6 (4)	91.3 (1.8)	98.8 (0.8)	84.4 (3.5)	95.0 (1.8)

Table 5.3

Significant Bonferroni Post Hoc Expression – Age Group Interaction Comparisons, Natural Viewing Condition

Comparisons	Mean Correct Response Difference	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Fear				

5-6 vs. 17-18	-3.44	0.75	-5.84	-1.03
5-6 vs. Adults	-3.31	0.75	-5.72	-0.91
7-8 vs.15-16	-2.44	0.75	-4.84	-0.03
7-8 vs. 17-18	-3.75	0.75	-6.15	-1.35
7-8 vs. Adults	-3.62	0.75	-6.03	-1.22
9-10 vs. 17-18	-2.87	0.75	-5.28	-0.47
9-10 vs. Adults	-2.75	0.75	-5.15	-.035
11-12 vs.15-16	-2.44	0.75	-4.84	-0.03
11-12 vs. 17-18	-3.75	0.75	-6.15	-1.35
11-12 vs. Adults	-3.62	0.75	-6.03	-1.22
13-14 vs. 17-18	-2.62	0.75	-5.03	-0.22
13-14 vs. Adults	-2.50	0.75	-4.90	-0.10
Disgust				
5-6 vs. 11-12	-3.62	0.87	-6.41	-0.84
5-6 vs. 13-14	-3.19	0.87	-5.97	-0.40
5-6 vs. 17-18	-4.00	0.87	-6.79	-1.21
5-6 vs. Adults	-4.87	0.87	-7.66	-2.09
9-10 vs. Adults	-3.62	0.87	-6.41	-0.84
Surprise				

5-6 vs. 7-8	-3.00	0.75	-5.41	-0.60
5-6 vs. 9-10	-3.75	0.75	-6.16	-1.34
5-6 vs. 11-12	-5.06	0.75	-7.47	-2.65
5-6 vs. 13-14	-4.19	0.75	-6.60	-1.78
5-6 vs. 15-16	-4.81	0.75	-7.22	-2.40
5-6 vs. 17-18	-4.50	0.75	-6.91	-2.09
5-6 vs. Adults	-4.75	0.75	-7.16	-2.34

Table 5.4

Significant Bonferroni Post Hoc Expression – Age Group Interaction Comparisons, Spotlight Viewing Condition

Comparisons	Mean Correct Response Difference	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Fear				
Adults vs. 5-6	2.44	0.75	0 .02	4.86
Adults vs. 7-8	3.19	0.75	0.77	5.61
Adults vs. 9-10	2.48	0.75	0.02	4.86

Adults vs. 11-12	2.62	0.75	0.20	5.04
Disgust				
Adults vs. 5-6	3.75	0.94	0.75	6.75
Adults vs. 9-10	3.5	0.94	0.50	6.5
Sadness				
5-6 vs. 11-12	-3.31	0.74	-5.68	-0.95
5-6 vs. 13-14	-3.31	0.74	-5.68	-0.95
5-6 vs. 15-16	-3.31	0.74	-5.68	-0.95
5-6 vs. Adults	-4.19	0.74	-6.55	-1.82
9-10 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 4 and 5 show the mean number of fixations and fixation durations 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 whereas the Adult group tended to have the lowest. The two oldest age groups, the 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.

Table 5.5

Mean Number of Fixations by Age Group and Emotional Expression – Natural Viewing Condition. The Standard Deviation is shown in parentheses.

Mean Number of Fixations

	Fear	**Anger**	**Disgust**	**Happy**	**Sad**	**Surprise**
5-6	23 (13)	20 (12)	29 (12)	16 (11)	20 (15)	20 (16)
7-8	22 (10)	18 (11)	15 (8)	14 (8)	17 (11)	17 (10)
9-10	22 (19)	17 (9)	17 (8)	13 (7)	15 (9)	16 (8)
11-12	18 (8)	15 (8)	15 (10)	11 (6)	15 (10)	15 (7)
13-14	22 (17)	16 (9)	16 (9)	14 (8)	19 (12)	17 (10)
15-16	17 (12)	15 (10)	16 (10)	12 (9)	16 (10)	14 (9)
17-18	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)

Table 5.6

Mean Fixation Durations (ms) by Age Group and Emotional Expression – Natural Viewing Condition. The Standard Deviation is shown in parentheses.

Mean Fixations Durations (ms)

	Fear	**Anger**	**Disgust**	**Happy**	**Sad**	**Surprise**
5-6	99 (78)	106 (67)	107 (57)	95 (55)	107 (65)	116 (57)
7-8	136 (69)	140 (92)	146 (91)	136 (88)	142 (82)	135 (81)
9-10	111 (51)	117 (66)	111 (59)	106 (62)	112 (54)	109 (51)
11-12	156 (55)	143 (65)	147 (63)	136 (69)	137 (67)	130 (53)
13-14	132 (68)	112 (57)	123 (59)	109 (56)	115 (62)	112 (51)
15-16	134 (70)	122 (61)	138 (69)	113 (56)	114 (62)	117 (57)
17-18	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)

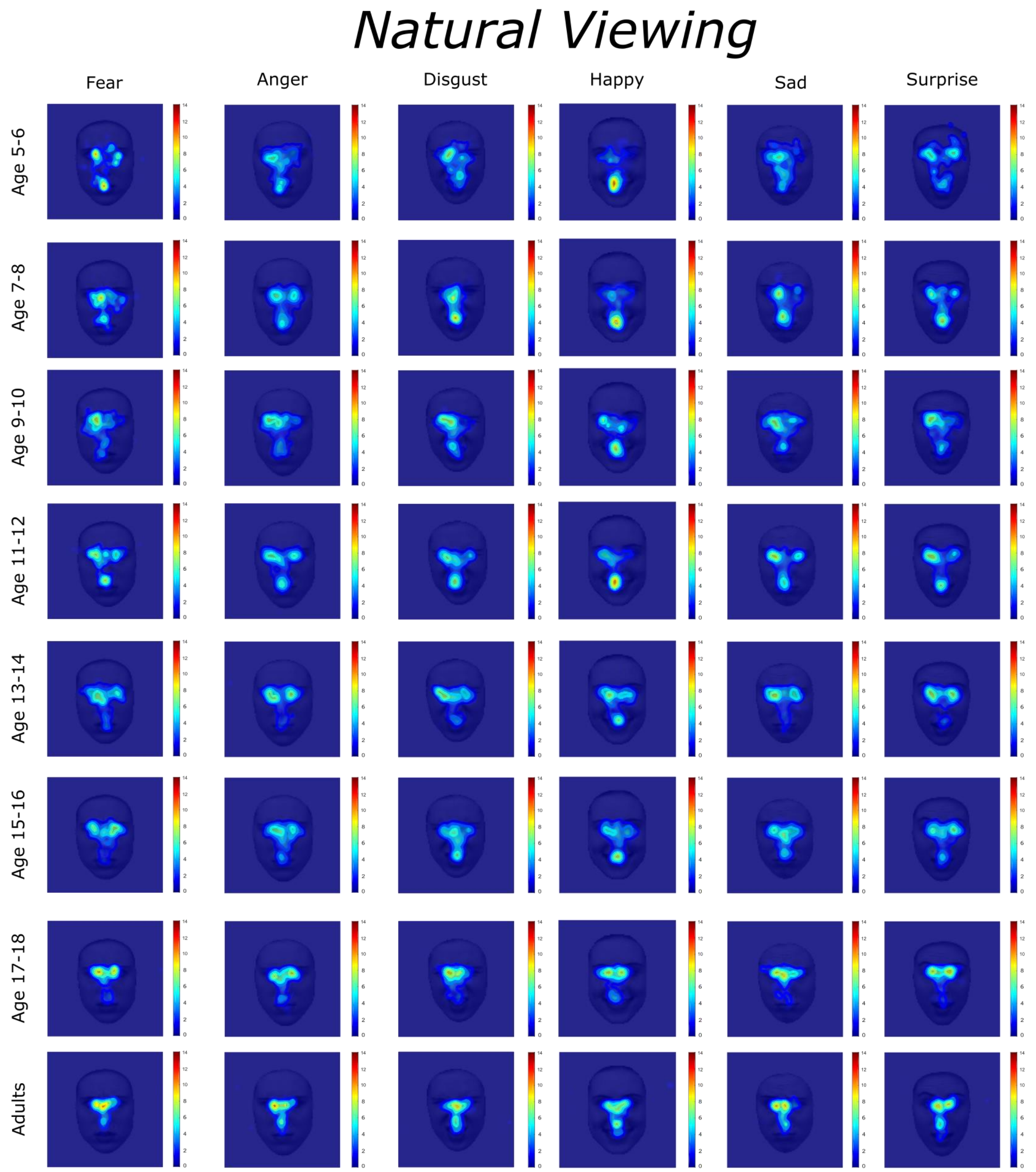

Figure 5.1 Natural viewing condition mean fixation duration (ms) colour maps for each age group and emotional expression. The colour bar represents mean fixation durations from 0-14 milliseconds.

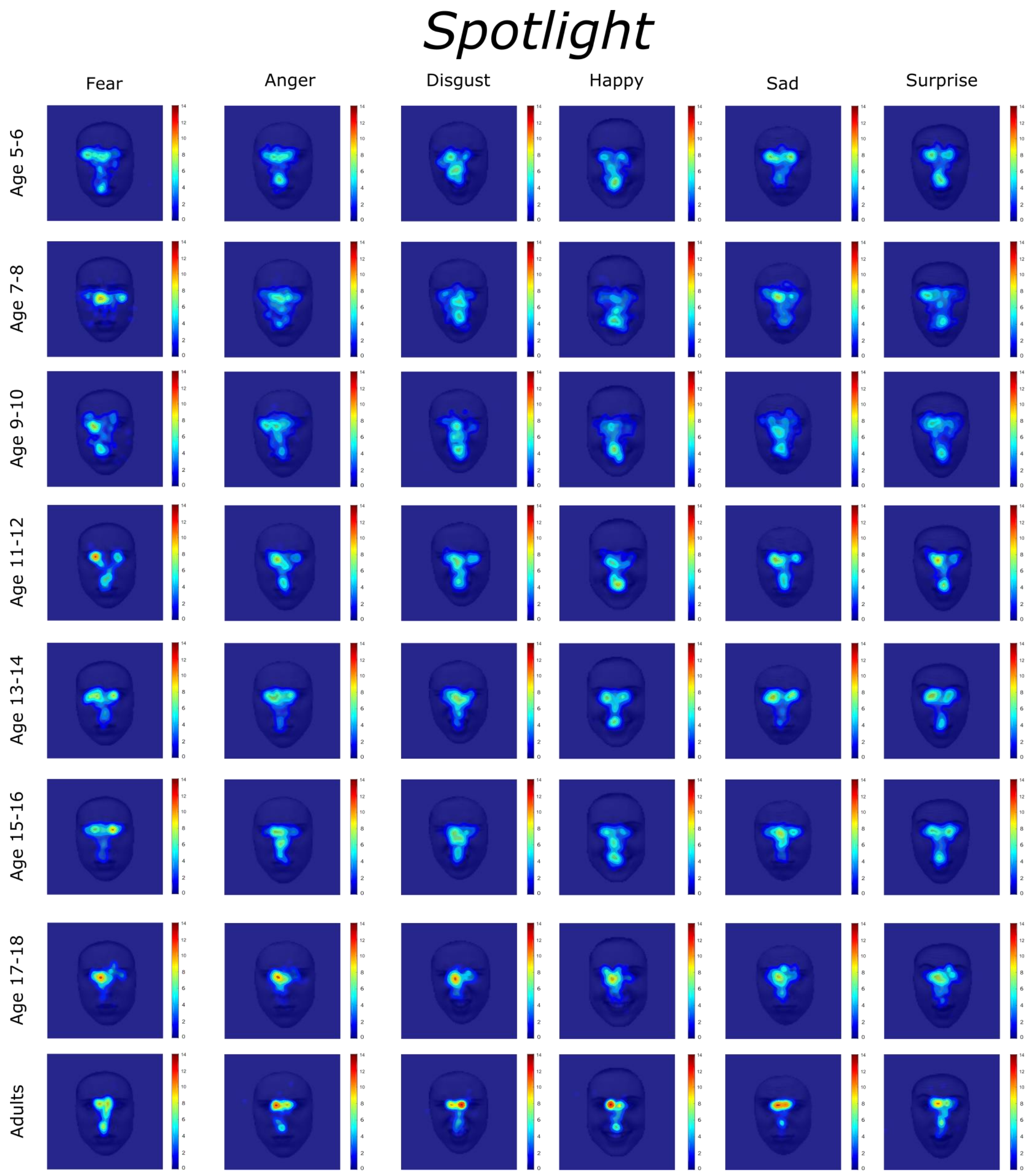

Figure 5.2 Spotlight viewing condition mean fixation duration (ms) colour maps for each age group and emotional expression. The colour bar represents mean fixation durations from 0-14 milliseconds.

Natural viewing mean duration fixation maps and comparisons of age group eye movement strategies per expression using Linear Mixed Modelling.

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 Figure 5.1) 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 5.2) 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 visualised by warmer coloured clusters. Figure 5.1 shows the mean fixation duration maps for each age group per emotion for the Natural Viewing condition, which we shall now discuss.

Subsequently, the mean fixation duration maps for each age group and expression were statistically analysed using the *i*Map 4 toolbox. We fitted Linear Mixed Models and computed pixel-wise ANOVAs to compare each age group's strategy with the adult age group strategy to identify any significant differences in the areas of the face that are fixated during emotion recognition. For the Linear Mixed Models, the fixation duration (Y) was therefore the response variable and age group (AGE) was the predictor; the observers were considered as a random factor. The design model could therefore be expressed as: Y ~ AGE + (1| observers).

Age groups with less significantly different fixated areas of the face were assumed to be more similar to the adult strategy for a given expression. Full details of the statistical analysis and processing stream used in *i*Map 4 can be found in Lao et al. (2017).

Fear.

Across age groups, the mean duration fixation maps show there was a tendency to fixate the left eye of the face during the recognition of fear expressions (Figure 5.1). 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 age groups also fixating the mouth, and the 15- to 16-year-old age groups also fixating the right eye.

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 pixel-wise Linear Mixed Model using *i*Map4. No significant differences were found between any of the age group's fixation biases and the adult group for fear.

Anger.

During recognition of anger (Figure 5.1), 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 both eyes.

The Linear Mixed Model analysis revealed there were no significant differences between each age group and the adult age group's mean fixation durations for anger recognition.

Disgust.

For the disgust expression, the ocular strategies varied over the course of development. The youngest age groups fixated the mouth and left eye more predominantly, and gradually the older age groups, from age 13 to 14, fixated more centrally the nasion area between the eyes (Figure 5.1).

The results from the Linear Mixed Model revealed no main effects of age so there were no significant differences between each age group's mean fixation durations and the adult group's 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 (Figure 5.1).

Again, no main effects or significant interaction were found for the Linear Mixed Model comparisons. Each of the age group's mean fixation durations therefore did not differ significantly from the adult group's during 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 (Figure 5.1). Overall, the eye region was fixated more than the mouth for all age groups except the 7- to 8- year-old group who showed predominant fixations to both the left eye and mouth.

The LMM analysis did not reveal any significant differences between each of the age group's mean fixation strategies and the adult groups.

Surprise.

The fixation strategies of the four youngest groups for recognising surprise expressions were concentrated towards the mouth and the left eye, or both eyes (Figure 5.1). The older age groups tended to focus more on both eyes.

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

Age group eye movement strategy comparisons by Multivariate Distance Analysis.

The Linear Mixed Model analysis of each age group's strategy 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 group's 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 group's strategies were most similar to the adult's 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. 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 the Spotlight conditions alongside the behavioural 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 age group as the group with the strategy which most differed from the Adult group. This divergence in strategy is illustrated in the plot where similarity dips to the lowest point for this age group (Figure 5.3). Beyond the 11- to 12-year-old age group, the older age groups show an upwards trend in similarity with the adult group's strategy, with the 17- to 18-year-old showing the highest similarity to the adult group in their strategy for fear recognition.

Anger

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

Disgust

Multivariate distance analysis determined that the 11- to 12- year-olds' strategy was the most distinct from the adult strategy for disgust recognition (Figure 5.3). From the age of 13- to 14- years, strategies became increasingly similar to that of the adults, with a slight dip in similarity for the 15- to 16- year-old age group. The 17- to 18- year-old age group showed the greatest similarity to the adult group.

Happiness

The 13- to 14- year-old age 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 adults (Figure 5.3).

Sadness

The 13- to 14- year-old group had the least similar strategy to the adults (Figure 5.3). After 13-14 years of age, the strategies increased in similarity to the adult's strategy with the 17- to 18-year-old group once again most similar to them.

Surprise

Similarly to fear, anger and disgust expressions, similarity in strategies towards the adult group increased from the age of 11-12 years onwards, with the 17- to 18- year-old group again showing the greatest similarity in strategies to the adults.

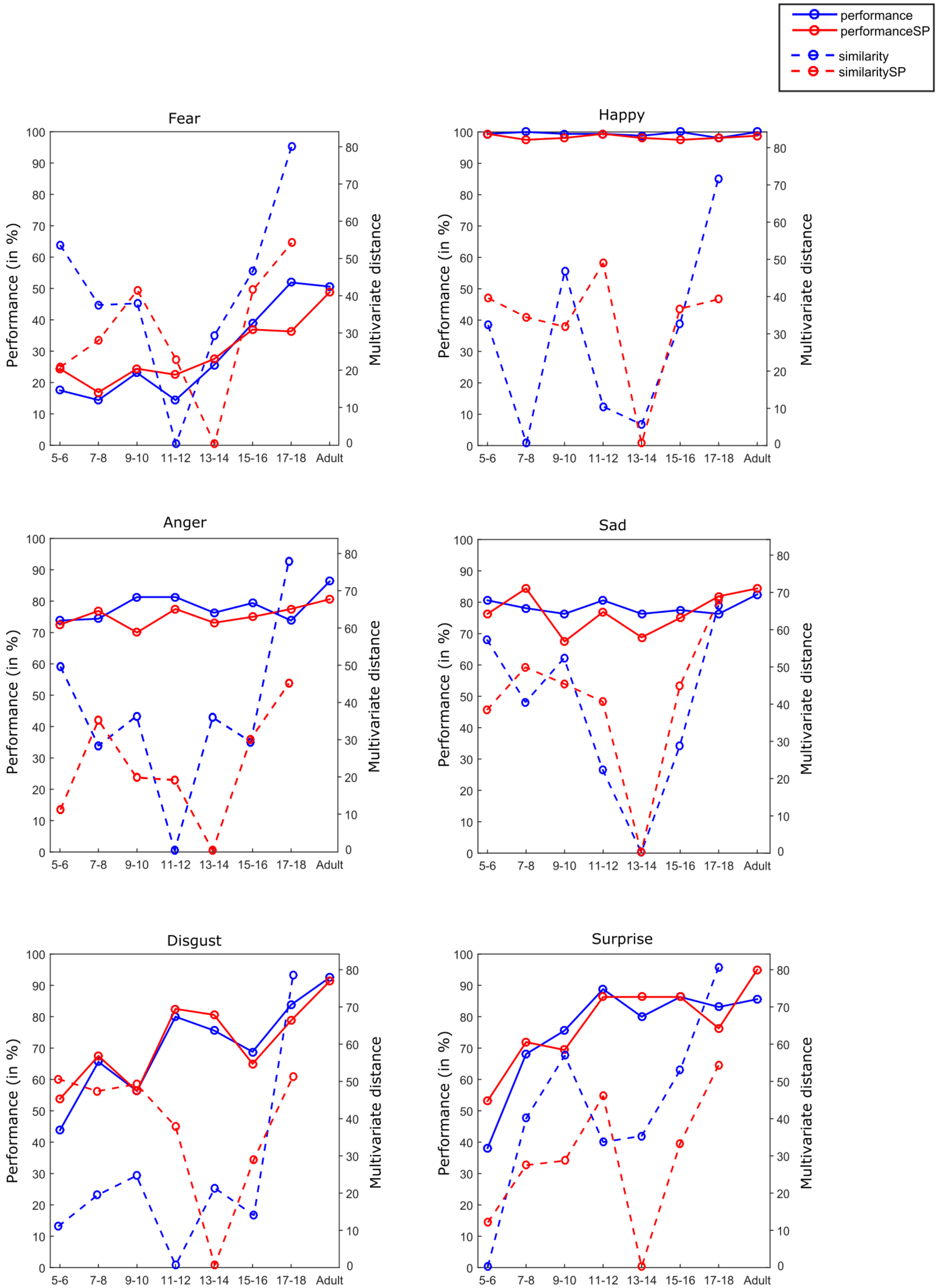

Figure 5.3 Multivariate Distance Analysis and Accuracy Performance Plots. Results for the Natural Viewing condition are shown in blue ink, and red for the Spotlight condition. Dotted lines plot the multivariate distance (right y-axis) for each age group compared to the adult group. Straight lines plot the mean recognition accuracy percentage (left y-axis) of each age group. The multivariate distance was scaled between 0 and 100 to make it comparable

across emotions with 0 being the furthest in similarity from the adult fixation map and 100 the closest.

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

The results from the Linear Mixed Model analysis showed there were no significant differences between each group and the adult group's fixation strategies for each of the emotional expressions tested. We therefore decided to verify whether differences in face scanning between each category of emotional expression could be identified, which would require collapsing the age group data. Before collapsing the age groups, we firstly 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 (Figure 5.4). 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. As no significant differences were found between expressions for each age group, we therefore collapsed the groups to analyse fixation strategies between each of the expressions.

We compared the fixation strategies between each of the expressions with *i*Map4 using Linear Mixed Models. 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 Figure 5.5. The p-values for the clusters illustrating the significant differences between expressions are provided in the supplementary information.

For both the natural viewing and spotlight conditions the majority of the expressions that showed differences in recognition fixation strategies were 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 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.

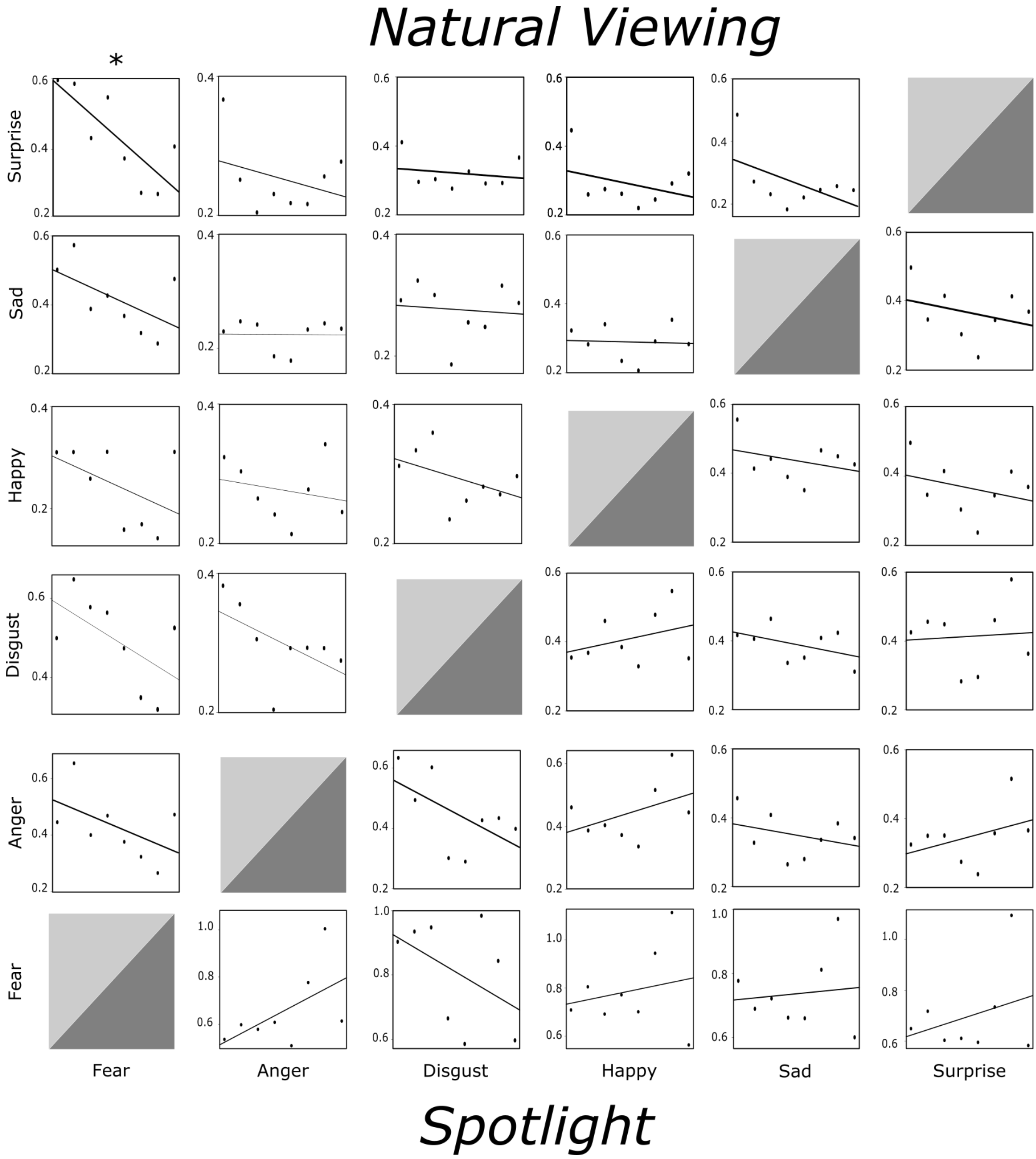

Figure 5.4 Linear regression across groups comparing fixation duration differences between each pair of expressions. The L^2 distance was computed for each comparison between expressions for each participant with the mean L^2 distance of each group represented by a point on the plot (the youngest to 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.

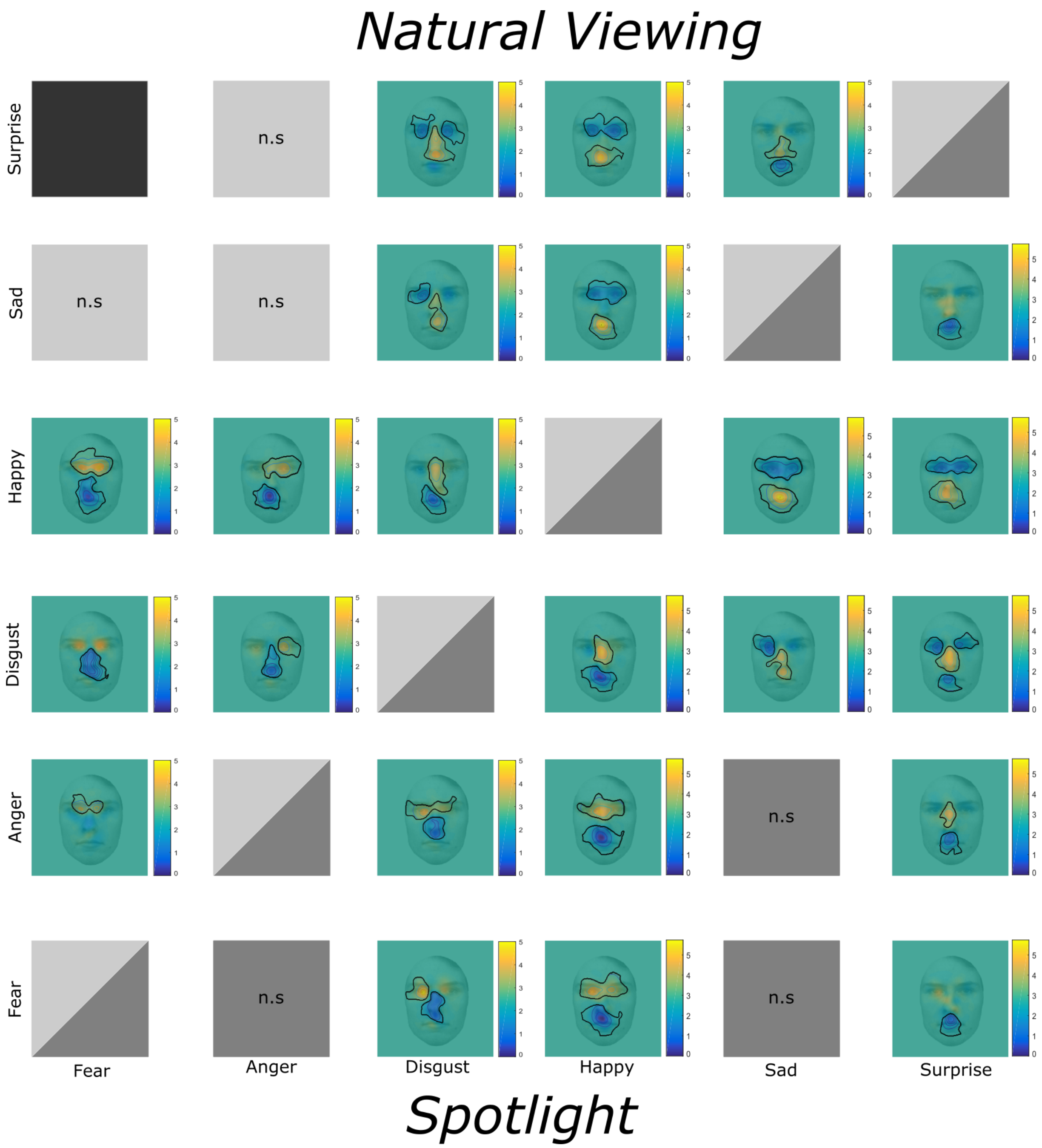

Figure 5.5 Mean fixation duration differences between expressions (with age groups collapsed). The clusters outlined in black represent areas of the face that are significantly differently fixated when comparing two expressions. The plots in the upper diagonal represent the comparisons between expressions for the natural viewing condition, and those in the lower diagonal are for the spotlight condition. For the natural viewing condition, the warmer colours represent the clusters fixated that significantly differ for the expression on the x-axis and the colder colours represent the expression on the y-axis. For the spotlight condition, the colour representation and axes are inverted so warmer colours illustrate fixation biases for the y-axis expressions and colder colours the x-axis expressions. Grey squares represent no significant differences between the expression comparisons. The black square represents no expression comparison analysis completed as the regression across groups comparing fixation duration differences between surprise and fear was significant.

Discussion

Our results demonstrate at which age perceptual strategies for emotion recognition become mature. Eye movements were recorded while children of different developmental age groups, from 5 years of age up to adulthood, viewed static faces expressing the 6 basic emotions during a recognition task. Firstly, we found that the eye movement strategies of 17- to 18-year-olds, the oldest adolescent group, were most similar to adults for recognition of the six emotional expressions tested: fear, anger, disgust, happiness, sadness and surprise. While this result could be expected, comparisons of the eye movement strategies of each age group with 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- to 14- year-old group for sadness recognition, the 11- to 12-year-old group for fear, anger, disgust and surprise, and 7- to 8- year-olds for happiness. Therefore, the dip in strategy similarity to adults did not occur at a uniform age across all of the expressions, just as recognition performance for each of the expressions does not develop in a uniform way (Gao & Maurer, 2010; Herba & Phillips, 2004; Lawrence, Campbell, & Skuse, 2015; Mancini, Agnoli, Baldaro, Bitti, & Surcinelli, 2013; Rodger, Vizioli, Ouyang, & Caldara, 2015; Rodger, Lao, & Caldara, 2018). Similarly, a recent lifespan study revealed that emotion recognition evolves non-uniformly throughout the lifespan (Richoz, Lao, Pascalis, & Caldara, 2018). Following the developmental dip, strategy similarity to the adult group increased in an upwards trend for all expressions except anger, for which there was a very slight trough at 15-16 years, and happiness for which there was a second marked dip in strategy similarity from 11-14 years, the ages during which the primary dip is found for all other expressions. A trend towards eye-movement strategies becoming more 'adult-like' for facial identity recognition has similarly been shown, although the age groups tested were not as young as those tested here and stopped at 12 years of age (Kelly et al., 2011).

While 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 a developmental dip occurs in performance during the ages of 10-14 years (e.g., Carey et al., 1980; Flin, 1980; Soppe, 1986). Such a dip is proposed to be the result of a change in encoding strategy or of biological changes that occur around the age of puberty (Leder, Schwarzer, & Langton, 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, which our results support. Regardless of the findings debated for facial identity, our results might relate to a reorganization of the face processing system resulting from the the ability to learn and decode more subtle expression signals, typical of more adult-like social interactions.

Using the *i*Map4 toolbox, we initially compared the recognition scanning strategies of each age group for each emotional expression to the adult group's scanning strategy to identify at which age strategies become mature. However, we found no significant differences in the strategies between each group and the adult group using the univariate analysis in *i*Map4. We therefore initiated a multivariate analysis to increase the sensitivity of comparisons between age groups and revealed which age group had the most similar recognition strategy to the adult group for each expression. Subsequently, we verified whether differences in scanning strategies were present between the emotion categories using *i*Map4 and collapsing the age group data. This analysis showed that similarly 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

(Figure 5.4). The fixation strategies for happiness differed significantly from all the 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 happiness and anger as they were focussed mainly towards 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 to the others. Overall, greater time spent looking at the left eye region differentiated the strategy for anger recognition in comparison to happy and disgust expressions. Finally, strategies for sadness and surprise recognition differed significantly as more time was spent looking at the mouth for surprise expressions in comparison to the lower nose area for sadness.

Interestingly, the areas of the face described above which were most densely fixated for recognition of the different expressions are comparable to the diagnostic features necessary for 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, Cottrell, Gosselin and Schyns (2005) identified the diagnostic features of the six basic expressions and a neutral expression. Facial feature use during recognition was analysed across a range of spatial frequencies and distances. The compilation of information use across all frequency bands revealed which features are necessary to recognise 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, or the nose region for disgust. A more recent developmental study using the Bubbles technique has shown that children from the age of 6 to 13 years show similar feature use when categorising fear, sad, happy and anger expressions (Ewing, Karmiloff-Smith, Farran, & Smith, 2017). The advantage of the eye-tracking tracking method here is that fewer trials are necessary to determine feature use and can thus be used 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 here 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 to healthy controls are attributed to a lack of attention to the eye region during the processing of fear expressions (Adolphs, Tranel, Damasio, & Damasio, 1994). When such patients were directed to look at the eyes during a recognition task they were able to recognise expressions of fear, suggesting that the patient's deficit lies in the failure to select the diagnostic features of the face for fear recognition rather than an inability to recognise fear itself (Adolphs et al., 2005; but see Caldara, Schyns. Mayer, Smith, Gosselin, & Rossion, 2005; Fiset, Blais, Royer, Richoz, Dugas, & Caldara, 2017; Richoz, Jack, Garrod, Schyns, & Caldara, 2015, for other types of patients who also do not attend to the eye region). 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; Jack, Garrod, Yu, Caldara & Schyns, 2012). Therefore inattention to certain features of the face drives deficits in emotion recognition for both healthy and clinical groups. Here, we show for the first time the fixation strategies used by children from 5 years of age up to adulthood for recognition of the six basic expressions. The present data can be considered as a benchmark for the normal processing of facial information during facial expression decoding in typically developing children.

Here, we found a U-shaped curve across development in the eye movement strategy similarity with adults, so the scan patterns throughout development are evolving. However, for three of the six basic expressions tested, no differences in recognition performance were found despite diverse strategies being used across groups, so it is difficult to relate strategies to performance with this finding. It is possible that the diagnostic criteria for some expressions are broader than 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 behavioural performance is not clear. 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 towards 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 of free viewing as opposed to training directed towards the diagnostic features of the face for each expression. Therefore, further studies are necessary to understand the relationship between eye movements, diagnostic information and performance.

Conclusions

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 the age of 5 up to adulthood. Notably, we found a developmental dip in strategy similarity to adults between the ages of 11 to 14 for all expressions except happiness, for which the dip occurred earlier, between the ages of 7-8 years. In contrast, no developmental dip was found for recognition performance. The present data can be considered as a benchmark for the normal processing of facial information during facial expression decoding in typically developing children.

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III. GENERAL DISCUSSION AND CONCLUSIONS

Chapter 6

General Discussion and Conclusions

6. General Discussion and Conclusions

In this thesis, I investigated visual information use during facial expression recognition in children from the age of 5 up to adulthood. My aim was to map the continued development of facial expression recognition for each of the 6 basic emotions as the progression of recognition ability throughout childhood and adolescence had not previously been studied (Herba & Phillips, 2004). Moreover, I aimed to chart not only *how well* recognition of facial expressions develops with age, but also *how* facial expression recognition is achieved throughout development by establishing whether perceptual strategies are similar across age and at what stage they can be considered mature. Specifically, the three experimental studies of this thesis had the following aims, which were identified from existing gaps in the developmental literature:

1. To provide a fine-grained mapping of the continued development of expression recognition for the six basic emotions by introducing a psychophysical measure to the literature;
2. To quantify the amount of signal and intensity information needed to recognise the six basic emotions across development;
3. To compare two recognition measures across the same cohort to understand the use of two types of stimuli commonly used in developmental facial emotion recognition studies (expressions at full intensity vs. expressions of varying intensities);
4. To establish at which age perceptual strategies for emotion recognition become mature.

I will now summarise the main findings and discuss the implications of these findings, including potential future studies, before closing with the limitations and conclusions of this thesis.

6.1 Main findings

Study 1: Mapping the Development of Facial Expression Recognition

The primary aim of the first study was to map the continuous development of facial expression recognition in children aged 5 up to adulthood for each of the six basic emotions and a neutral expression, which had not previously been studied within the same experimental paradigm, using a psychophysical approach. To the best of our knowledge, this was the first time a psychophysical approach had been used to investigate the development of facial expression recognition. There were several advantages in implementing a psychophysical adaptive staircase method in a developmental study. Such methods are efficient in determining an observer's recognition threshold as the range of stimuli presented is reduced by staying close to the observer's threshold with each presentation based on the previous response. This efficiency allowed us to implement a paradigm including all six basic expressions and a neutral expression in a developmental study for the first time, which otherwise may have been too demanding for children as more trials would have been required. The method is response-driven as the stimulus threshold is adapted according to the participant's response. Therefore, unlike previous approaches in the developmental literature, the increments in stimulus intensity are not established a priori. In this way, a precise measure of recognition performance can be obtained, as the threshold is identified online, in real time. The level of sensitivity achieved by this approach is therefore beneficial to a developmental study, as a finer-grained representation of what is happening across development is possible.

The psychophysical approach used here provided an unbiased fine-grained mapping of the continued development of expression recognition for the six basic emotions and a neutral expression. We provided a visual mapping of the mean recognition thresholds for each expression and age group (figure 2 of this study). While previous studies have identified unique developmental trajectories for different emotional expressions (Boyatzis, Chazan & Ting, 1993; Vicari et al., 2000; Herba & Phillips, 2004), for the first time we characterise these developmental trajectories by modelling recognition ability across age. A general linear model was used to reveal the developmental trajectories of the mean recognition thresholds and identified three main trends: disgust, neutral, and anger expressions showed a steep improvement across development; sadness and surprise showed a more gradual improvement; finally, recognition of happiness and fear remained stable from 5 years old, suggesting that coding for these two expressions is already mature by 5 years of age. For expressions showing a steep improvement with age such as anger, the insight that in early childhood these expressions are not easily recognised from the face has implications for caregivers and educators working daily with young children.

By also mapping the response biases of the age groups in confusion matrices, we were able to show how categorisation errors contributed to recognition performance. For example, the high confusion rates found during fear recognition and the high variability of these confusions could account for the poor performance in recognising this emotion across age groups. Finally, by computing a similarity matrix which correlated the average recognition threshold across expressions and groups, two main phases in the development of facial expression recognition were identified ranging from 5 to 12 years old, and 13 years old to adulthood. Given the divergence of the youngest adolescent group's overall threshold to the older groups in the second phase, further studies are needed to establish whether there is an additional developmental phase during early adolescence.

Lastly, the approach offers a novel psychophysical tool to measure impairments for specific facial expressions in developmental clinical populations and beyond, and has recently been used to examine facial expression recognition impairments in adult women with eating disorders in a collaboration with our group (Wyssen et al., 2019).

Study 2: Quantifying Facial Expression Signal and Intensity Use during Development

In the second study, we aimed to take this fine-grained mapping of the development of facial expression recognition from the first study further by quantifying how much visual information is needed to recognise an expression across development by comparing two measures of visual information, signal and intensity. Since many different measures have been used in the developmental literature, we also wanted to compare two recognition measures across the same cohort for the first time to understand the use of two types of stimuli commonly used in facial emotion processing studies (expressions at full intensity vs. expressions of varying intensities). We used the same psychophysical approach as the first study, this time with a repeated measures design, and found the quantity of signal and intensity needed to recognise sad, angry, disgust, and surprise expressions decreased with age. The processing of both types of information therefore becomes more discriminative during development. As in the first study, recognition of fear and happiness was stable from 5 years of age, suggesting that the coding for these two expressions is already mature by this age.

We used mutual information analysis, again a novel methodological approach in the developmental literature, to establish how similar the response profiles (e.g. the sequence of responses across trials) of the signal and intensity measures were for each individual on a continuum of age. This analysis revealed that response profiles for both the intensity and signal measures become more similar with age for sad, angry, disgust, and surprise expressions. As the response profiles for intensity and signal are similar only in adulthood, expressions at full intensity (as in the signal condition) and expressions of varying intensities (as in the intensity condition) cannot be compared straightforwardly during development. This critical point is another previously unexplained factor, along with differences in age groups, expressions, and tasks, for the differences in recognition trajectories found throughout the developmental literature.

Study 3: Developmental Eye Movement Strategies for Decoding Facial Expressions of Emotion

In the final study we moved from investigating how much visual information is needed to recognise an expression during development to investigate which information is used by tracking eye movements during expression recognition. To identify at which age perceptual strategies for recognition of facial expressions of emotion become mature, we tracked the eye movements of children and adolescents from the age of 5 up to adulthood using *i*Map4, a robust data driven toolbox (Lao et al., 2017). While univariate analysis did not reveal any significant differences between each of the age groups' fixation patterns and the oldest group's, more detailed multivariate analysis revealed that the 17-18-year-old group's fixation patterns were most similar to the adults for all six emotions. Furthermore, a developmental dip in strategy similarity to adults was found for each expression between 11-14-years, and 7-8-years for happiness. This developmental dip might relate to a reorganisation of the face processing system resulting from the ability to learn and decode more subtle expression signals, typical of more adult-like social interactions. However, given that no such developmental trough was found for recognition performance, further investigation is required to confirm this possibility. Performance did not differ significantly across age groups for happy, angry, and sad recognition, but perceptual strategies diverged. Therefore, a unique strategy was not a prerequisite for optimal recognition performance for these expressions. As this is the first study to investigate eye movements and expression recognition across development, further studies are required to verify the relationship between eye movements, the processing of diagnostic information, and performance.

The three studies presented in this thesis investigated the processing of visual information during facial expression recognition in children from the age of 5 up to adulthood using behavioural and eye tracking methods. The studies revealed that facial expression recognition continues to develop into adulthood as the use of visual information becomes more discriminative. Both recognition performance and perceptual strategies for the expressions develop non-uniformly. In addition to mapping the unique developmental trajectories for recognition of the six basic expressions, the data also revealed several distinct developmental stages where, for example, a developmental dip occurs in perceptual strategy similarity, or during which recognition thresholds are more similar, between 5 to 12 years and adolescence to adulthood. Further investigation of these potential phases is required, particularly since no separate eye-tracking studies of this stage of development exist.

I will now discuss some of the implications from the methodological approaches and findings of our studies, and describe potential future studies to investigate some of these implications.

6.2 Implications and Future Studies

The findings from the experimental studies brought several implications of this work to the fore, and at the same time stimulated several interesting questions for potential future studies. These potential questions are highlighted in the table below. Each table heading indicates the relevant sections which subsequently discuss the question in more detail.

Table 6.1 Future Study Questions (discussed in the sections indicated by the headings)

6.1 Main findings, Study 3: Eye-tracking study of Facial Expression Recognition during Development
Study 1: Is there a relationship between eye movements, the processing of diagnostic Information, and performance for facial expression recognition during development?
6.2.2 The interplay of perceptual and conceptual development in facial expression recognition
Study 2: Is recognition of fear higher for multimodal representations compared to facial expressions across development?
Study 3(a): Does conceptual knowledge predict the representational structure of facial emotion perception during development?
Study 3(b): Do response errors follow similar patterns across age? (Analysis of confusion matrix categorisation errors).
Study 4: How does executive functioning relate to facial expression recognition during development?
Study 5: Do improvements in conceptual understanding explain the rate of improvement in perceptual tasks for some or all of the six basic emotions?
Study 6: How does sensorimotor simulation contribute to facial expression recognition during development, and is simulation related to developmental conceptual representations of emotion?
6.2.3 Reorganisation of the Facial Expression Processing System during Development?
Study 7: Neurodevelopmental study to establish if neurological changes in the prefrontal cortex and executive functioning subserve the developmental reorganisation found in our studies.
Study 8: Does pubertal status influence facial expression recognition, in particular for older or peer aged faces?

6.2.1 Developmental Measures: Sensitivity and Task Complexity

The literature review highlighted several yet-to-be studied gaps in the literature, in particular the lack of studies mapping the continued development of facial expression recognition from early childhood up to adulthood which the experimental studies of this thesis attempted to address. On reviewing the literature, one explanation for this lack of studies (albeit which has somewhat grown since the outset of this thesis) is the inherent difficulty in finding a measure of recognition that can be applied across many different age groups. The most common behavioural methods to test facial expression recognition include matching and labelling tasks, as well as studies which adapt the intensity of expressions to assess recognition performance across age groups. The facility of matching tasks is clear, as by the age of 10 a high level of performance is already possible (e.g. Bruce et al., 2000; Mondloch et al., 2003; Vicari et al., 2000). More complex tasks are necessary to test older children. Labelling tasks require the child to retrieve the correct emotion label for the target expression verbally and are therefore viewed as more complex in comparison to matching tasks which, as described earlier, are closer to a purely perceptual type of task in which emotions are discriminated on the basis of visual properties alone (Adolphs, 2002). While task complexity is greater in labelling tasks requiring a verbal label for the emotion presented, studies using labelling tasks which attempt to test visual recognition as opposed to conceptual understanding may accept general descriptions of how the person is feeling instead of accurate verbal labels (e.g. Vicari et al., 2000; Widen & Russell, 2013) as we did, for example "she doesn't like that" in place of disgust.

Labelling tasks have frequently been used in studies investigating sensitivity to expression intensity (e.g. Herba et al., 2006; Pollak & Kistler, 2002; Thomas et al., 2007). Up until now, the intensity increments of such studies have been established a priori, so the granularity of the recognition measure can only be as fine as the predefined increments. The advantage of introducing a psychophysical approach to the literature was twofold. Firstly, a precise measure of performance can be obtained as the intensity increments are not predefined. Instead, the expression intensity is incremented or decremented as a function of the observer's performance. Secondly, by staying close to the observer's recognition threshold in this way, the range of stimuli presented is reduced. This efficiency in the number of trials is therefore ideal for a developmental study and permitted us to include all six basic emotional expressions and a neutral expression within the same experimental paradigm for the first time. In considering the challenge of finding an appropriate balance between the sensitivity of the measure used and the complexity of the task to accurately assess recognition performance across different developmental age groups, adaptive psychophysical methods are an effective contribution to the literature which can certainly be further exploited.

6.2.2 The Interplay of Perceptual and Conceptual Development in Facial Expression Recognition Tasks

A second challenge in testing facial expression recognition across a range of ages is establishing what capacities are actually being tested. The paradigms described in the literature review and experimental chapters of this thesis aim to measure the perceptual development of facial expression recognition with perceptual tasks. However, as described in various theoretical models of facial emotion processing in Chapter 1, (e.g. Adolph's 2002 *Processing of Emotional Facial Expressions as a Function of Time*; Jack and Schyn's 2015 *Information and Transmission Decoding Framework*) conceptual knowledge of the emotion signalled by the face is also involved in the recognition process. As is now described, the influence of conceptual knowledge cannot be precluded even in perceptual tasks of facial expression recognition.

The recognition of emotion from faces is a complex process that is developed over an extended period and is influenced by many factors. As described in the opening chapter, the predominant view in the emotion literature has been the “basic emotion” theory in which facial features and muscle movements are necessary and sufficient cues to recognize the emotion a person is experiencing (e.g. Buck, 1994; Ekman, 1992). However, over time, alternative, constructivist views which hold that experience and contextual information influence emotion perception and are necessary for emotion recognition (e.g. Aviezer et al., 2008; Barrett, Lindquist, & Gendron, 2007; Russell, 1980; Russell, 1994) have continued to gather support. Factors shown to influence the development of facial expression recognition include emotional experience (e.g. Pollak et al., 2000; Pollak and Kistler, 2002; Pollak et al., 2009; Pollak and Sinha, 2002), socio-economic experience (e.g. Caspi, Taylor, Moffitt, & Plomin, 2000; Goodyer, 2002), and cultural experience (e.g. Geangu et al., 2016; Caldara, 2017). Therefore, with such evidence of the influence of experience on the development of emotion recognition, the previous predominant view that we can read emotion from the face in a purely perceptual manner is no longer adequate.

The ability to recognise emotional expressions does not emerge uniformly during childhood and adolescence. This finding is widely acknowledged by other developmental studies including our own (Boyatzis et al., 1993; Gao and Maurer, 2010; Herba and Phillips, 2004; Lawrence et al., 2015; Mancini et al., 2013; Rodger, Junpeng, & Caldara, 2018; Rodger, Vizioli, Ouyang, & Caldara, 2015; Vicari et al., 2000). Recognition of some emotions precedes others. However, task differences in the methodologies applied by different developmental studies have also contributed to discrepant findings in the rate at which different emotions are recognised during development. Essentially, the differences in tasks have made it difficult to tease apart the development of perceptual and conceptual representations of emotion. Perhaps this difficulty is another reason for the lack of studies, described earlier, in children of this age range and why the number of infant studies has been greater, as it is clearer in young infants that perceptual discrimination is being tested. Our findings show that recognition of all expressions except happiness and fear improve with age at different rates. Since the visual stimuli were tightly controlled in the same way for all participants, this suggests that conceptual factors may also be influencing recognition development. It is possible that a full conceptual representation has not yet been achieved for the expressions which develop later, and hence influences recognition of these expressions. Possibilities for testing such a hypothesis are now discussed below.

With regard to happiness and fear, for which no developmental improvement is found, this would suggest that conceptual representations of these expressions are already equivalent to those of adults from an early age. However, each of these expressions were at the high and low end of recognition performance. Happiness was recognised consistently well across age groups with low levels of signal and intensity. Following the logic that conceptual representations influence recognition, this suggests that the conceptual representation for happiness is mature from an early age. However, despite fear similarly showing no developmental improvement, I would argue that while the *perceptual representation* for fear is mature given the equivalent use of visual information across age groups, it is possible that the *conceptual representation* for this expression is not mature. Performance for fear was low across all age groups. As described in the studies, almost 100% signal or intensity was required for all ages to maintain recognition performance at a level of 75%. Several suggestions for poor performance in fear recognition are provided in the experimental chapters. Here, I would highlight that since performance was limited to visual stimuli alone, visual information alone is not sufficient for highly accurate fear recognition in a paradigm of several emotional expressions. It is possible that information from several senses is necessary for higher performance of fear recognition in such a paradigm. Therefore, I would suggest that with a multimodal representation of fear it is possible that the performance dynamics we saw for visual information would change, with developmental differences possibly emerging, as adults should perform better with more sensory information. It is of course possible that children also perform better with more sensory information, but could they also effectively integrate this information as well as adults? These remain empirical questions to be investigated.

Recent theoretical advances include growing evidence that a perceiver's conceptual knowledge about emotion influences emotion perception, even when a facial expression is presented in isolation (Gendron, Lindquist, Barsalou, & Barrett, 2012; Lindquist, Barrett, Bliss-Moreau, & Russell, 2006; Nook, Lindquist & Zaki, 2015). A recent study with adults found that conceptual knowledge predicts the representational structure of facial emotion perception (Brooks and Freeman, 2018). When adults believed that two emotions were more conceptually similar, faces from these categories were perceived as more similar, even when any physical similarity in the stimuli had been controlled for. Replication of such a study with children would clearly provide further clarity on how perceptual and conceptual representations of emotion interact and develop over time. Similarly, in study 1 we represented the categorisation errors made across development in confusion matrices. As a future project, more detailed analysis of these errors could further inform the aforementioned conceptual and perceptual similarity by identifying which expressions are similarly confused across development. The initial pattern of errors represented in the different age group confusion matrices of the first study appear to be similar across groups, but with higher error rates in younger groups, so warrant further analysis.

Another possibility to investigate the interplay of perceptual and conceptual development in facial expression recognition is the triangulation of measures. Few developmental studies of facial expression recognition have used triangulation methods to try to understand how emotion perception develops in line with other cognitive abilities or stimulus categories. For example, executive functioning has been shown to develop throughout adolescence with changes in the prefrontal cortex during this stage thought to subserve such development (Blakemore & Choudhury, 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004). Executive functioning has also been shown to predict emotion understanding and facial expression recognition in preschoolers (Martins, Osório, Veríssimo, & Martins, 2016; Rosenqvist, Lahti-Nuuttila, Laasonen, & Korkman, 2013), but has yet to be studied in older children and adolescents. Processing speed, response inhibition and working memory have all been shown to develop during adolescence (Luna, Garver, Urban, Lazar, & Sweeney, 2004). It would therefore be valuable to investigate how executive function relates to facial expression recognition throughout development. Essentially, by investigating both perceptual and conceptual emotion recognition tasks in a future study, we can map the developmental rates of each and see how they correspond. It could be that increases in conceptual understanding explain the rate of improvement found in perceptual tasks.

Finally, as described in the introduction, it is also important to consider how sensorimotor simulation contributes to emotion recognition and how this relates to conceptual representations of emotions. A recent review of conceptual representations in the brain argues that the evidence for conceptual representations being embodied, grounded in perception and action is compelling (Kiefer & Pulvermüller, 2012). In addition, it has been suggested that sensorimotor simulation may be particularly effective for emotion recognition when the perceived expression is subtle or ambiguous, as the expressions were in studies 1 and 2 of this thesis (Beffara et al., 2012). Similarly to the volume of developmental facial expression recognition studies at the outset of this thesis, few studies have addressed the influence of sensorimotor simulation on expression recognition during childhood and adolescence. Therefore, a study impeding the embodiment of certain expressions could further inform us about conceptual representations and the role of sensorimotor simulation in emotion recognition during development. In younger children since conceptual representation of emotions may not be as robust as for adults, we might expect that impeding embodiment affects recognition to a lesser extent than in adults. A baseline recognition score would be required for participants to contrast the effects of impeding embodiment from developmental improvements per se. Some expressions may be better embodied than others due to the level of experience with expressions. Modern embodiment theories hold that the body with its sensorimotor capacities allows the conceptual system to develop in relation to how the world is experienced (Barrett & Lindqist, 2008). The role of experience in facial expression recognition has already been demonstrated by Pollak's notable studies, discussed earlier, with neglected and abused children. Anger recognition is consistently better amongst this group of children due to their greater level of exposure to angry faces. Therefore, those less exposed to angry expressions may less well embody this expression and show a slower developmental recognition trajectory, as we found with typically developing children. Happiness recognition rates were high in our studies with typically developing children. By comparing the embodiment of happiness with children of depressed mothers for example, it is possible developmental differences would emerge across such cohorts.

Ultimately, the majority of developmental studies of facial expression recognition have focused on measuring this ability in isolation. Future work is required to further understand how facial expression recognition develops in relation to other aspects of cognitive, emotional, and sensorimotor functioning. Such potential work would be in line with the neuroconstructivist framework discussed in chapter 2, and would further highlight the role of the environment in emotion processing.

6.2.3 Reorganisation of the Facial Expression Processing System during Development?

The data from all three of our experimental studies point to a reorganisation in the processing of facial expressions during development. Firstly, I will summarise these findings before describing a future neurodevelopmental study to investigate if such a reorganisation is evidenced at the neural level.

In study 3, we identified a reorganisation in the processing of facial expressions as the similarity in fixation strategies of each age group with the adult group showed a developmental dip between the ages of 11-14 for all expressions, except happiness for which the dip occurred between 7-8 years. In study 1, representational similarity analysis revealed two main phases in the development of facial expression recognition ranging from 5 to 12 years and 13 years to adulthood, similarly pointing to a reorganisation in the facial expression processing system. Finally, study 2 indicated there is a more gradual tuning of the facial expression processing system as the processing of signal and intensity information only becomes similar during early adulthood for all expressions except fear and happiness. Importantly, as the response profiles become more similar with age, erroneous responses become less random. This suggests that the representations of expressions are more robust in adult participants given that they produced systematic confusions, for example, fear for surprise.

To further investigate what is occurring during this reorganisation, it is necessary to understand what is happening at the neural level before, during, and after the developmental dip in fixation strategy similarity and phase shift described above, which occur within the same period. The dip occurs between the ages of 11 and 14, which marks the transition into adolescence. During adolescence significant physiological changes take place with the onset of puberty as well as significant brain development; in particular changes in the structure of the social brain in late childhood and early adolescence (Blakemore & Choudhury, 2006; Mills, Lalonde, Clasen, Giedd, & Blakemore, 2012; Somerville, 2013).

Blakemore and Choudhury (2006) highlight two significant changes in the brain before and after puberty. The frontal cortex continues to be myelinated well into adolescence, while other sensory and motor areas are already fully myelinated in the first years of life. The implication of this they suggest, is that the transmission speed of neural information in the frontal cortex should increase throughout childhood and adolescence. Secondly, the synaptic density of the prefrontal cortex changes during adolescence. A wave of synaptogenesis occurs in the prefrontal cortex at the onset of puberty, followed by synaptic pruning after puberty. Such pruning is thought to be necessary for the fine-tuning of functional networks by increasing the efficiency of synaptic circuits. These changes in the prefrontal cortex affect the development of executive functions (Blakemore & Choudhury, 2006), which largely reside in the prefrontal cortex and frontal lobe (Diamond, 2013). It would be interesting to investigate whether the developmental dip in fixation strategy similarity described above, corresponds with the changes occurring in the prefrontal cortex at this time, and whether they are related to executive function, as questioned in the previous section. Given that the prefrontal cortex responds rapidly to faces and facial expressions (Kawasaki et al., 2001; Marinkovic, Trebon, Chauvel, & Halgren, 2000), it is possible that synaptic growth and pruning in adolescence are related to the changes in emotion processing we have found in adolescence, which result in the ability to learn and decode more subtle expression signals, typical of more adult-like social interactions.

Lastly, few studies have investigated the relationship between the onset of puberty and facial expression recognition performance. A recent study found no influence of puberty on facial expression recognition (Vetter, Drauschke, Thieme, & Altgassen, 2018). However, as the authors describe, participants' performance was close to ceiling which may indicate that the task was too easy, or not sensitive enough to reveal significant effects. The results are therefore not conclusive. Lawrence et al., (2015) found pubertal status influenced disgust and anger recognition, two of the slowest developing expressions in our study along with neutral (Rodger et al., 2015), so further studies are necessary for more conclusive evidence of whether puberty influences facial expression recognition or not.

6.3 General Limitations and Perspectives

The limitations of each study are provided in the experimental chapters. Some general limitations of the experimental studies are now considered.

Cross-sectional studies

The studies mapping the development of facial expression recognition are cross-sectional. A longitudinal study, beyond the limits of a doctoral thesis, of how facial expression recognition develops over time within the same group of individuals could provide a variety of rich measures to closely assess the ongoing development of emotion recognition. To the best of my knowledge, to-date there are no longitudinal behavioural studies of the development of facial expression recognition, so such a study would be highly valuable.

Emotion Recognition beyond the Face

While the focus of this thesis has been the development of facial expression recognition, it is important to acknowledge the multimodal nature of emotional expression and the contribution of all sensory modalities for effective expression recognition. In the natural environment, recognition of emotion from the face includes the integrative processing of temporal, dynamic, body, voice, and contextual information. There is both behavioural and neuropsychological evidence for this multimodal contribution to emotion recognition (Young, 2018). However, research in multimodal emotion recognition is a fairly recent development which continues to grow with advances in methods facilitating the possibilities for this approach. Studies addressing the multimodal nature of emotional expression and recognition have demonstrated the contribution of voice, body, temporal and contextual information and their interactions (e.g. Aviezer et al., 2008; Campanelle & Belin, 2007; de Gelder, Stienen, & Van den Stock, 2013; de Gelder & Vroomen, 2000; Nummenmaa, Glerean, Hari, & Hietanen, 2014; Schirmer & Adolphs, 2017; Yovel & O'Toole, 2018). Recent developmental evidence has shown that the integration of multimodal information begins early in life and continues to develop during childhood. For example, six-month-old infants can transfer emotional information from auditory to visual modalities for expressions of happiness (Palama, Malsert, & Gentaz, 2018), and six and a half month old infants can correctly match whole body and vocal expressions of emotion (Zieber, Kangas, Hock, & Bhatt, 2014). Pre-schoolers recognise emotion from whole-body expressions (Nelson & Russell, 2011), and contextual visual information improves facial expression recognition for 5 to 15-year olds (Theurel et al., 2016). It is possible that for better performance in recognition of some emotional expressions, multimodal sensory information is necessary. As suggested in study 1, this is one possible explanation why recognition of fear from static facial stimuli alone is commonly poor in both adult and developmental studies.

Age of face stimuli

Adult face stimuli were used in each of the three studies. Memory is more accurate for own-age relative to other-age faces. This phenomenon, known as the own-age bias, was established by studies of face identity recognition. While the research questions of this thesis were not concerned with emotion recognition memory for different aged faces, it is possible that the developmental trajectories reported here would differ if different aged faces were used.

It is worth noting that few studies have examined the own-age bias in children for emotionally expressive faces, so it is not clear whether or not face age influences expression recognition. A recent study with young adults found that emotionally expressive faces reduce the own-age bias (Cronin, Craig, & Lipp, 2018). Recognition of older adult faces improved when the face was emotionally expressive compared to neutral. Similarly, the only known developmental study of the own-age bias with emotionally expressive faces found no own-age advantage in children's recognition. However, only two groups of children aged 5-8 and 9-13 were included in the study (Griffiths, Penton-Voak, Jarrold, & Munafò, 2015).

A recent face identity study tracked the developmental progression of the own-age bias with age-matched faces from early childhood through adolescence into adulthood for the first time (Picci and Scherf, 2016). Puberty was found to influence the own-age face processing bias. Before puberty, children showed enhanced recognition for adult female faces, whereas with puberty an advantage for peer faces emerged, and particularly peer faces that matched one's own pubertal status as puberty progressed. The first two experimental studies of this thesis were similarly the first two studies to trace the developmental progression of facial expression recognition ability from childhood through to adulthood, and reveal novel findings with this approach. A study of the own-age bias in facial expression recognition of children entering puberty and beyond may yield similar novel results as those found by Picci and Scherf for face identity.

Dynamic versus static face stimuli

To implement the QUEST adaptive procedure static facial stimuli were required. It is possible that the developmental trajectories recorded for facial expression recognition could change if dynamic stimuli were used in place of static stimuli. A leading question in the literature that continues to be debated is whether there is a recognition advantage for dynamic facial expressions. Dynamic displays of facial emotion have been increasingly used as stimuli in recent years on the premise that dynamic stimuli are more ecologically valid and representative of daily life interactions than static images. Despite this premise, the findings of a dynamic advantage for facial expression recognition are mixed.

Within the developmental literature, very few studies have compared recognition performance for both static and dynamic facial expressions of emotion (Nelson, Hudspeth, & Russell, 2013; Nelson & Russell, 2011). Of the existing studies, the results were equivocal and did not reveal a dynamic recognition advantage over static stimuli for the facial expressions tested (Nelson, Hudspeth, & Russell, 2013; Nelson & Russell, 2011). All six of the basic emotions were not studied, so further studies are necessary to establish whether a dynamic advantage exists or not for all of the basic emotions, or perhaps for less studied emotions. A recent lifespan study found a dynamic advantage for anger and surprise but not for the other expressions tested (fear, happiness, sadness, disgust) in younger participants (Richoz, Lao, Pascalis, & Caldara, 2018). Further work is therefore necessary to confirm whether a dynamic advantage exists for some facial expressions of emotion but not others during development.

Discrete Age Group Categories versus Continuous Variables

Developmental studies of facial expression recognition to date have used discrete age group categories which have varied in the number of years they incorporate, the minimum being a 3-

year age span before our first study was introduced (e.g. Montirosso, 2010). In our initial study, we wanted to reduce the age group ranges at the same time as addressing the continued development of expression recognition, so we included groups of 2-year age increments (5-6, 7-8, 9-10 etc.). However, any delineation of age into discrete categories is clearly arbitrary rather than data-driven and leads to a loss of statistical power in the findings of age-group differences (Altman & Royston 2006; Cohen 1983; MacCullum et al. 2002; Royston, Altman & Sauerbrei 2006).

In study 2, we used a data-driven approach by analysing age in years on a continuous rather than a categorical scale. By examining individual responses along an age continuum, as opposed to the mean responses of age group categories, a finer level of analysis was possible that provided a precise picture of differences occurring during development. This approach revealed a gradual reduction in information use for recognition of four of the six expressions tested and, for the same expressions, a gradual increase in the similarity of response profiles with age. In a lifespan study, our research group also analysed age on a continuous scale (Richoz et al., 2018). This analysis permitted the identification of 'peak efficiency' for recognising dynamic and static facial expressions of emotion during the lifespan. In a similar way, further validation of our findings could be provided by re-analysing the data from studies 1 and 3 of this thesis along a continuum of age.

Conclusions

At the outset of this thesis, studies of facial expression recognition in school-aged and older children, and in particular of continued development from early childhood up to adulthood, were lacking. The experimental studies of this thesis attempt to provide an initial mapping of the continued development of facial expression recognition by profiling visual information use.

Using behavioural and eye tracking methods novel to the literature, the studies revealed that facial expression recognition continues to develop into adulthood as the use of visual information becomes more discriminative. Both recognition performance and perceptual strategies for facial expressions of emotion develop non-uniformly. In addition to mapping the unique developmental trajectories for recognition of the six basic expressions, the data also revealed several distinct developmental stages where, for example, a developmental dip occurs in perceptual strategy similarity, or during which recognition thresholds are more similar, e.g. between 5 to 12 years and adolescence to adulthood. Further investigation of these potential phases is required, particularly since no separate eye-tracking studies of this stage of development exist. By attempting to map normative development in this way, impairments that diverge from typical development can be more easily identified and targeted with appropriate interventions. Similarly, emotion recognition training in typically developing children has been shown to be effective, and could potentially benefit wider social processing skills; skills that are becoming increasingly important in a globalised, culturally integrated, and highly socially-connected information age. Finally, while the experimental studies attempted to fill some understudied areas of the literature, many possibilities for future work were identified in doing so. Ultimately, the majority of developmental studies of facial expression recognition have focused on measuring this ability in isolation. Future work is required to further understand how facial expression recognition develops in relation to other aspects of cognitive and emotional processing, and the constraints interacting with this development.

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Helen Rodger

- I am enthusiastic, enjoy learning and new challenges; my cross-disciplinary background verifies this.
- I am thorough and conscientious in my approach to all tasks; I am a willing and able problem solver and enjoy tailoring technological solutions for specific applications through consultation with others; examples from my project experience demonstrate this.
- I have wide experience of working with a number of multidisciplinary teams. From this I have developed good communication skills and am very personable.
- I enjoy establishing and maintaining valued working relationships.

Education

Sep 2011–pres: **Ph.D Student & Teaching Assistant, Prof. Caldara's Visual & Social Neuroscience Laboratory, Department of Psychology, University of Fribourg, Switzerland.** Research Topic: Mapping the development of facial expression recognition from early childhood to adulthood. Methodologies: Cross sectional analyses of behavioural and physiological measurements including eye tracking.

2007 – 2009: **Master of Science Psychological Studies (Merit), University of Glasgow**
Masters Project (Grade **A**): *The Influence of Culture on Perception and Face Processing during Development* (Eye tacking, MATLAB 2006a, SPSS), supervised by Dr Georgina Wardle, conducted in Dr Roberto Caldara's Visual Perception Lab.

1999 – 2000: **Master of Science Information Technology (Software & Systems), University of Glasgow**
Masters Project (Grade **A**): *Developing a Resource Management Web Site for the Department of Computing Science* (Oracle 8i, Java Servlets, Swing 1.1 & HTML), supervised by Dr Richard Cooper
Subjects: Java Programming, Object-Oriented Programming & Design, Databases & Information Systems, Systems Analysis & Design, Human Computer Interfaces, Human Factors in Information Technology

1995 – 1999: **Master of Arts English Language and Literature (2:1), University of Glasgow**
Subsidiary Subjects: English Language, French, Psychology, & Statistics.

Work Experience

September 2018-Present:
Junior Researcher, Visual & Social Neuroscience Laboratory, Department of Psychology, University of Fribourg

March 2004-July 2011:
L**earning Technologist**, **Centre for Academic Practice and Learning Enhancement (CAPLE), University of Strathclyde**
Project: *Implementation of the University of Strathclyde's Virtual Learning Environment (VLE)*
My role involved 2 core functions:
<u>1) Software Development</u>

- I designed and developed the VLE's interface with the Student Records System
- I was responsible for systems/application integrations on the project
- I liaised with IT services, Registry and Academic Staff teams to enhance the development of the VLE service.

Technologies: SQL, Perl, UNIX shell scripts and XML
<u>2) Staff development and support</u>

- I provided training and support to academic and administrative staff using the VLE.

- I lead and co-lead scheduled and tailored departmental training workshops, and regularly had one-one ad hoc support appointments with staff.
- I designed interactive online courses for teaching staff to participate in and learn about good practice in teaching and learning online.

January 2001- March 2004:

Software Engineer, BT Exact, Glasgow

Project: *Broadband, Client: BT Wholesale*

I worked on the eCo Broadband Development Team developing an electronic customer ordering (eCo) application used by Service Providers to place Broadband orders for local customers. The eCo client is a Siebel CRM Call Centre implementation, accessed by sales staff to create and service orders, or to check for the availability of Broadband in an area, via an HTML or dedicated client. As BT's priority project at the time, this involved working with teams across the country to integrate the eCo client application with a number of key BT systems. I worked on a number of high-profile 'gold-card' application developments as I had a record of implementing robust solutions to exemplary Siebel coding standards.

Technologies: Siebel 2000, eScript, Oracle 8i, Unix & PL/SQL

Key Skills: Producing designs, implementing and delivering robust solutions under demanding time-scales, developing in line with quality assurance standards, software release planning & co-ordination, coaching & mentoring

Project: *ukonline.gov.uk, Client: Syntegra & The Office of the e-Envoy, The Cabinet Office*

I worked as part of a team developing an e-Democracy web portal ''CitizenSpace" for online access by the public to government consultations and discussion forums. I was specifically responsible for developing routines to provide statistics for the use of the discussion forums.

Technology: ASP, VBScript, HTML, PLSQL, IIS & Oracle 8i. Introduction to the J2EE platform

Key Skills: Requirements capture, user-driven design, developing prototypes, aligning test strategies, content management

***Voluntary Community Projects*:**

I was involved in three schools' projects at BT. The first was an annual project to encourage girls into IT. This involved organising games and tasks to help primary-seven girls to think about what working in IT involves. I also took part in an email mentoring programme with a local primary school, again to help students become familiar with IT and think about future work roles. Lastly, I facilitated IT problem-solving activities with teams of P7 pupils for a Careers Scotland project fair for schools across Glasgow.

Teaching Experience

Teaching Assistant, University of Fribourg, *Sep 2011 – Sep 2018*:

- For 2 years, I was responsible for designing and delivering the course *Expérimentation assistée par ordinateur* in French for second year students.
- I supervised 15 Bachelor students for their thesis working while completing my PhD.
- I supervised 14 groups of 2nd year students for their practical project work in Experimental Psychology.
- I have also delivered 2-hour lecture courses for the Cognitive Neuroscience and Affective and Social Neuroscience Master's Degree Programmes.

Experte en Anglais, Examens de maturité, *2013*, invitée par Sévereine Meier, Gymnase D'Yverdon.

Teaching Assistant, MSc IT, Department of Computing Science, University of Glasgow

Sep – Dec 2000:

- I worked daily in the IT lab and tutorial groups helping students with java programming problems and other IT subject-related queries.

Research Experience

Sep 2011-Aug 2018 **Ph.D Student and Teaching Assistant, Eye & Brain Mapping Lab, Department of Psychology, University of Fribourg.**
50% research for the Ph.D and other research projects and 50% teaching, detailed in the teaching section. I took a 1.5-year pause to have my daughter and worked 50% subsequently from Sep 2017.

March 2012-present **Graduate Student, Swiss Affective Sciences Graduate School, CISA, University of Geneva**
As a member of the Graduate School I participate regularly in the Graduate Seminars, Workshops and Summer School provided as research training by international scholars in the affective sciences.

June 2008 – Sep 2011
Visiting Postgraduate, Cognitive Centre for Neuroimaging (CCNI), Department of Psychology, University of Glasgow
I have been working in Dr Roberto Caldara's Visual Perception lab to:

- Complete my MSc project using eye-tracking technology to investigate face processing strategies in children aged 5-12 years
- Investigate the influence of culture on perceptual processing in a variety of tasks (see publications)
- Implement and analyse an fMRI project following an introduction to fMRI experimental design, and analysis course (BrainVoyagerQX) at the CCNI.

Key skills: Eye-tracking, MATLAB 2006a, E-Prime, BrainVoyagerQX SPSS & Statistica

February – May 2008
Research Assistant, Scottish Council for Research in Education (SCRE), University of Glasgow

- I worked mainly with Dr Dely Elliot, Educational Psychologist, one day-a-week to gain experience in educational psychological research.
- Projects included: NEET group study; SQA study to evaluate the Understanding Standards Website; Joseph Rowntree Foundation 'Shaping Educational Attitudes and Aspirations', and 'Engineering the Future: the Promotion of Engineering through the Creation of a Structured School-University Interface'.

Key skills: coding semi-structured interview data; chart and graph production using Chartsmith, conducting telephone interviews; data analysis in SPSS

Publications & Conference Proceedings

Peer-reviewed Journal Articles:

Rodger, H., Lao, J., Stoll, C., Pascalis, O., Dye, M.W.G., & Caldara, R. (under review). The Recognition of Facial Expressions of Emotion in Deaf and Hearing Individuals.

Rodger, H., Sokhn, N., Lao, J., Liu, Y., & Caldara, R. (under review). Developmental eye movement strategies for decoding facial expressions of emotion.

Rodger, H*., Stoll, C*., Lao, J*., Richoz, A.-R., Pascalis, O., Dye, M.W.G., & Caldara, R. (2019). Quantifying facial expression intensity and signal use in deaf signers. *Journal of Deaf Studies and Deaf Education, 1-10. *These first authors contributed equally to this work.*

Wyssen, A., Lao, J., **Rodger, H.**, Humbel, N., Lennertz, J., Schuck, K., Isenschmid, B., Milos, G., Trier, S., Whinyates, K., Assion, H.-J., Ueberberg, B, Müller, J., Klauke, B., Teismann, T., Margraf, J., Juckel, G., Kossmann, C., Schneider, S., Caldara, R. & Munsch, S. (2019). Facial Emotion Recognition Abilities in Women Suffering from Eating Disorders. *Psychosomatic Medicine: Journal of Behavioral Medicine*, 81, 155-164.

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Rodger, H., Vizioli, L., Ouyang, X., & Caldara, R. (2015). Mapping the Development of Facial Expression Recognition. *Developmental Science.* doi: 10.1111/desc.12281

Kelly, D.J., Liu, S., **Rodger, H.**, Miellet, S., Ge, L. & Caldara, R. (2011). Developing Cultural Differences in Face Processing. *Developmental Science*, *14* (5), 1176-1184.

Rodger, H., Kelly, D., Blais, C., & Caldara, R. (2010). Inverting faces does not abolish cultural diversity in eye movements*. Perception 39*(11) 1491 – 1503

Miellet, S., Zhou, X., He, L., **Rodger, H**., & Caldara, R. (2010). Investigating cultural diversity for extrafoveal information use in visual scenes. *Journal of Vision 10* (6) article 21.

Conference Abstracts:

Talks

Rodger, H., & Caldara, R. (2015). Quantifying visual information use for facial expression recognition during development, *17th European Conference on Developmental Psychology*, University of Minho, Braga, Portugal.

Rodger, H., & Caldara, R. (2015). Quantifying visual information use for facial expression recognition during development, *Biennial Meeting of the International Society for Research on Emotion (ISRE)*, University of Geneva, Switzerland.

Rodger, H., & Caldara, R. (2015). Quantifying information use for facial expression recognition during development, *14th Biannual Congress of the Swiss Psychological Society (SSP),* University of Geneva, Switzerland

Rodger, H., Vizioli L., Ouyang, X., Lao J., & Caldara, R. (2013). Mapping the ontogenesis of facial expression recognition, *Biennial Meeting of the International Society for Research on Emotion (ISRE)*, UC Berkeley, U.S.A.

Rodger, H., Vizioli L., Ouyang, X., Lao J., & Caldara, R. (2013). Mapping the ontogenesis of facial expression recognition, 16th *European Conference on Developmental Psychology,* University of Lausanne, Switzerland.

Rodger, H., Vizioli L., Ouyang, X., Lao J., & Caldara, R. (2013). Mapping the ontogenesis of facial expression recognition, 13th Biannual Congress of the Swiss Psychological Society (SSP)*,* University of Basel, Switzerland.

Vizioli L., Lao J., **Rodger, H**. & Caldara, R. (2012). Culture shapes interbrain synchronization during human goal decoding*. Alpine Brain Imaging Meeting*, Champéry, Switzerland.

Kelly, D.J., Miellet, S., **Rodger, H.**, & Caldara, R. (2010). Tracking cultural diversity in visual perception across development. *Experimental Psychology Society Meeting*, UCL, UK.

Miellet, S., **Rodger, H**., He, L. & Caldara, R. (2009) Investigating cultural diversity for extrafoveal information use in scenes**.** *ECEM2009: 15h European Conference on Eye Movements,* Southampton, UK.

Posters

Lao J., Vizioli L., **Rodger, H**. & Caldara, R. (2012). Neural Adaptation Reveals Early Cultural Tunings in Perceptual Sensitivity to Local/Global Shapes. *Alpine Brain Imaging Meeting*, Champéry, Switzerland.

Rodger, H., & Caldara, R. (2010). First fixation toward the geometric center of human faces is common across tasks and culture. *10th Annual Meeting Vision Sciences Society*, Naples, Florida**.**

Continuing Professional Development

Apr-June 2018: **Mindfulness-based Stress Reduction (MBSR)** 8-week evidenced based course. Training attention and cultivating awareness through meditation and yoga.
Dec 2014: **Project Management for Research**, CUSO, PDRP, Université de Lausanne.
31.10.2014 : **Developing a Comprehensive Skills Profile as a Doctoral student**, CUSO, PDRP.
02.14-10.14: **Time Management**, CUSO, PDRP, Université de Fribourg.
03.05.2013: **Introduction to Robust Statistics using Matlab**, Université de Fribourg, Programme Doctoral Romand en Psychologie
23.04.2013: **Knowing social skills and their impact on self-confidence**, REGARD, Université de Fribourg
4&12Oct 2012: **Quantitative statistics: Multilevel analysis**, Université de Fribourg, Programme Doctoral Romand en Psychologie
30.05-01.06.2012 **Research and Methods in Social Neuroscience**, Université de Genève, Programme Doctoral Romand en Psychologie
Jan/Feb 2012: **Programming in Matlab: Beginners and Advanced**; Université de Fribourg, Programme Doctoral Romand en Psychologie
7-8 Nov 2011: **Module Action et Intention**; Université de Genève, Programme Doctoral Romand en Psychologie
October 2010: **An introduction to fMRI experimental design, and analysis course** (using BrainVoyagerQX), CCNI, University of Glasgow.
June 2010: **E-Moderating online course**, All things in moderation www.atimod.com.
Dec 2009: **Moodle Starter online training course** 40 hours, The Consultants-E, Barcelona, Spain.
Jan-Apr 2007: **Springboard Women's Development Programme** University of Strathclyde
July 2002: **Siebel 2000 Certified Consultant** To achieve Certification from Siebel University the requirements were: the completion of a 3-week Siebel eBusiness Essentials & Core Consultant Course, and a grade above 72% in the Siebel eBusiness 2000 Comprehensive Exam.
Feb 2003: **J2EE Programming** Scottish Enterprise / Learning IT course introducing the J2EE platform: JDBC, JSP & Servlets, Enterprise JavaBeans, JNDI, RMI & CORBA
Nov 2002: **Oracle PL/SQL Essentials** QA Edinburgh: Building and utilising Oracle database structures including functions, procedures, packages and triggers. Best practice techniques for writing and maintaining efficient code.
Oct 2001: **Coaching and Leadership Skills** BT, Manchester
Sep 2001: **Object-Oriented Analysis & Design using the UML** QA Glasgow: Object modelling principles; use cases and activity diagrams; progression from requirements capture through to systems analysis and design.

Languages
French: 2015 Passed exam **B2-C2 FLE "blended learning": Lexique et structure II**, Language Centre, University of Fribourg, Switzerland

Interests
SPORTS & WELLBEING- I enjoy sports, particularly running, yoga and hill-walking. I'm a PADI certified scuba-diver. In spring 2018, I completed an 8-week Mindfulness-Based Stress Reduction program.I try to incorporate this philosophy in my daily life. I subsequently translated the live course from French to English for an English participant.
TRAVEL- I like visiting other countries; I took 6 months out of my previous role to travel around the world. **ARTS & SOCIAL-** I also enjoy reading, cinema, drawing, concerts - and going out with friends for food or dancing.

Prof Roberto Caldara	Prof Niamh Stack	Catherine Milligan
Chair in Cognitive Neuroscience	Course Director, MSc Psychological Studies	Head of Learning Technology Enhancement
University of Fribourg	University of Glasgow	University of Strathclyde

Je déclare sur mon honneur que ma thèse est une oeuvre personnelle, composée sans concours extérieur non autorisé, et qu'elle n'a pas été présentée devant une autre Faculté.