Developmental changes in the critical information used for facial expression processing

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Abstract

Facial expression recognition skills are known to improve across childhood and adolescence, but the mechanisms driving the development of these important social abilities remain unclear. This study investigates directly whether there are qualitative differences in child and adult processing strategies for these emotional stimuli. With a novel adaptation of the Bubbles reverse-correlation paradigm (Gosselin & Schyns, 2001), we added noise to expressive face stimuli and presented sub-sets of randomly sampled information from each image at different locations and spatial frequency bands across experimental trials. Results from our large developmental sample: 71 young children (6 –9 years), 69 older children (10-13 years) and 54 adults, uniquely reveal profiles of strategic information-use for categorisations of fear, sadness, happiness and anger at all ages. All three groups relied upon a distinct set of key facial features for each of these expressions, with fine-tuning of this diagnostic information (features and spatial frequency) observed across developmental time. Reported variability in the developmental trajectories for different emotional expressions is consistent with the notion of functional links between the refinement of information-use and processing ability.

1. Introduction

The ability to interpret emotional signals in faces critically facilitates interpersonal interactions by helping us understand and respond appropriately to those around us. This capacity is observable from early infancy, with generalized discrimination of facial expressions from at least 6-7 months (de Haan & Nelson, 1997; Walker-Andrews, 1997), yet these early skills are far from adult-like (Widen, 2013). Facial expression recognition abilities improve across childhood and adolescence (e.g., De Sonneville et al., 2002; Gao & Maurer, 2009; Herba & Phillips, 2004), particularly for complex and subtle expressions (Johnston, Kaufman, Bajic, & Sercombe, 2011; Thomas, Graham, & LaBar, 2007), with different developmental trajectories observed for different emotions (e.g., Lawrence, Campbell, & Skuse, 2015; Rodger, Vizioli, Ouyang, & Caldara, 2015).

The mechanisms driving the development of these abilities remain unclear. As in the face *identification* literature, debate continues as to whether improvements in *expression* processing reflect broad or face-selective development. Some propose that face-processing mechanisms are mature qualitatively (and perhaps quantitatively, Crookes & Robbins, 2014) as young as 3–6 years and any development improvement reflects broader perceptual and cognitive change, e.g., concentration, spatial attention and meta-memory (Crookes & McKone, 2009; McKone, Crookes, Jeffery, & Dilks, 2012). Consistent with this account, hallmarks of specialist face processing are observed in the youngest ages tested, e.g., configural/holistic processing (de Heering, Houthuys, & Rossion, 2007; Durand, Gallay, Seigneuric, Robichon, & Baudouin, 2007), adaptive norm-based coding (Burton, Jeffery, Skinner, Benton, & Rhodes, 2013; Jeffery et al., 2010). Rival proponents of face-selective development highlight structural and functional change in brain regions associated with expression processing across childhood, e.g., pre-frontal cortex, amygdala, fusiform gyrus

(Golorai, Liberman, Yoon, & Grill-Spector, 2010; Kanwisher, McDermott, & Chun, 1997; Lobaugh, Gibson, & Taylor, 2006; Thomas et al., 2001) and EEG variability in neural sensitivity to emotional expressions in children, adolescents and adults (Batty & Taylor, 2006). Still, finding clear qualitative developmental differences has proven challenging (see McKone et al., 2012 for a review).

In adults, computational models and empirical studies employing reverse-correlation approaches have revealed that a complex, distinctive pattern of *information-use* underlies facial expression processing (e.g., Dailey, Cottrell, Padgett, & Adolphs, 2002; Susskind, Littlewort, Bartlett, Movellan, & Anderson, 2007). Correct categorizations of basic facial expressions are characterised by a critical or 'diagnostic' subset of visual information that differs across emotions (e.g., furrowed brow for anger, wide-open eyes for fear) and may be optimized to disambiguate these categories (Smith, Cottrell, Gosselin, & Schyns, 2005).

Little is known about the information that children use to categorize facial expressions and crucially, whether they show the hallmark adult sensitivity to available information and associated flexibility in information-use across emotions. Refinement of information-use with age and face experience may account for improved processing ability by helping children learn to focus on the most reliable cues for their judgments (Johnston et al., 2011). Preliminary (but contradictory) evidence indeed suggests developmental differences in information-use. Pollux, Hall, and Guo (2014) reported that adults are more biased than 8-9 year olds to look at the eye region during a free-viewing expression categorisation task. However, Karayanidisa, Kellya, Chapmana, Mayes, and Johnston (2009) reported that the value of the mouth region increased significantly with age for 5–12 year olds during a 'feature selection' style expression-categorisation task. As with adults, it is unlikely that simplistic accounts of information-use (e.g., eyes vs. mouth, upper face vs.

lower face) that fail to consider the variable importance of different features for different emotion categories can fully characterise qualitative changes over developmental time.

Differences in children's reliance upon information from across the range of spatial frequencies (SF) could also contribute to their outcomes (relative to adults) on face tasks. For adults, the mid-band (8-25 cycles per face) provides the optimal information for judgments of face identity (Costen, Parker, & Craw, 1994, 1996; Näsänen, 1999; Ruiz-Soler & Beltran, 2006) and expression, although the specific diagnostic spectra may vary with emotion category (Smith & Schyns, 2009) and task particulars (Smith & Merlusca, 2014). To our knowledge, only two studies have investigated SF biases in children's expression processing, with contrasting results. Deruelle and Fagot (2005) used the hybrid faces technique to explore how 5-8 year olds and adults extract emotion and gender information from low- and high-passed faces (no mid-band condition). They revealed that all three groups relied on high SF more than low SF information for expression categorizations (smile vs. grimace) with the reverse profile for gender categorisations. The second SF study assessed the drop-off in contrast thresholds associated with adding low-, mid- and high-SF noise to expressive faces in 10-year-olds, 14-year-olds and adults (Gao & Maurer, 2011). All three groups relied heavily upon mid- and low -F information to perform emotion categorizations, with the key developmental difference being a need for greater contrast in the younger samples to counter the added noise. A crucial need remains for further developmental investigations of SF biases in facial expression categorisation.

The Bubbles paradigm (Gosselin & Schyns, 2001) provides an elegant methodology to characterise the SF specific information used by children to categorise facial expressions. This reverse-correlation technique pinpoints the most critical information for categorical judgments by presenting sub-sets of visual information via randomly positioned apertures ('Bubbles'), at different locations and spatial frequencies. Reverse-correlating categorisation performance (correct vs. incorrect) with the information presented allows researchers to establish the critical SF-specific visual information driving performance.

Hitherto the Bubbles technique has predominantly been used with adults (cf., Humphreys, Gosselin, Schyns, & Johnson, 2006), in part because bias-free, comprehensive sampling of a stimulus requires a considerable number of trials. Here, by testing a large number of participants over a relatively small number of trials we are able to provide the first full developmental characterisation of information-use for expression judgments. We tested two groups of children: young (6–9 years) and older (10-13 years), to encompass age ranges where changes in expression-processing ability occur for four basic expressions: fear, sadness, happiness, anger (Gao & Maurer, 2009; Rodger et al., 2015), and compared their performance to that of adults.

The diagnostic information for a particular categorisation is said to represent a bridge between the visual information that is useful for making the categorisation (termed "available information") and internal representations of that category in memory ("represented information", Gosselin & Schyns, 2002; Schyns & Oliva, 1997). This framework predicts that observers will not encode the same information across all contexts, but rather change their strategy as a function of their current task. Emotion categorisation in adults shows exactly this, with behavioural (Smith et al., 2005; Smith & Merlusca, 2014) and neural evidence (Schyns, Petro, & Smith, 2007, 2009) supporting encoding of emotion-specific diagnostic information from the earliest stages (170ms post stimulus onset). The small amount of developmental evidence available (e.g., Deruelle & Fagot, 2005) points possibly to a similarly variable and strategic processing strategy in children. Our study tests directly whether children draw upon a fixed or varied set of facial features for their categorisations across emotions.

To the extent that a small number of facial expressions might be critically adaptive for successful development (e.g., happiness as a cue to approval and a guide to learning, Wu, Gopnik, Richardson, & Kirkham, 2011) and for survival (e.g., fear as a cue to danger, Tamietto & de Gelder, 2010), we might expect that even young children will process these particular emotional expressions in a sophisticated and potentially adult-like manner. For example, we predict that children, like adults, will make use of the mouth region across SF bands for happiness, (Smith et al., 2005). For fearful faces, we expect children to make use of the wide-open eyes, an important visual cue that is sufficient to activate the amygdala even when presented subliminally (Breiter et al., 1996; Whalen et al., 1998). This cue has important functions for the sender (faster saccadic reaction times, increased field of view, Susskind et al., 2008), making it a consistent, reliable cue.

Predictions regarding information-use for judgments of sad and angry expressions are less obvious. Some studies report that sensitivity to these expressions develops gradually (Gao & Maurer, 2009; Rodger et al., 2015), which could signal idiosyncratic information-use profiles that become increasingly adult-like with age. Critically, however, other studies have identified little or no developmental change in accuracy for recognition of sadness or anger (Lawrence et al., 2015). Thus it remains an empirical question whether information-use in young and older children will resemble that of adults for these expressions.

2. Methods

2.1. Participant information

Participants comprised 54 adults (18-43 years, *M*=26.6, *SD*=5.0; 16 males), 71 6-9-year-olds (*M*=8.5, *SD*=0.9; 35 males, hereafter 'young children') and 69 10-13-year-olds (*M*=11.3, *SD*=0.8; 37 males, hereafter 'older children'). An additional 1 adult, 21 young children and 13 older children were excluded due to poor performance on the emotion categorisation task (below chance for any emotion). Children were recruited from schools in London (UK) and Perth (Australia).

2.2 Stimuli

Eight images (two male identities each displaying fear, sadness, happiness and anger) were extracted from the California Facial Expressions database, which features actors producing expressions according to the Facial Action Coding System (FACS; Ekman & Friesen, 1978), verified by a certified coder and normalised for the location of the eyes and the mouth (Dailey, Cottrell, & Reilly, 2001).

Participants judged the emotional expressions of sub-sampled versions of these images (for full methodological details, see Gosselin & Schyns, 2001). Specifically, face images were decomposed into five non-overlapping spatial-frequency (SF) bandwidths of one octave (120–60, 60–30, 30–15, 15–7.5 and 7.5–3.8 cycles/image; remaining bandwidth = constant background). For each trial, information was independently sampled from each SF band via randomly positioned circularly symmetric Gaussian apertures whose number and size (3 cycles/scale) were adjusted to ensure equivalent information sampling across each scale. The trial stimulus comprised the sampled information from each band re-combined into one image that contained high, mid and low SF information in randomly determined locations (see Smith et al, 2005 for more details and a visual illustration). Sampling density (i.e., total number of bubbles) was adjusted independently for each participant and expression to maintain 75% correct categorisation (staircase algorithm). All three age groups commenced the task with the same number of bubbles (125) to avoid biased information sampling across groups (a key tenet of the bubbles approach). Our adaptive procedure then ensured that as the task progressed, when participants performed well, less information was presented to them via fewer bubbles; when performance was poorer, more information was presented via more bubbles. This calibration ensured that the task remained comparably challenging for all participants and for all emotional expressions. Stimuli appeared centrally for 1000ms on a light grey background at a viewing distance of 70cm (subtending a visual angle of approximately 6.94°x 4.42°).

2.3 Procedure

The task was presented as a game (The Puzzle Bubble Game), completed in approximately 15 minutes by adults in university testing rooms and 20 minutes by children in quiet school rooms. The aim of the game was to identify each face's feelings, which was made challenging by "cheeky puzzle bubbles" that conceal parts from view[1]. Responses were made by the participant via a labelled keyboard press (labels=photographs of the 4 expressions displayed by a third face identity as well as a question mark: 'I don't know' response) or verbally to the experimenter (by the very youngest children). Participants had unlimited time to respond.

The task consisted of a training and test phase. To maintain attention and motivation, an experimenter sat with each participant and provided enthusiastic praise and encouragement throughout. In training, we ensured participants could correctly categorise each expression (minimum 75% accuracy) when intact and shown for an unlimited time and when intact and shown for 1000ms. Auditory performance feedback was provided after each training trial.

The test phase consisted of 8 blocks of 24 trials (192 total). Some children completed slightly fewer due to time constraints (mean trials completed by young children=185, SD=16.6; older children=189, SD=8.75). Blocks were separated by generic "keep up the

[1] For ease of explanation, we told participants that the bubbles concealed things from view; however, in truth the bubbles more accurately *revealed* information (like windows through an opaque mask).

good work" screens (odd numbered blocks) and a brief entertaining game called the Puzzle Bubble Challenge (even numbered blocks). Here, participants guessed the name of a film, geographical location, or television program depicted in an image initially obscured and seen through only a small number of bubbles. The task became easier as the experimenter provided participants with additional clues/information.

3. Results

3.1 Performance metrics

The use of an unbiased equivalent 'starting point' for each participant and facial expression (of 125 bubbles) prevented us fully matching accuracy for children and adults in the relatively small number of trials. Age-related increases in the accuracy of participants' emotion categorisations support developmental improvement in facial expression processing (Figure 1). A repeated measures ANOVA investigating the effect of age (young children, older children, adults) and expression (fear, sadness, happiness, anger) on percentage correct during the bubbles task identified a significant main effect of age, $F(2,191) = 22.75$, $p<.001$, $\eta_p^2 = .19$. Adults (M=75.9, SD=11.6) performed significantly better than older children (M=72.8, SD=15.0; $t(121)=2.79$, $p<.01$), who in turn performed significantly better than younger children (M=68.1, SD=17.1; $t(138)=4.26$, $p<.001$.

There was also a significant main effect of expression, $F(3, 573) = 314.49$, $p<.001$, $\eta_p^2 = 0.62$. Accuracy was significantly superior for happiness (M=84.9, SD=3.9) compared to fear (M=75.5, SD=9.6; $t(193) = 13.45$, $p<.001$), which was superior to sadness (M=72.1, SD=12.5; $t(193) = 3.53$, $p <.01$), which was superior to anger (M=55.4, SD=14.8; $t(193) = 13.45$, $p<.001$). These effects were qualified by a significant age x expression interaction, $F(6, 573) = 9.70$, $p<.001$, $\eta_p^2 = .09$. This reflected the fact that all comparisons were significant aside from a) older children vs. adults for fear, p=.79 and b) older children vs.

adults for sadness, *p*=.29 c) young children vs. adults for categorising happy, *p*=.50 and d) fear vs. sad faces for adults, *p*=.23.

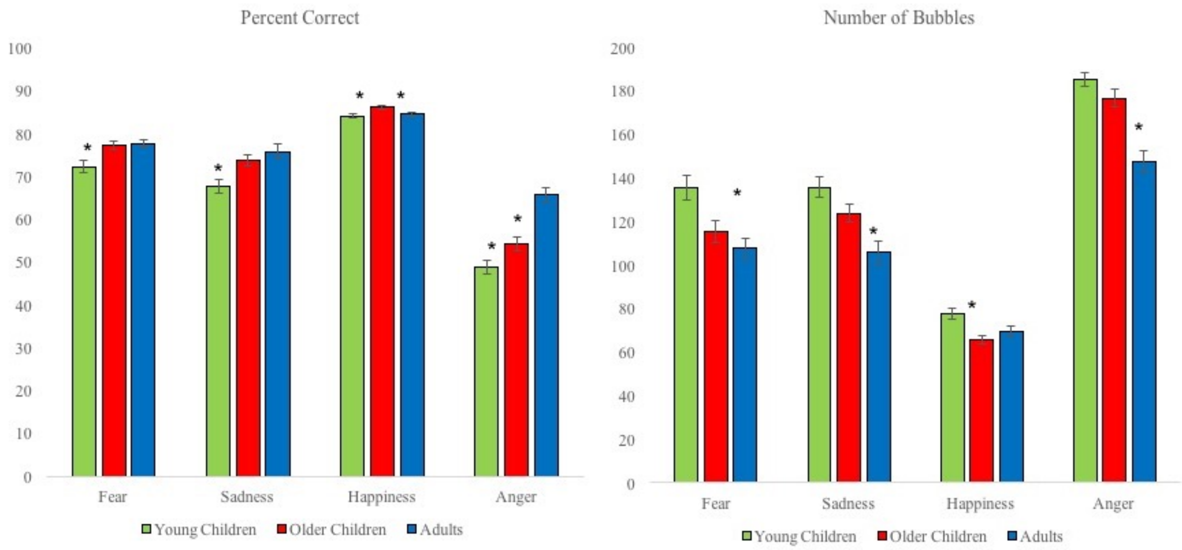

Figure 1. Task difficulty was modulated online to target each participant's performance around 75%. Mean accuracy of emotion expression categorisations (on the left) and median number of bubbles required to achieve this performance level (on the right) for each age group. Asterisks denote significant group differences (p<.05).

A complementary performance metric is the median number of bubbles required to reach mean accuracy levels for each emotion. This value provides a direct indicator of task difficulty with respect to the amount of visual information participants required to achieve a particular performance level. In line with the accuracy results, a repeated measures ANOVA confirmed a significant main effect of age, $F(2,191) = 19.46$, $p<.001$, $\eta_p^2 = .16$. Young children (M=133.6, SD=24.1) required significantly more information than did older children (M=120.3, SD=20.7; $t(138) = 3.47$, $p<.01$), who in turn required significantly more information than adults (M=107.6, SD=24.6; $t(121) = 3.10$, $p<.01$). There was also a significant effect of expression, $F(3,573) = 384.77$, $p<.001$, $\eta_p^2 = .66$. Participants required more bubbles to identify anger (*M*=171.7, *SD*=35.0) than all three other expressions, *t*s >16.0, *p*s < .001, and fewer bubbles to identify happiness (*M*=71.1, *SD*=19.7) than all three other expressions, *t*s>16.3, *p*s <.001. There was no significant difference in the amount of information required for fear (*M*=120.6, *SD*=43.2) and sad expressions (*M*=123.1, *SD*=39.8), $t(193) = .78$, p=.43. Here again, a small but significant interaction ($F(6,573) = 4.67$, p <.001, $\eta_p^2 = .04$, highlighted the variable nature of these developmental changes across emotion categories. Younger children always required numerically more bubbles than older children, but this group difference was significant only for the 'easiest' expressions: fear and happiness (sad p=.06; angry p=.08). By contrast, older children required significantly more bubbles than adults for only the 'hardest' expressions: sadness and anger (fear p=.29, happiness p=.22).

Tension between equating information sampling and performance accuracy across participant groups is difficult to avoid in this developmental context. However, in a supplementary analysis we were able to extract a subsample of children from the full cohort that were well-matched on both key performance metrics for categorisations of fear, sadness and happiness (in most cases these children were also well matched with the adult group on categorisation accuracy for each expression). We obtained these groups by excluding the lowest performing young children independently for each emotion (i.e., different children were dropped across conditions). See Table 1 for detailed information about this revised subgroup of children. For fear and sadness, we excluded those performing below 60% correct. For happiness – where overall performance was considerably better– we excluded those performing below 80% correct. For anger – where overall performance was relatively poor – to obtain matched groups we excluded those children from both the younger and older child groups whose accuracy was below 40% correct (older children: new N= 59, M =57.8, SD = 10.7).

3.2 Classification images

Within each age group, and for each expression, we divided trials into two categories: when the information presented resulted in correct vs. incorrect categorisation ('don't know' was considered incorrect[2]). The bubble masks associated with correct categorisations for each emotion were then summed together and the sum of all bubble masks associated with incorrect categorisations subtracted from them for that emotion to generate classification images revealing the specific information driving correct vs. incorrect categorisations. To maximise data collection with this developmental population we sampled information only from the face images (as per Smith et al., 2005) and not from any surrounding non-face region. In order to conduct the specially designed corrected statistical tests for classification images (Chauvin, Worsley, Schyns, Arguin, & Gosslin, 2005) it is necessary to select a baseline region where one expects to observe no difference in information use. Here the sampled non-face regions around the face image (e.g. the neck, the hairline) formed this region. By applying $p<.05$ peak threshold and cluster size criterion, we established those regions that were statistically associated with correct categorisation performance, henceforth termed diagnostic information or features (see Chauvin, Worsley, Schyns, Arguin, & Gosselin, 2005 for statistical tests). Diagnostic regions are presented for each of the sampled SF bands in green (younger children), red (older children) and blue (adults) in Figures 2-5 panel A, for fear, sadness, anger and happiness categorizations respectively[3]. To visualise the overall diagnostic information we also selected a representative emotional face for each emotion and revealed only the information significantly associated with correct

[2] Don't know responses were used very infrequently by all participant groups: young children M=1.6%, STD = 2.7, older children M= 1.7%, STD = 2.1, adults M=4.2%, STD = 4.8.
[3] Unthresholded classification images are provided in Supplementary Figure 2 for fear and sadness, and in Supplementary Figure 3 for anger and happiness alongside the diagnostic information for ease of interpretation.

categorisation performance across the SF scales (see Effective Faces, Figures 2 to 5, panel B).

The effective images and diagnostic information results reveal both striking similarities and differences in the specific cues that drive expression judgments in participants of different ages. All three groups shift their information processing strategies across categories to extract the most useful visual features for different emotions, e.g., switching from using the widened eyes for fear, smiling mouth for happiness, downturned mouth for sadness, tensed brow-ridge for anger. There is no indication that children (or adults) use a fixed strategy dependent on any feature; rather all groups modify their information-use to target informative visual cues. Importantly, the visual information employed by adults is very much in line with a number of published studies using the same method but with larger trial numbers and different stimulus sets (Smith et al, 2005; Schyns, Gosselin & Smith, 2007; Smith & Merlusca, 2014), which validates the use of this task with a relatively lower number of total trials than has been used in previous studies.

Crucially, the profile of information use observed in the better matched-subsample of young children closely aligned with our findings with the full cohort. This convergence strongly suggests that developmental differences in information use during expression categorizations do not simply reflect discrepancies in observer *accuracy* with age. There was a clear and close resemblance between the information used by the higher performing subsamples of young children, and by the main cohort for categorisations of fear, anger and happiness (see Figures 2 to 5, panel C). In the case of sadness, some differences emerged, e.g., there was no longer strong evidence for use of wrinkles on the forehead, instead the left eye and brow brought young children more in line with older children and adults, and the use of mouth cues was slightly more tightly focused in this higher performing group. Crucially however, the profile of the young children is by no means adult-like. There is still a strong reliance upon piecemeal cues from the higher spatial frequency bands rather than more integrated, holistic information use from the mid-band, and little consideration of the right eye. The alignment between the profiles of information observed with the higher performing subsamples and the full cohorts of young and older children reported above serves to allay potential concerns that developmental differences in information use during expression categorisations simply reflect discrepancies in observer accuracy with age.

To formalise the differences in diagnostic information across the three groups, we directly compared the classification images for each emotion and spatial scale (i.e. young vs. older children, young children vs. adults and older children vs. adults). To this end, we simply subtracted the non-thresholded, but already z-transformed, classification images generated above (for each spatial scale and emotional expression), for the comparison conditions of interest (e.g. young vs. older children). We then applied the same rigorous statistical tests ($p<0.05$ threshold and cluster criterion) to these newly highlighted diagnostic (difference) regions to establish where group differences in profiles of information use were significant. Our use of the non-thresholded classification images reflects our desire to ensure that significant differences are not over represented as a result of regions 'just missing' a statistical threshold. To visualise these differences, we again selected a representative emotional image and reveal only the information that is used significantly more by one group than another (see Figures 2-5, panel D). Note that we used the classification images from the high performing subset of younger children to limit any unfairness in direct comparison resulting from discrepancies in performance accuracy with our original groupings.

For the categorization of fearful expressions (Figure 2) there are clear differences across the groups in the diagnostic features underlying correct categorisation. As expected, the wide open eyes and opened mouth dominate the diagnostic information across all age groups, though there appears to be a trimming of information use to the focal point of these key features with age. The most striking age-related statistical differences are in the use of lower spatial frequency information from the eyes, nose and mouth – by young children, which is largely absent from the adult profile. The extent to which the older children made statistically more use of the nose than adults is also borne out in the difference images (Figure 2D), alongside their strong reliance on the high frequencies of the right hand side eye. The difference in the use of the right eye in SF Band 1 between adults and children is not significant, however, indicating that children's use of this information was present but at below-threshold levels.

For the harder emotional categories (sadness, anger), there are marked age-related statistical differences in information-use (Figures 3 and 4). While all age groups made use of the downturned mouth for sadness, only older children and adults rely significantly on information in the eye region (Figure 3 A, B). It is interesting to note, however, that the particularly high performing subset of young children do show a clear significant association between performance and the *left* eye, but this still differs from the profile of older children and adults (Figure 3C). Difference images confirm that the adults use eye information (in particular the right side eye) significantly more than young children. Similarly, the older children make more use of the left side eye than do the younger children, but we note that this difference does not reach significance.

For the most 'difficult' angry faces, both the younger and older children focused solely on the pinched eyes and furrowed brow. Unlike adults, these groups made no use of the highly informative information in the taut mouth. High performing subsets of both younger and older children also fail to show any evidence of a significant use of mouth information (see Figure 4C), and this difference is borne out as significant in the difference images (Figure 4D) [4]. Finally, for happiness (the expression for which children's performance is best for accuracy and number of bubbles), the pattern of diagnostic information observed is very similar for all groups.

Finally, following Smith et al, 2005, in a supplementary analysis we submitted a model observer to the same categorization task as completed by our participants to benchmark the available information in the current experiment (see Supplementary Methods). Importantly we matched the model parameters with that of each participant group categorizing each emotional expression i.e. equating performance accuracy **and** number of information samples during the task in a series of separate models. Results reveal strikingly similar information to be significantly associated with correct performance for each emotional expression across the participant group specific models (see Supplementary Figure 3). Thus, the underlying differences in the amount of information provided (number of bubbles) and categorization performance accuracy had only minimal impact in changing the information available to perform the emotion categorization task across participant groups (and not in any way that mirrored the observed human differences in information use).

Although model observers could be considered a powerful benchmark against which to track developmental differences in the current context, our primary interest in this work is to track the development of human information processing with increasing age. Computer models do not necessarily represent the apex of such development in the same way as real adults, and the differences between human and model observers have previously been shown

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[4] Please note that it was not possible to match the performance of younger or older children to adults for their anger categorisations leaving a residual performance difference of 10% for younger children compared to adults. The use of the z-transform should minimise any resulting unfairness driven by the performance differences when directly comparing information use across the groups (Figure 4D), however this cannot be entirely ruled out. Note too, however, that the differences are not one-sided as one might expect should adults have an unfair advantage due to their improved categorization accuracy.

to provide important insights in their own right (Smith et al, 2005). The most appropriate benchmark, therefore, remains that of adult human observers performing the same task.

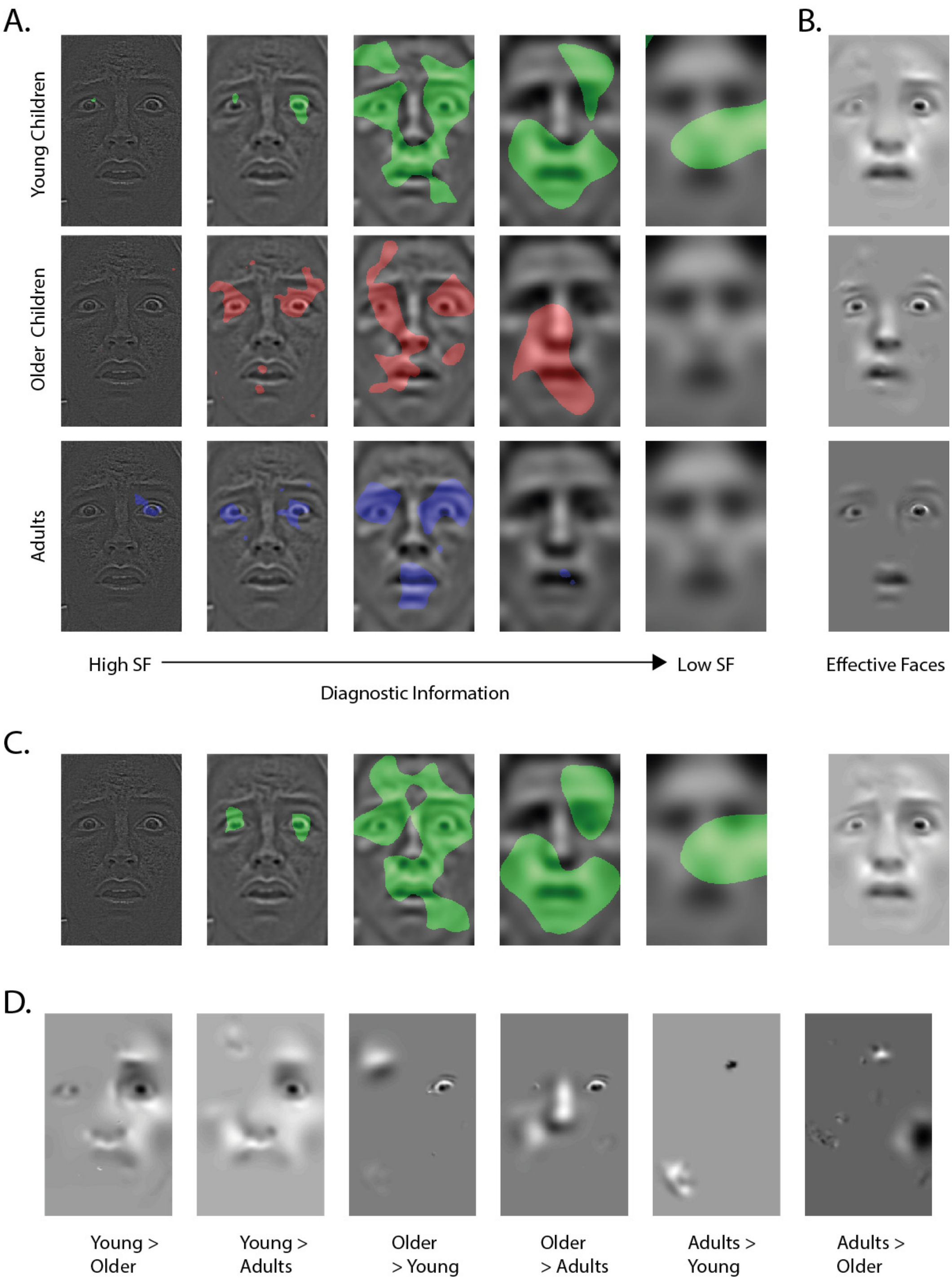

Figure 2. A. The diagnostic information (i.e. information that is significantly associated with performance driving fearful categorizations, for young children in green, older children in red and adults in blue. B. Only the diagnostic information extracted from each SF scale of a sample image and recombined to visualise the information used by each participant group to complete their successful face categorizations. C. As A and B for the high performing sub-

sample of young children. D. Information that is used significantly more by one group than the other (p<0.05), extracted from a sample image and combined across SF scales to visualise. (Note Young = higher performing subset of young participants as per C).

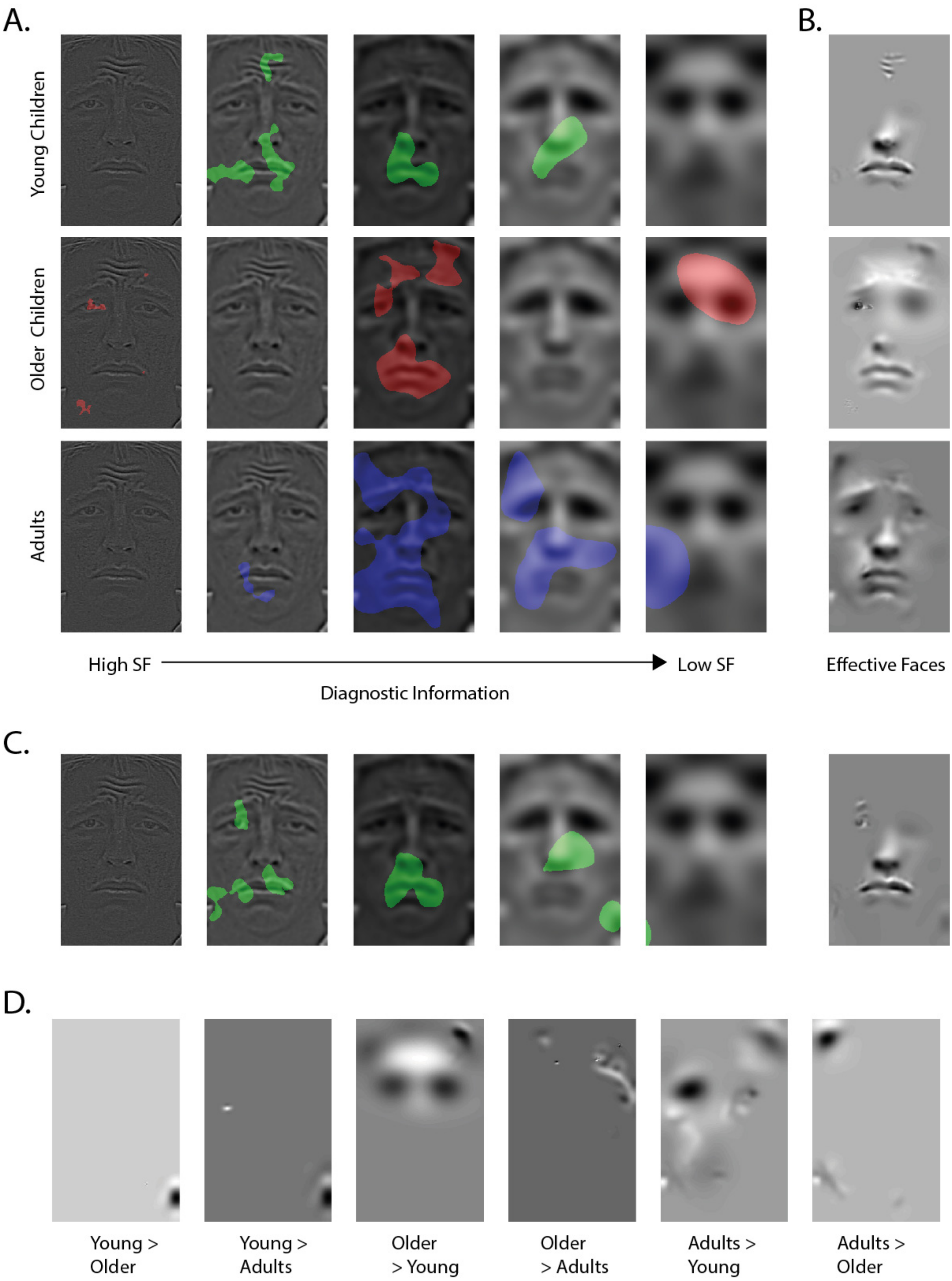

Figure 3. as Figure 2, for sadness categorizations.

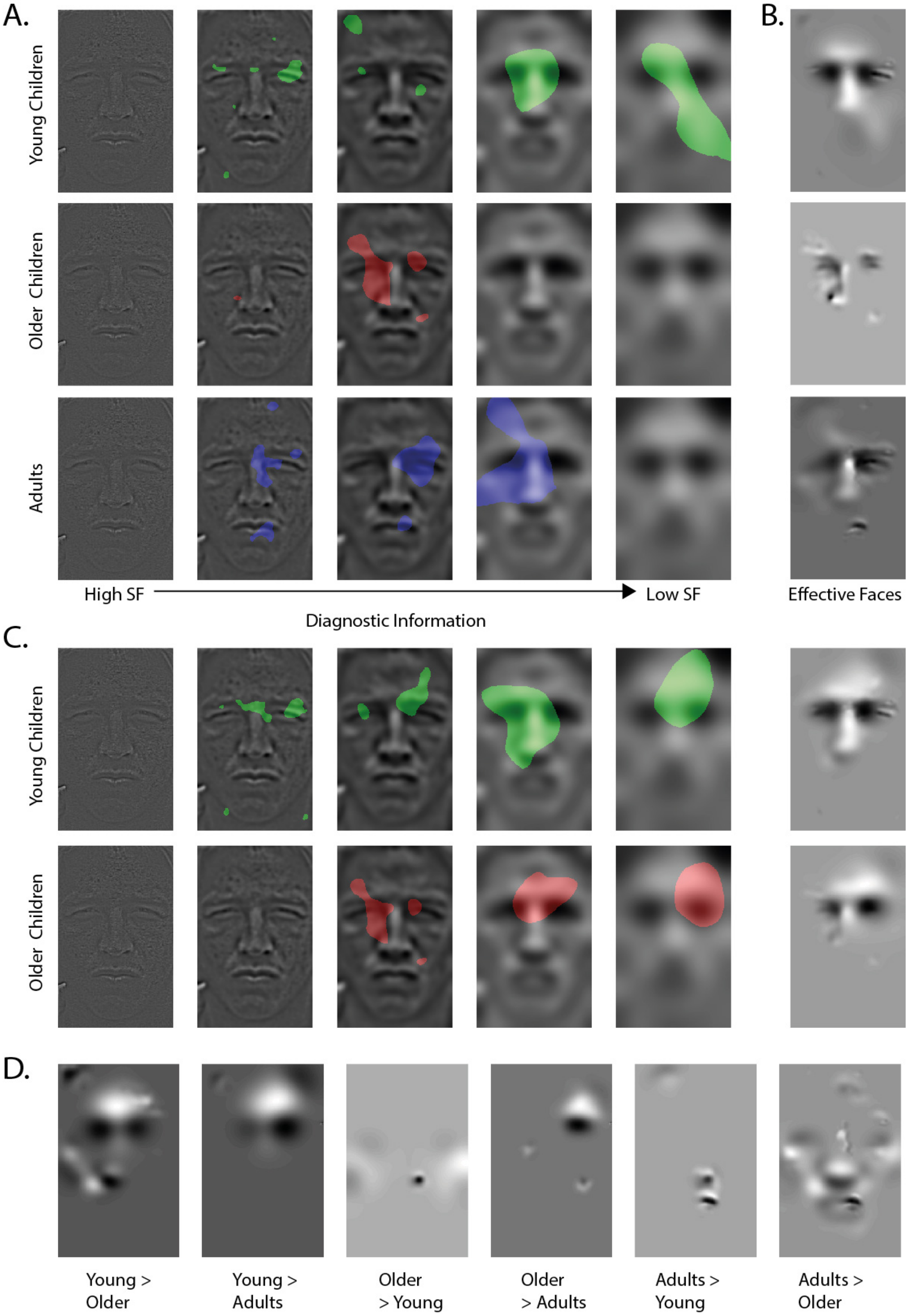
A.
B.
Young Children
Older Children
Adults
High SF
Low SF
Diagnostic Information
Effective Faces
C.
Young Children
Older Children
D.
Young > Older
Young > Adults
Older > Young
Older > Adults
Adults > Young
Adults > Older

Figure 4. as Figure 2, for anger categorizations. *(Note Older = higher performing subset of older participants as per C).*

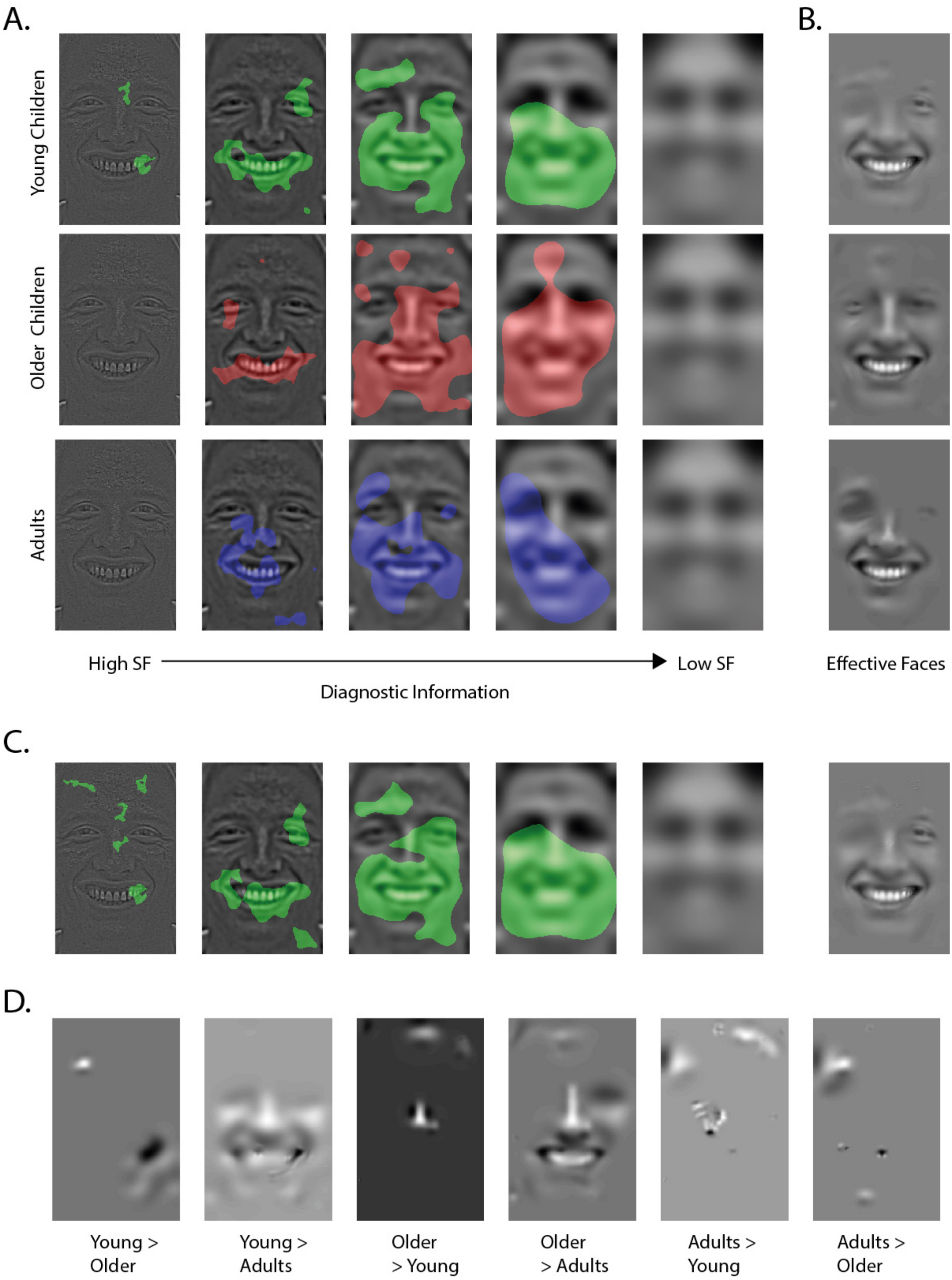

Figure 5 as Figure 2, for happy categorizations.

4. Discussion

The current study constitutes the first direct investigation of information-use during emotional expression judgments across developmental time. Our unique application of the influential 'Bubbles' reverse correlation paradigm with typically developing children and an adult comparison sample has revealed an intriguing mix of parallel and contrasting face processing strategies across age groups. Moreover, the complex profiles of information-use we observed for fear, sadness, happiness and anger in young and older school-aged children appear to be broadly linked with their strengths and weaknesses in processing ability for these different emotion stimuli.

We identified clear developmental differences in expression-processing abilities across age groups. Participants' emotion-categorisation accuracy improved with age, as did their processing efficiency (as measured via the amount of visual information required to achieve performance outcomes: number of bubbles). This evidence of age-related improvement in expression processing is theoretically important because at least one recent study struggled to find evidence of developmental differences in face abilities when task difficulty levels are equated (e.g., Crookes & Robbins, 2014). In itself, this finding constitutes a strong challenge to any claims of quantitatively mature face perception in early development.

Across expressions participants showed consistently stronger categorisation accuracy for happy faces, followed by fear, sadness, and then anger. The relatively strong performance observed for fearful faces contrasts with much of the extant adult expression processing literature (e.g., Palermo & Coltheart, 2004; Tottenham et al., 2009), where this is one of the more difficult expression to categorise. It is difficult to draw strong conclusions about the specific design element or combination of elements driving this difference, given the many differences across studies (e.g. . Moreover 'Bubbles' technically addresses a question differing subtly, but perhaps importantly, from traditional perceptual studies. Rather than simply assessing emotion recognition, the reverse correlation approach is designed to pinpoint the visual information significantly associated with accurate stimulus categorisations, i.e., revealing the information that participants rely upon consistently when deciding if a face looks scared, sad, happy or angry. Thus the current results indicate that participants found it relatively easy to draw out the visual cues pertinent to making fearful judgments, which is not strictly the same thing as finding these judgments effortless.

When we examine the specific information driving participants' expression categorisations, similarities between the children and adults emerge – even when the groups were matched for processing ability. For example, young children, older children and adults all modulated their processing strategies to draw upon different features when categorising fear, sadness, happiness and anger, in order to target the most informative visual cues. The features that were significantly used by participants for each expression were broadly similar across age-groups. Young children, older children and adults all significantly used the widened eyes for fear, smiling mouth for happiness, downturned mouth for sadness, tensed brow-ridge for anger. These distinct processing profiles constitute important new evidence of strategic information-use from 6 years and are consistent with categorical (cf. continuous) perception of emotion in all three age groups (Cheal & Rutherford, 2011; de Gelder, Teunisse, & Benson, 1997).

Profiles of information-use were by no means *identical*, however, across age groups. For the most part, information-use became increasingly more targeted across developmental time. Young children and, to a lesser extent, older children relied upon a wider range of visual features and information for their judgments compared to adults. These extra cues may have introduced additional noise to result in impaired, rather than improved performance accuracy. Importantly, in the case of three of the four emotions presented, this developmental shift reflected quantitative refinement rather than qualitative differences in the diagnostic information relied upon by participants.

Young and older children's profiles of information-use were broadly adultlike for judgments of fear, happiness and sadness, but not anger. There instead, we observed qualitative differences in features driving correct categorization judgements, e.g., use of the mouth region was significantly reduced (essentially absent) in both child groups. Perhaps importantly, children's categorization accuracy was also particularly poor for this expression: anger was the only emotion for which percentage correct could not be statistically matched across age groups. This result – along with the subtler improvements in performance observed as children's information-use became more refined for the other expressions - provides additional support for the notion that information-use optimization is functionally important for face perception. If strategic information use aids efficiency, then then it follows that quantitative and (perhaps particularly) qualitative divergence from the mature profile would come at a cost to performance.

The developmental shifts observed during this experiment support a role for experience in participants' outcomes on the bubbles task. From a long-term perspective, increased opportunities to interpret emotional expressions displayed by different faces that are associated with age and life experience might have contributed to these developmental differences in participants' sensitivity to the most diagnostic cues for these judgments. It is pertinent to note that the current study did not collect information about the cultural background of individual participants, which is known to impact upon how adults view, interpret and extract information from faces (e.g., Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Jack, Caldara, & Schyns, 2012; Jack, Garrod, Yu, Caldara, & Schyns, 2012). An interesting future direction for developmental research could be to investigate directly how and when these cultural differences emerge, and whether they are refined/amplified – as we might expect - with increases in age and (own-race) face experience.

It is also possible that from a short-term perspective (e.g., within the current experiment), older children and adults may have been better cognitively equipped to 'tune in' to the most useful stimulus properties of the exemplars presented across the 192 trials of the experiment. Presentation of two identities modelling each expression meant that participants gained considerable exposure to these particular exemplars and it is possible that this could have impacted on the results. The convergence between the current results and previous adult findings (e.g., Smith et al., 2005), however, provide little reason to think the current results would not generalise, e.g., to larger and more diverse stimulus sets. Nevertheless, information use during expression categorisations *can* vary as a function of task demands (Smith & Merlusca, 2014), making this issue an interesting open question for future research.

The current study represents an important step forward in our understanding of how children read and understand facial displays of emotion. Characterising information-use during expression-categorisation judgments is an important endeavour in its own right because children's abilities in this domain are inextricably linked with their successful social and cognitive development (Widen, 2013). Future studies that investigate the development of information processing on a finer grained level (e.g. at every year of development) may provide further important insights, although such work would require intimidatingly large samples of children. Equally, our findings crucially open the door for future research with other populations by providing a normative baseline against which we can compare profiles of information-use in conditions such as Williams syndrome or autism spectrum disorder, where face processing represents a relative strength and weakness respectively.

This work confirms also that the application of the Bubbles paradigm is not limited to intense psychophysical investigation of typical adult participants. The adult results obtained here with a relatively small number of trials (total) converge nicely with those from studies with much more exhaustive testing sessions (Smith et al., 2005; Smith & Schyns, 2009; Smith & Merlusca, 2014). Though perhaps surprising at first glance, we note that stable Bubbles solutions have also been reported with modest trial numbers in individual level analyses associated with EEG studies (e.g., Schyns, Petro, Smith, 2007; 2009). Nevertheless, it is exciting to show here that with minor adaptations, this approach can be used to investigate information processing strategies in children as young as six years of age.

We have known for some time that expression-reading abilities are far from adult-like during childhood, yet few have investigated whether there are differences in how children perceive and process such stimuli in such a detailed manner. With this powerful paradigm, we have identified sophisticated information-processing strategies in school aged children that tend to qualitatively resemble those of adults. After pinpointing the diagnostic information for categorisations of fear, sadness, happiness and anger, it is clear that children's interpretation of emotion information is far more complex than any simple affective distinction based on a small fixed set of features (e.g., is that face happy vs. not happy). This study reveals a complex profile of strategic information-use from the youngest ages tested, which becomes increasingly refined across developmental time, broadly in line with improvements in processing ability.

Supplementary Material

Data associated with this article is archived with the Open Science Framework https://osf.io/gk4vx/.

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Figure Legends

Figure 1. Task difficulty was modulated online to target each participant's performance around 75%. Mean accuracy of emotion expression categorisations (in blue) and median number of bubbles required to achieve this performance level (in red) for each age group. Asterisks denote significant group differences ($p<.05$).

Figure 2. A. The diagnostic information (i.e. information that is significantly associated with performance driving fearful categorizations, for young children in green, older children in red and adults in blue. B. Only the diagnostic information extracted from each SF scale of a sample image and recombined to visualise the information used by each participant group to complete their successful face categorizations. C. As A and B for the high performing sub-sample of young children. D. Information that is used significantly more by one group than the other ($p<0.05$), extracted from a sample image and combined across SF scales to visualise.

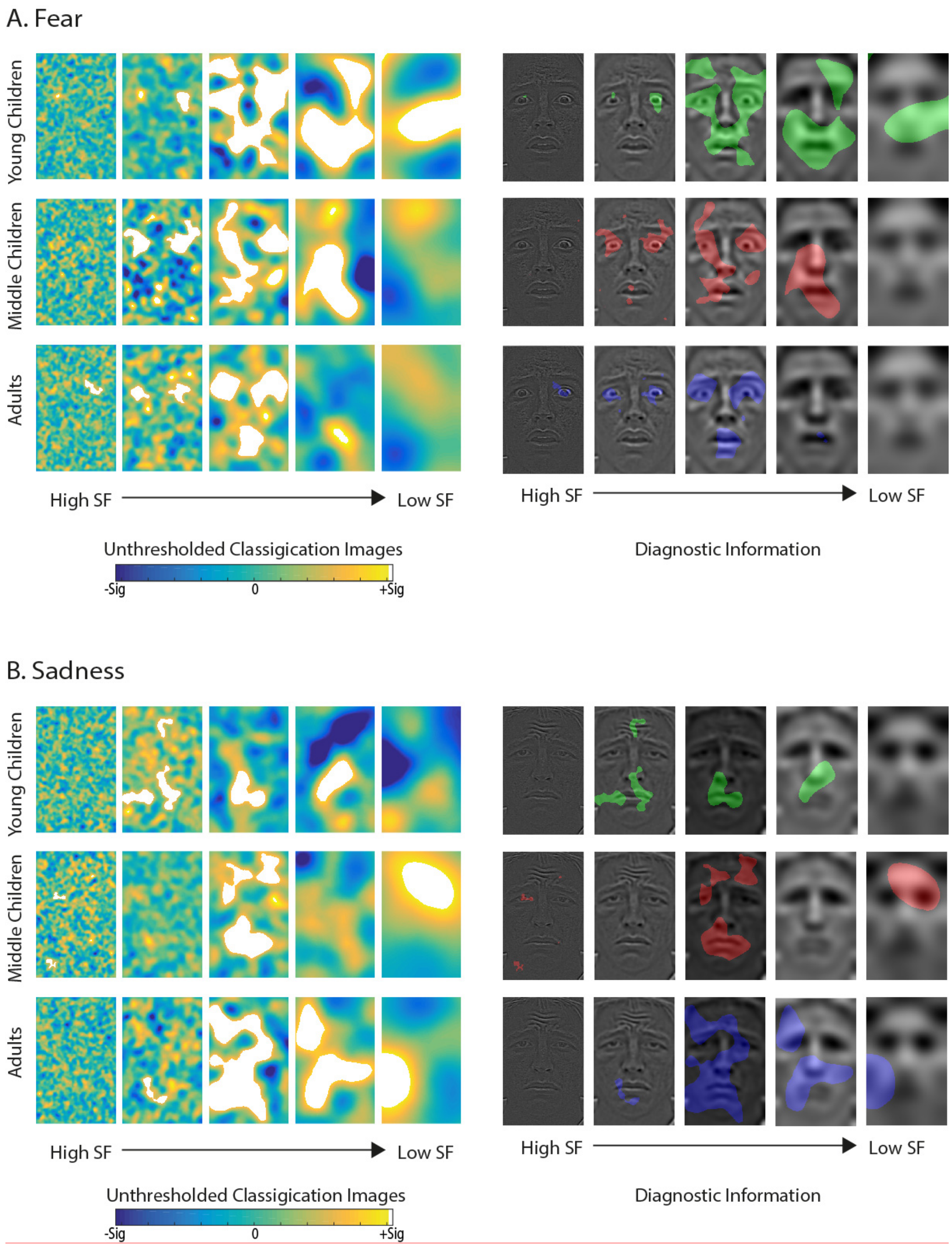
Figures 3 to 5 as Figure 2 for sadness, anger and happy categorizations respectively.

Table 1. *Descriptive statistics for matched subsample of young children.*

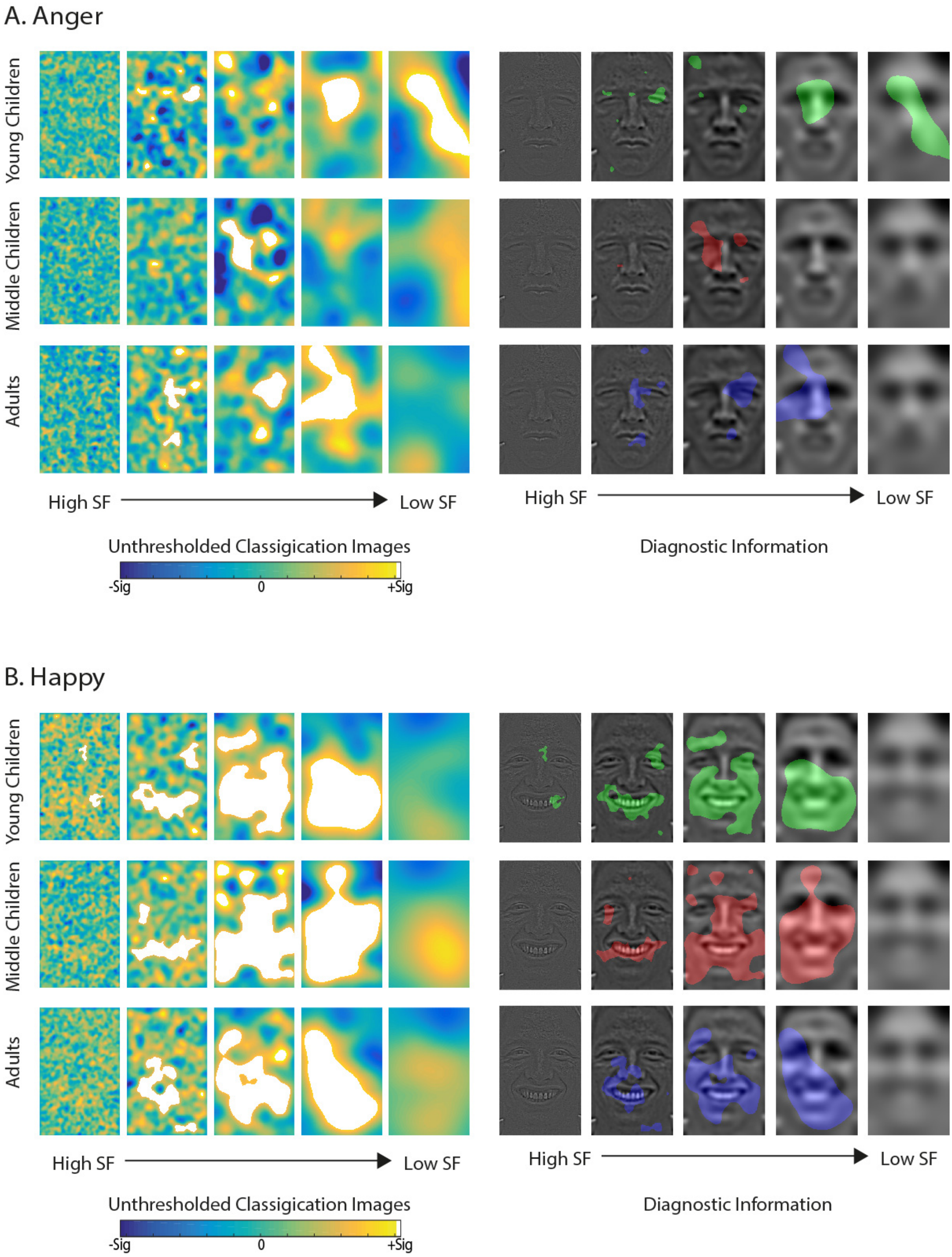
Expression	Exclusion criterion (accuracy)	N	Percent correct			Number of Bubbles		
			M (SD)	Group Difference		M (SD)	Group Difference	
				vs. older children	vs. adults		vs. older children	vs. adults
Fear	60%	59	76.7 (6.5)	t(126) = .33, p = .74	t(111) = .58, p=.55	113.6 (32.7)	t(126) = .25, p = .79	t(111) = .90, p = .36
Sadness	60%	57	73.2 (6.8)	t(124) = .29, p = .77	t(109) = 1.44, p = .15	124.0 (34.5)	t(124) = .04, p = .96	t(109) = 2.63, p = .01
Happiness	80%	60	85.2 (3.1)	t(127) = 1.41, p = .15	t(112) = 1.15, p = .25	75.2 (21.1)	t(127) = 2.89, p <.01	t(112) = 1.54, p = .12
Anger	40%	51	55.0 (10.6)	t(1108) = 1.34, p = .18*	t(103) = 4.75, p < .01	176.7 (27.8)	t(108) = .17, p = .86*	t(103) = 4.53, p <.01

- Note – These anger categorisation statistics relate to comparisons with the revised group of older children (N=59)

Supplementary Materials



Supplementary Figure 1A. Unthresholded classification images (left hand side) for fearful categorisations by each participant group with significant regions highlighted at the top end of the colourmap scale in white. Alongside this the diagnostic images (right hand side) showing those significant regions superimposed on a representative stimulus. 2B. As 2A but for sadness categorizations.



Supplementary Figure 2. As Supplementary Figure 1 for anger (A) and happy (B) categorizations.

Ideal Observer Model

Following the approach outlined in Smith et al (2005), the original investigation of expression processing using the Bubbles approach, we submitted a model observer to the same categorization task as that completed by our three groups of participants. The model Pearson correlated the pixel intensity values of individual face stimuli (i.e., with randomly positioned Bubbles sampling information from across the 5 spatial frequency bands) with the entire (intact) stimulus set and made its categorization choice as the emotion category of the image giving the highest correlation (winner-take-all). We matched the performance of the model with that of each participant group categorizing each emotion (percentage correct) by adding an adjustable density of evenly distributed white noise. Importantly we conducted separate models for all participant groups and emotion categories with the defined information sampling density (number of bubbles) set to match that of each group. Bubbles analysis proceeded identically to that of the human participants. Figures 1A and B, below, detail the results of the model observer that can be considered to be one benchmark of the information available to perform the task. Although the human participants had the option of a “Don’t know” response, these were made very infrequently (young children M = 1.6%, older children = 1.7%, adults = 4.2%) and under the instruction that they only be used in a situation where it was not possible to perform the task at all (as opposed to not decide on a decision). Therefore, to all intents and purposes, ‘Don’t know’ responses in fact simply reflect incorrect categorization decisions in the participants and therefore did not try to include such a response for the model observer.

The information revealed to be diagnostic is strikingly similar across the three models per emotion category with strong overlap in the significant available information for each (simulated) ‘age group’, with relatively few instances of deviation (see Supplementary Figure 4). Importantly where differences can be observed they do not correspond to differences observed in the human participants. For example, the models running to the parameters of older children and adults results in a wider spread of significant information as opposed to that based on the younger children, in direct opposition to the pattern observed in young children. As such, it is very difficult to attribute the information processing differences that we observe between participant groups to the relatively small, yet admittedly significant, differences in performance accuracy and amount of information samples (number of bubbles) provided for each group.

Smith, M. L., Cottrell, G., Gosselin, F., & Schyns, P. (2005). Transmitting and decoding facial expressions. *Psychological Science, 16*(3), 184-189.

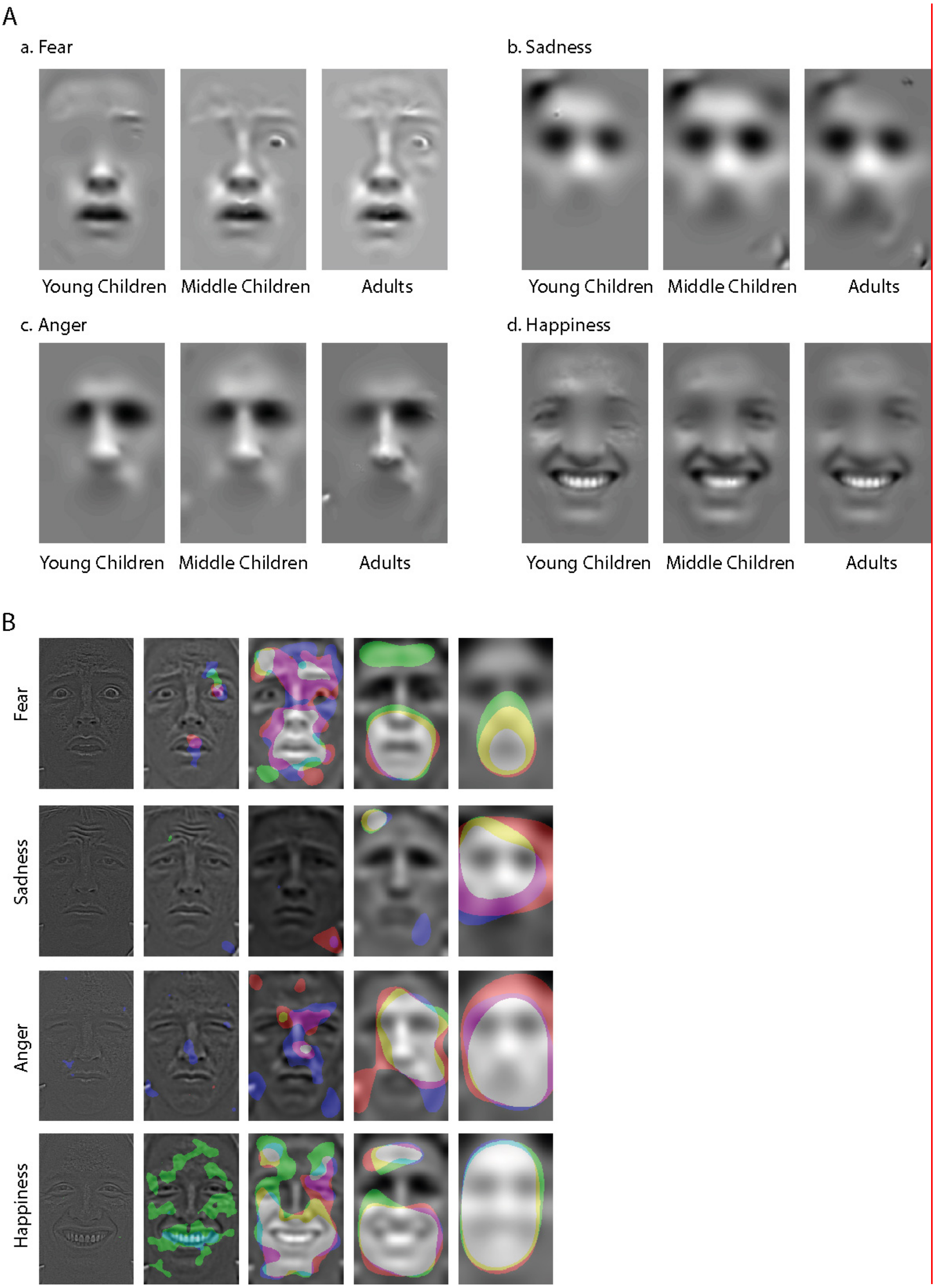


Figure 3. A. Effective faces depicting regions significantly associated (p<0.05, corrected) with correct performance of the model observer for each emotional expression and participant age

group category. B. Significant regions for each participant group highlighted on a sample expressive face at each sampled SF band. Significant regions for models using the parameters of young children are highlighted in green, those using the parameters of older children are highlighted in red, and those using the parameters of adults are in blue. Overlapping regions are coded in their RGB colour space combination, and in particular when the same region was found to be significant for all three age group models it is depicted in white.