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The autistic brain can process local but not global emotion regularities in facial and musical sequences

Running title: Impaired processing of global regularity in ASD

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Lay summary

We investigated how the autistic brain responds to local (short timescale) and global (long timescale) emotion regularities in blocks of 125 sequences of five-item facial images (Experiment 1) and musical chords (Experiment 2). Local versus global regularities were established based on the emotional type of the five images/chords in a sequence as compared to the majority of the sequences, with local regularity generated at an individual sequence level and global regularity at a whole block level. Specifically, in the blocks examining local regularity, the majority of the sequences contained five images/chords expressing the same type of emotion (either pleasant or unpleasant), and violations to this local regularity were detected when the fifth images/chords in a sequence conveyed a different emotion than the first four. In the blocks examining global regularity, most sequences consisted of four images/chords with the same emotional type and a fifth image/chord expressing a different emotion. Violations to this global regularity at a whole block level were realized when a sequence had all five images/chords expressing the same type of emotion. Results from 20 individuals with ASD and 21 age- and IQ-matched individuals with typical development showed that, unlike typically developing participants, ASD participants exhibited intact brain responses to violations of local but not global emotion regularity for both facial and musical sequences. These findings suggest that emotion regularity processing is modulated by the timescale of the stimuli in ASD.

Abstract

Whether autism spectrum disorder (ASD) is associated with a global processing deficit remains controversial. Global integration requires extraction of regularity across various timescales, yet little is known about how individuals with ASD process regularity at local (short timescale) versus global (long timescale) levels. To this end, we used event-related potentials to investigate whether individuals with ASD would show different neural responses to local (within trial) versus global (across trials) emotion regularities extracted from sequential facial expressions; and if so, whether this visual abnormality would generalize to the music (auditory) domain. Twenty individuals with ASD and 21 age- and IQ-matched individuals with typical development participated in this study. At an early processing stage, ASD participants exhibited preserved neural responses to violations of local emotion regularity for both faces and music. At a later stage, however, there was an absence of neural responses in ASD to violations of global emotion regularity for both faces and music. These findings suggest that the autistic brain responses to emotion regularity are modulated by the timescale of sequential stimuli, and provide insight into the neural mechanisms underlying emotional processing in ASD.

Keywords: autism spectrum disorder, regularity, global deficit, facial emotion, musical emotion

Introduction

Local and global processing are two styles in which humans process information: While local processing focuses on the specific details of a stimulus, global processing integrates details into a coherent whole (Happé & Frith, 2006). Whereas typically developing (TD) individuals demonstrate a global processing bias (e.g., Krakowski et al., 2016; Rezvani, Katanforoush, & Pouretemad, 2020), an atypical local bias and a global processing deficit have been proposed for individuals with autism spectrum disorder (ASD). ASD is a neurodevelopmental disorder characterized by difficulties with social communication and social interaction, as well as restricted and repetitive behaviors and interests (APA, 2013). Two cognitive theories have tried to account for the relationship between local and global processing in ASD. Weak Central Coherence (WCC) theory proposes that the local bias results from ASD individuals' deficit in processing global information (Frith, 1989; Frith & Happé, 1994; Happé & Booth, 2008; Happé & Frith, 2006), whereas Enhanced Perceptual Functioning (EPF) theory posits that enhanced local processing can occur without a global processing deficit in ASD (Mottron & Burack, 2001; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006). Thus, the main difference between EPF and WCC theories is whether ASD individuals have deficits in processing global information.

Global processing involves two complementary processes—regularity extraction and integration (Erickson & Thiessen, 2015). Specifically, integration of local parts/details into a whole is based upon regularity extraction, a process that analyzes and derives the relations (similarities) among the parts of a stimulus. With regularity, people can anticipate upcoming events, detect those in violation of the regularity, and integrate the events into the context. Previous studies on global processing in ASD mainly focus on integrative processing, and the results have been controversial. While some studies show reduced/impaired ability for individuals with ASD to integrate information in composite faces (Gauthier, Klaiman, & Schultz, 2009; Teunisse & de Gelder, 2003), large letters (D'Souza, Booth, Connolly, Happé, & Karmiloff-Smith, 2016; Guy, Mottron, Berthiaume, & Bertone, 2019), fragmented pictures (Booth &

Happé, 2018; Neufeld et al., 2020), and coherent and biological motions (Brieber et al., 2010; Koldewyn, Whitney, & Rivera, 2010; Martínez et al., 2019), other studies demonstrate intact integration in ASD across these conditions: composite faces (Brewer, Bird, Gray, & Cook, 2019; Stevenson et al., 2018; Ventura et al., 2018), large letters (Baisa, Mevorach, & Shalev, 2021; Soriano, Ibáñez-Molina, Paredes, & Macizo, 2018; Van der Hallen, Vanmarcke, Noens, & Wagemans, 2017), fragmented pictures (D'Souza et al., 2016; Jobs, Falck-Ytter, & Bölte, 2018), and coherent and biological motions (Cusack, Williams, & Neri, 2015; Manning, Charman, & Pellicano, 2015; van Boxtel, Dapretto, & Lu, 2016). In summary, mixed results have been reported in studies of integrative processing based on the regularities of stimulus structures, while no studies have directly examined regularity processing in ASD.

Nevertheless, a few studies report that individuals with ASD are able to learn statistical relations in long sequences (at least with a duration of 108 seconds) (Haebig, Saffran, & Ellis Weismer, 2017; Mayo & Eigsti, 2012; Roser, Aslin, McKenzie, Zahra, & Fiser, 2015), despite showing atypical neural responses to these relations (Jeste et al., 2015; Marin et al., 2020; Scott-Van Zeeland et al., 2010). In fact, regularities can occur on different timescales, short (local) or long (global), constituting a local versus global distinction (Sanders & Poeppel, 2007). Thus, relative to static stimuli, dynamic stimuli or sequences may be better able to disentangle local from global regularities. In sequences, for example, local regularity may exist within a trial; global regularity may exist across trials. When presented with four identical tones followed by a deviant pitch, individuals with ASD show reduced mismatch negativity (MMN) amplitudes to violations of local regularity in deviant trials, despite preserved P3b responses to violations of global regularity (across trials), suggesting impaired early sensory prediction processing but intact conscious expectation processing in ASD (Goris et al., 2018). Given that the local deviant detection in Goris et al. (2018) cannot rule out the effect of memory trace for physical characteristics of repeated sounds, it would be worth investigating the processing of more abstract regularity at both local and global levels in ASD. Through the lens of emotion processing, the present study examines regularity processing on different timescales across auditory and visual domains in ASD.

Understanding emotions in self and others creates a basis for social communication (Shariff & Tracy, 2011). Poor ability to understand emotions, which not only influences our own reaction to others but also impacts how others react to us, may be one of the main causes of social-communication difficulties in ASD (Philip et al., 2010; Uljarevic & Hamilton, 2013). The human face is a crucial transmitter of social information (Jack & Schyns, 2015), and impaired facial expression recognition has been proposed as a candidate marker for ASD (Loth et al., 2018). Therefore, examining facial emotion regularity processing at the local and global levels would not only contribute to better understanding of autistic social-communication difficulties, but also provide evidence for the debate of global processing in ASD.

Behavioral studies have demonstrated impaired emotional recognition from whole faces in ASD (e.g., Davidson, Hilvert, Misiunaite, Kerby, & Giordano, 2019; Evers, Steyaert, Noens, & Wagemans, 2015; Griffiths et al., 2019; Harms, Martin, & Wallace, 2010; Lozier, Vanmeter, & Marsh, 2014; Sucksmith, Allison, Baron-Cohen, Chakrabarti, & Hoekstra, 2013; Yeung, Han, Sze, & Chan, 2014). Results from fMRI (functional magnetic resonance imaging) studies show that altered facial emotional processing is correlated with abnormal activation of fusiform gyrus (Critchley et al., 2000; Deeley et al., 2007; Greimel et al., 2010; Pierce, Müller, Ambrose, Allen, & Courchesne, 2001) and amygdala (Hadjikhani, Joseph, Snyder, & Tager‐Flusberg, 2007; Klapwijk et al., 2016; Pierce et al., 2001). Unlike fMRI, ERPs (event-related potentials) can reveal the time course of facial emotional processing, separating early pre-attentive detection from late conscious processing. Focusing on early-stage facial expressive perception, some ERP studies revealed reduced amplitudes (Akechi et al., 2010; Apicella, Sicca, Federico, Campatelli, & Muratori, 2013; Batty, Meaux, Wittemeyer, Rogé, & Taylor, 2011; de Jong, van England, & Kemner, 2008; Faja, Dawson, Aylward, Wijsman, & Webb, 2016) and delayed peak latencies (Apicella et al., 2013; Batty et al., 2011) of N170 in ASD, suggesting neural abnormalities in encoding facial expressions. However, studies focusing on emotion processing at a later stage yielded mixed results. Dawson, Webb, Carver, Panagiotides, and McPartland (2004) found that individuals with ASD exhibited comparable amplitudes of N300 and late negativity to fearful versus neutral faces, suggesting that fearful faces did not affect attentional processing in ASD. However, Tye et al. (2014) reported an N400 effect to fearful versus neutral faces in ASD, reflecting increased attention allocation to negative emotional stimuli in ASD. This discrepancy may be because the tasks required different processing strategies involving local versus global processing: while watching a circle appear around the center of a facial image may require attending to the specific details in the study by Tye et al. (2014), passively viewing a facial image may not impose focus on any specific information of the image (Dawson et al., 2004).

While the aforementioned studies mainly focused on emotional processing of facial expressions, little is known about how emotion regularity is processed in ASD. Deruelle, Rondan, Salle-Collemiche, Bastard-Rosset, and Da Fonséca (2008) examined local-global processing using high- (i.e., local facial features) and low-spatial frequency information (i.e., global configuration of facial expression) as stimuli. The results suggest that children with ASD showed enhanced behavioural performance to local versus global facial expressions. Similarly, an ERP study showed that, in children with ASD, fearful faces elicited higher P1 amplitudes than neutral faces only in the local processing condition, suggesting fast extraction of facial expressions driven by local information in ASD (Vlamings, Jonkman, van Daalen, van der Gaag, & Kemner, 2010). In summary, although previous studies have investigated the neural activities associated with facial emotional processing in ASD, none have focused on the neural responses to emotion regularity among facial expressions. That is, only single, or individually presented, facial expressions were used in previous studies. In contrast to single facial expressions, sequential facial expressions can incorporate both local and global emotion regularities, making it possible to investigate brain responses to emotion regularities at both local and global levels. Since the different timescales resemble real-life experiences, examining regularity processing in facial emotions at both local and global levels would contribute to a better understanding of social-communication difficulties in ASD.

Besides facial emotional processing, auditory emotional processing also constitutes an important part of social communication in everyday life. As sequentially presented auditory stimuli, music has been regarded as having the potential to ameliorate facial emotional processing impairments in ASD (Brown, 2017; Katagiri, 2009; Wagener, Berning, Costa, Steffgen, & Melzer, 2020). However, previous studies on the processing of music emotions in ASD have yielded mixed results. While one fMRI study showed preserved neural activity during the processing of musical emotions in ASD (Gebauer, Skewes, Westphael, Heaton, & Vuust, 2014), another study reported altered brain activities in the premotor area and the left anterior insula, particularly in response to happy music (Caria, Venuti, & de Falco, 2011). Similarly, in behavioral studies, while showing preserved identification of discrete musical emotions expressed by psychoacoustic cues such as tempo and intensity (Järvinen et al., 2016; Quintin, Bhatara, Poissant, Fombonne, & Levitin, 2011), individuals with ASD demonstrate impairments in rating emotions conveyed by tonality and temporal variation (Bhatara et al., 2010) and in rating emotional valance in music (Kopec, Hillier, & Frye, 2012). The discrepancy among these results may be because individuals with ASD have differential performance on the processing of local psychoacoustic cues versus the global context of tonality. However, this hypothesis needs to be tested by simultaneously manipulating local and global musical emotional information, which has not been done in previous behavioral or neural studies.

It the present investigation, we used ERPs to explore whether individuals with ASD would show abnormal neural responses to local (within trial) and global (across trials) emotion regularities in sequential facial expressions (Experiment 1); and if so, whether this abnormality would generalize to the music domain (Experiment 2). An emotional oddball paradigm was used in both experiments, where each standard or deviant stimulus comprised five facial-images/chords constructed based on an abstract regularity of emotional type (i.e., belonging to the same type of emotion or not), rather than using physically identical repetitions. Within a sequence, local regularity was defined by the five facial images/chords expressing the same type of emotion (pleasant or unpleasant). Across sequences, global regularity was defined by the fifth facial-images/chords expressing a different emotion from that of the first four facial-images/chords. To dissociate local from global processing of emotion regularity, we manipulated the frequency of deviant sequences. Specifically, for the blocks with local deviations, the standard sequences (with a frequency of 84%) had five different images/chords expressing the same emotion, while the deviant sequences (with a frequency of 16%) had four different images/chords expressing the same emotion followed by an image/chord associated with a different emotion. In this case, the fifth images/chords violated the local emotion regularity of the deviant sequences (within trial). Such a violation of the local regularity is at the individual sequence level. For the blocks with global deviations, however, the standard sequences (with a frequency of 84%) were those in which the fifth image/chord expressed a different emotion than the first four, while the deviant sequences (with a frequency of 16%) were those in which all five different images/chords expressed the same type of emotion. As such, the fifth images/chords in the deviant sequences violated the global emotion regularity of the standard sequences (across trials). Such a violation of the global regularity is at the whole block level.

We mainly focused on three ERP components that are related to the processing of deviants: the mismatch negativity (MMN), P3b, and the late negativity. The MMN is an early ERP component which reflects a preattentive, automatic response (Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001). Following the MMN, the P3b is a later component associated with conscious access (Sergent, Baillet, & Dehaene, 2005). It has been suggested that the MMN is observed in response to violations of local regularity at a preattentive level, whereas the P3b is shown to respond to violations of global regularity at a conscious level (Bekinschtein et al., 2009; Goris et al., 2018). Different from the MMN and P3b, the late negativity reflects the top-down allocation of attention for the inspection of memory traces (Mecklinger, Rosburg, & Johansson, 2016). If ASD were associated with a local processing bias that may not result in a global processing deficit as posited by EPF theory (Mottron & Burack, 2001; Mottron et al., 2006), then violations of local facial and musical emotion regularities would elicit an MMN in both the ASD and TD groups. In contrast, if individuals with ASD had a global processing deficit as proposed by WCC theory (Frith, 1989; Frith & Happé, 1994; Happé & Booth, 2008; Happé & Frith, 2006), then we would expect that violations of global facial and musical emotion regularities might elicit a P3b or a late negativity in TD only, but not in ASD (e.g., Pijnacker, Geurts, Van Lambalgen, Buitelaar, & Hagoort, 2010). In addition, given that ASD is thought to be associated with a global processing deficit across modalities (Foster et al., 2016; Foxton et al., 2003; Happé & Frith, 2006), we expected to observe similar patterns of ERP results across visual and auditory domains in ASD.

Experiment 1: Neural responses to local and global emotion regularities in sequential facial expressions

Understanding facial expressions is an important component of social communication (Jack & Schyns, 2015). Although making emotional inferences from facial expressions is a fast and easy process for most people (Jack & Schyns, 2015), it has been suggested that lack of understanding of facial expressions can serve as a candidate diagnostic marker for ASD (Loth et al., 2018). Thus, in Experiment 1, we used images of facial expressions to investigate the neural responses to local and global facial emotion regularities in individuals with ASD. We predicted that ASD participants would exhibit an MMN (an early ERP component) in response to violations of local facial emotion regularity, but not any later components (the P3b or the late negativity) for violations of global facial emotion regularity, given that there are atypical local bias (e.g., Mottron & Burack, 2001; Mottron et al., 2006) and a global deficit hypotheses (e.g., Frith & Happé, 1994; Happé & Frith, 2006) in ASD.

Method

Participants

A priori power analysis was conducted to calculate the minimum sample size using GPower 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). Power calculations indicated that 34 participants across groups would provide 80% power to detect a moderate (f = 0.25) interaction between group (ASD vs. TD) and stimulus type (standard vs. deviant) at a significance level of 5%. Therefore, 21 ASD participants aged 8-20 and 21 TD participants aged 9-25 were recruited for this study. Data from one ASD participant were discarded because of excessive drift artifacts. The final set of participants thus consisted of 20 ASD and 21 TD participants.

ASD participants were recruited from a rehabilitation center for individuals with ASD in China. All the individuals with ASD had a clinical diagnosis of ASD, which was further confirmed using the Autism Diagnostic Observation Schedule – Second Edition (ADOS-2, Lord et al., 2012) by a psychologist, who had received formal training and achieved clinical and research reliability for administration of this semi-structured interview. The ADOS-2 Module 3 was used for participants <18 years, and Module 4 for participants ≥18 years. TD participants were recruited from mainstream schools for students with no disabilities or neurological/psychiatric disorders in China. Raven's Standard Progressive Matrices (RPM, Raven, 2000) was used to measure non-verbal IQ in all participants.

Table 1 displays participants' demographic characteristics. The two groups were matched on age, years of education, years of musical training, and IQ. All participants were right-handed, with normal hearing, normal or corrected-to-normal vision. All research procedures were approved by the ethics committee of Shanghai Normal University, and performed in accordance with the ethical standards of the Declaration of Helsinki. Each participant and—for participants below the age of 18—a parent signed a written consent form prior to the experiments and were paid for their participation.

Insert Table 1, about here.

Stimuli and procedure

Forty-eight facial expression images were selected from the Chinese Facial Affective Picture System (CFAPS, Gong, Huang, Wang, & Luo, 2011). Among these images, 24 happy smiling facial images represented pleasant expression, and 24 angry facial images represented unpleasant expression (see Supplementary text for details).

Consistent with the oddball paradigm employed by previous studies (Bekinschtein et al., 2009; Wacongne et al., 2011), five-image sequences were presented in two types of blocks: four blocks with local deviations and the other four with global deviations (see Figure 1 for examples). In the blocks with local deviations, local standards (five different facial images with the same emotion) with a high frequency (84%) were infrequently (16%) interrupted by local deviants (four different facial images with the same emotion followed by a facial image with a different type of emotion). In the blocks with global deviations, global standards (four different facial images with the same emotion followed by a facial image with a different type of emotion) with a high frequency (84%) were infrequently (16%) interrupted by global deviants (five different facial images with the same emotion). For each sequence, the five faces that appeared consecutively were physically different.

All stimuli were presented using Eprime v2.0 (Psychology Software Tools Inc.). Within the sequences, each image was presented at the center of a computer screen for 250 ms with a stimulus onset asynchrony of 500 ms, resulting in sequences of 2,250 ms. Intertrial intervals were jittered between 700 and 1,000 ms, during which a fixation point was presented at the center of the screen. In order to avoid selective attention on the local sequences (Plaisted, Swettenham, & Rees, 1999), participants were informed that each sequence consisted of five images and that a few of the sequences might be different from the majority of these sequences. Their task was to count the number of those deviant sequences, and report the number after each block.

Each block consisted of 125 trials, the first 25 of which were frequent sequences that helped establish the rule at the beginning. The following 100 trials consisted of 80 frequent sequences and 20 rare sequences in random order. Each participant received four replications of each block type (block with local or global deviations), resulting in a total of eight blocks (each with an approximate duration of 7 minutes). The gender (male and female) and the valence (pleasant and unpleasant) of emotional faces were balanced across the blocks. Block order was completely randomized. Between blocks, there were self-paced breaks, resulting in a total duration of approximately 1 hr.

Insert Figure 1, about here.

Electroencephalography (EEG) recording and analysis

EEG data were recorded from 64 standard scalp locations (International 10–20 system) by Eego system (ANT Neuro, Netherlands), digitized at a rate of 1,024 Hz, with a 0.05 Hz low cutoff filter and a 100 Hz high cutoff filter. The electrode of CPz served as the online reference, and an electrode placed between Fz and Fpz served as the ground. Horizontal EOG was recorded with an electrode placed 1 cm from the left canthi. All electrode impedances were kept below 20 KΩ during the experiment. ERP waveforms were time-locked to the onset of the fifth facial image in each sequence.

The data were referenced off-line to the algebraical mean of left and right mastoid electrodes. By using the Basic FIR filter in EEGLAB, high-pass filtering the data at 0.1 Hz was applied to remove the linear trends and then, the low-pass filter at 30 Hz. An Independent Component Analysis (ICA) was carried out to remove blink artifacts, without using any automatic artifact rejection sequence. Trials were averaged offline with an epoch length of 1200 ms, including a baseline from 200 ms to 0 ms before the stimulus onset. After the time window was selected, the amplitudes were averaged under each condition for each participant.

Given the emotional oddball paradigm, several classic oddball-evoked ERP components were expected, such as the MMN, N2, and P3b (Campanella, Delle-Vigne, Kornreich, & Verbanck, 2012; Campanella et al., 2002; Everaert, Spruyt, Rossi, Pourtois, & De Houwer, 2014; Folstein & Van Petten, 2008; Putkinen, Tervaniemi, Saarikivi, Ojala, & Huotilainen, 2014; Sanger, Thierry, & Dorjee, 2018; Schirmer & Escoffier, 2010; Virtala, Huotilainen, Putkinen, Makkonen, & Tervaniemi, 2012). Moreover, since a similar display of emotional sequences has been shown to evoke the late negativity (Bublatzky, Flaisch, Stockburger, Schmälzle, & Schupp, 2010; Erhan, Borod, Tenke, & Bruder, 1998; Sanger et al., 2018) and the late positive component (LPC, Liu, Huang, McGinnis-Deweese, Keil, & Ding, 2012; Moore, Shafer, Bakhtiari, Dolcos, & Singhal, 2019; Schupp et al., 2000), these later components were also expected in the present experiment. Latencies, scalp distribution, and amplitudes of these ERP components were expected to occur equivalently in response to auditory and visual stimuli, except that the N2 may be more easily evoked by the auditory than the visual modality (Halgren et al., 1998). Prior investigations have shown that the MMN is a difference wave obtained by subtracting the ERPs elicited by the standard from those elicited by the deviant, and it was typically prominent from about 100 to 200 ms after stimulus onset with a frontocentral distribution (Garrido, Kilner, Stephan, & Friston, 2009). The N2 was typically measured around the peaks between 180 to 300 ms over frontocentral channels (Folstein & Van Petten, 2008; Holroyd, 2004). The present study thus quantified the MMN and N2 components by comparing the mean amplitudes elicited by standard with deviant stimuli during the time windows of 130–180 ms and 180–250 ms, respectively, after the onset of the fifth image over frontocentral electrodes. Furthermore, the P3b is known to be maximal from approximately 250 to 550 ms after stimulus onset over centroparietal electrodes (Luck & Hillyard, 1994; Polich, 2007; Sanger et al., 2018; van Dinteren, Arns, Jongsma, & Kessels, 2014), and the late negativity and LPC are known to be maximal from approximately 600 to 1000 ms after stimulus onset over centroparietal electrodes (Liu et al., 2012; Moore et al., 2019; Sanger et al., 2018; Schupp et al., 2000). Therefore, we measured the P3b and LPC/late negativity by comparing the mean amplitudes elicited by standard with deviant stimuli during the time windows of 250–550 ms and 600–1000 ms, respectively, after the fifth image onset over centroparietal electrodes. These parameters fitted well with the actual timings and scalp distributions of the MMN, N2, P3b, and LPC/late negativity (see Figure 2).

For statistical analysis, the MMN and N2 amplitudes over a cluster of nine frontocentral electrode sites (Fz, F1, F2, F3, F4, FC1, FC2, FC3, FC4) were subjected to two-way repeated-measure analysis of variance (ANOVAs) with group (ASD, TD) as a between-subjects factor and stimulus type (standard, deviant) as a within-subjects factor. The amplitudes of P3b and LPC/late negativity over a cluster of nine centroparietal electrode sites (Pz, P1, P2, P3, P4, CP1, CP2, CP3, CP4) were subjected to similar two-way repeated-measure ANOVAs. To examine local versus global processing of facial emotions, repeated-measure ANOVAs were conducted for blocks with local and global deviations, respectively.

Bayesian analyses

To get more conservative results and assess the strength of evidence, we ran Bayesian hypothesis testing and calculated Bayes factors (*BF*s) by using JASP software (van Doorn et al., 2021), with the default priors. The *BF* is the ratio of the probability of one hypothesis over another and can quantify the relative strength of evidence for the alternative (H_1) and null (H_0) hypotheses (Brydges & Bielak, 2020; Love et al., 2019; Wagenmakers et al., 2018). Typically, $1 < BF < 3$ is considered *weak* evidence for H_1, $3 < BF < 10$ *moderate*, and $BF > 10$ *strong*, whereas $0.33 < BF < 1$ indicates *weak* evidence for H_0, $0.10 < BF < 0.33$ *moderate*, and $BF < 0.10$ *strong* (Jeffreys, 1961; Lee & Wagenmakers, 2014). For example, a *BF* of 12 means that the data are 12 times more likely under H_1 than under H_0, providing strong evidence in support of the presence of an effect.

Results

Local regularity processing of facial emotions

As shown in Table 2, there was moderate evidence for the interaction between group and stimulus type for the MMN amplitudes (130–180 ms time window, *BF* = 6.46), as deviant images elicited an MMN in ASD participants, but not in TD participants (see Figure 2). Although the ANOVA on the N2 amplitudes (180–250 ms time window) showed weak evidence for the interaction between group and stimulus type (*BF* = 1.49), simple-effects tests did not show significant differences between deviant and standard images for either group. However, there was strong and moderate evidence for the group by stimulus type interaction for the P3b (250–550 ms time window, *BF* = 13.57) and LPC/late negativity (600–1000 ms time window, *BF* = 3.24) amplitudes, respectively, as only TD participants responded to the standard and deviant images differently by showing a P3b and an LPC (see Figure 2).

Insert Table 2, about here.

Global regularity processing of facial emotions

As presented in Table 3, there was moderate evidence for the group by stimulus type interaction for the P3b amplitudes (*BF* = 3.09), as a P3b was present in TD participants, but not in ASD participants. Strong evidence for the group by stimulus type interaction was also observed for the LPC/late negativity amplitudes (*BF* = 61.56), reflecting that TD participants, but not ASD participants showed different neural responses to deviant and standard images through an LPC (see Figure 2).

Insert Table 3, about here.

Insert Figure 2, about here.

Discussion

The findings indicate that local facial emotion regularity elicited an MMN in ASD but not in TD participants. Unlike ASD participants, TD participants exhibited a P3b and an LPC in response to local facial emotion regularity. Reflecting preattentive detection of deviants (Bekinschtein et al., 2009; Wacongne et al., 2011), the presence of MMN indicates that the autistic brain is able to detect violations of local emotion regularity embedded in sequential facial expressions at an automatic level. On the other hand, considering the ERP morphology and topographic distribution, the LPC observed in TD participants might be the continuation of the P3b component. The violations of facial emotional regularities may increase the investment of attentional resources during the task, as revealed by the P3b effect. This might have downstream consequences for the adjustment of attentional resources and thus leads to greater difficulty in conscious processing, which is reflected by the LPC effect (Chen et al., 2007; Folstein & Van Petten, 2011; Teixeira-Santos et al., 2020). Given that the P3b and its late component are associated with attentional control/conscious access (Moore et al., 2019; Sergent et al., 2005), the absence of the P3b and LPC in ASD participants indicated that they were unable to redirect the attention to violations of local emotion regularity at a conscious level. Together, our findings indicate that although both ASD and TD participants can show neural responses to violations of local facial emotion regularity, their response patterns differ from each other in the manner of processing (conscious vs nonconscious).

Regarding global processing, our findings indicate that global facial emotion regularity elicited a P3b, followed by an LPC in TD participants, but not in ASD participants. In line with previous findings (Bekinschtein et al., 2009; Wacongne et al., 2011), the P3b and LPC observed in TD participants suggest that global processing is highly dependent on attention and conscious awareness of the stimulus. In this scenario, the absence of the P3b and LPC in ASD participants suggests that the autistic brain cannot detect violations of global facial emotion regularity in a conscious manner.

Experiment 2: Neural responses to local and global emotion regularities in sequential chords

Since auditory emotional processing is also an important component of social communication, we examined neural responses to local versus global emotion regularities extracted from sequential chords in Experiment 2. Although individuals with ASD are reported to have enhanced or intact musical abilities, such as the ability to perceive pitch changes (Bonnel et al., 2010; Bonnel et al., 2003; Heaton, Hermelin, & Pring, 1998; Heaton, Pring, & Hermelin, 1999; Stanutz, Wapnick, & Burack, 2014) and melodic contour (Bouvet, Simard-Meilleur, Paignon, Mottron, & Donnadieu, 2014; Chowdhury et al., 2017; Foster et al., 2016; Germain et al., 2019; Jiang, Liu, Wan, & Jiang, 2015), whether they are spared in processing local and global musical emotion regularities remains uncertain. To this aim, we replaced the facial images in Experiment 1 with affective chords for Experiment 2, where chord sequences were presented in blocks with local and global deviations to elicit local- and global-level novelty responses, respectively. If individuals with ASD could process local information (e.g., Mottron & Burack, 2001; Mottron et al., 2006) but not global information (e.g., Frith & Happé, 1994; Happé & Frith, 2006), then we would expect to observe early ERP components such as the MMN to local musical emotion regularity, but not later ERP components to global musical emotion regularity in ASD.

Method

Participants

The participants were identical to those in Experiment 1.

Stimuli and procedure

The experimental paradigm was the same as in Experiment 1, except that emotional facial images were replaced by affective chords (see Figure 3 for examples). The sequences were composed using consonant (pleasant sounding) and dissonant (unpleasant sounding) chords (see Supplementary text for details). Following previous studies (Steinbeis & Koelsch, 2011; Zhou, Liu, Jiang, & Jiang, 2019), the consonant chords in the present experiment were major chords in the root position (e.g., C-E-G-C). Dissonant stimuli were non-triads (e.g., C–F sharp–B–C). The root notes ranged from G3 to F#4, resulting in 12 chords in each affective category.

Insert Figure 3, about here.

The experimental procedure and task were identical to those of Experiment 1. Chords were presented binaurally through loudspeakers (Logitech Z120) in a sound-proofed room. The order of Experiments 1 and 2 was counterbalanced across participants.

EEG recording and analysis

The EEG recording, preprocessing, and data analyses were identical to those in Experiment 1.

Results

Local regularity processing of musical emotions

As illustrated in Table 4, although there was moderate or weak evidence against the interaction between group and stimulus type for all components, there was strong evidence for the main effect of stimulus type for the MMN (*BF* = 15.27) and N2 (*BF* = 14.35) amplitudes. Specifically, for both groups, local musical emotional information elicited an MMN, followed by an N2 (see Figure 4).

Insert Table 4, about here.

Global regularity processing of musical emotions

As shown in Table 5 and Figure 4, there was strong evidence for the stimulus type by group interaction for the LPC/late negativity amplitudes (*BF* = 29.19), reflecting that only TD participants responded to the standard and deviant chords differently by showing a late negativity.

Insert Table 5, about here.

Insert Figure 4, about here.

Discussion

The MMN observed in the blocks with local deviants in musical emotions is consistent with previous ERP studies on musical emotions (e.g., Virtala et al., 2012), indicating that both groups showed comparable neural responses to violations of local musical emotion regularity automatically. Since the N2 is considered a mismatch-related subcomponent and is associated with attentive control (Folstein & Van Petten, 2008), it is possible that the N2 reflected attention-related mismatch detection of local emotional deviants in the two groups.

However, the findings on global processing showed that TD participants, but not ASD participants, exhibited a late negativity in response to global musical emotion regularity. The late negativity is an ERP component often observed in memory tasks, reflecting the top-down allocation of attention for the inspection of memory traces (Mecklinger et al., 2016). Previous studies have demonstrated that the late negativity could be elicited during evaluations of musical tonal (Loui, Grent, Torpey, & Woldorff, 2005) and rhythmic (Neuhaus & Knösche, 2006) regularities and the processing of phonological representations (Mah, Goad, & Steinhauer, 2016), although these studies did not include explicit memory tasks. In this case, the absence of the late negativity in ASD suggested that the autistic brain was unable to evaluate violations of global emotion regularity in musical sequences based on memory traces.

General discussion

The present study is the first to investigate the neural responses to local and global emotion regularities extracted from facial and musical sequences in individuals with and without ASD. For facial emotion regularity processing, violations of local emotion regularity elicited an MMN in ASD participants but a P3b and an LPC in TD participants, whereas violations of global emotion regularity elicited a P3b and an LPC in TD participants only. Likewise, for musical emotion regularity processing, although violations of local emotion regularity elicited an MMN and an N2 in both groups, violations of global emotion regularity elicited a late negativity in TD participants only. Our results provide insight into the neural mechanisms underlying emotion regularity processing in visual and auditory domains and offer novel evidence for the debate over whether global processing is impaired in ASD.

Implications for visual and auditory emotion regularity processing in ASD

One of the main findings of this study is that the autistic brain can respond to local but not global emotion regularity in sequential facial expressions. Consistent with previous behavioral studies suggesting preserved local processing on facial emotional information in ASD (Deruelle et al., 2008), our findings provide further electrophysiological evidence for this finding. Specifically, for local facial processing, despite different patterns of neural responses between the two groups, ASD participants showed an MMN in response to the deviant emotion of a fifth facial image that violated the local emotion regularity of a five-image sequence. Given that the MMN reflects an automated and nonconscious response to a mismatch during a pre-attentional phase (Bekinschtein et al., 2009; Wacongne et al., 2011), our finding indicates that the autistic brain can respond to violations of local emotion regularity in facial expressions at an early processing stage.

Regarding the global regularity processing of facial emotions, a P3b and an LPC (the continuation of the P3b component) in response to violations of global facial emotion regularity were observed in TD participants, but not in ASD participants. Similar results were also found in the blocks with local deviations, where TD participants, but not ASD participants, exhibited a P3b and an LPC in response to violations of local facial emotion regularity. Indeed, the P3b and LPC reflect conscious detection of stimulus sequences in relatively later processing stages (Liu et al., 2012; Moore et al., 2019; Sanger et al., 2018; Schupp et al., 2000). For the blocks with global deviations, the five different facial images in the standard sequences were those in which the fifth image expressed a different emotion than the first four, whereas the five different facial images in the deviant sequences all expressed the same emotion. Therefore, the fifth image in the deviant sequences violated the global emotion regularity at the block level, rather than the emotion regularity in the deviant sequences *per se* (at a sequence level). In this scenario, the absence of the P3b and LPC in ASD indicates that the autistic brain cannot consciously respond to violations of the global facial emotion regularity extracted from the standard sequences.

Another main finding of this study is that ASD individuals' neural local processing bias observed in facial expressive sequences also generalized to the music (auditory) domain, as evidenced by their intact MMN and N2 in response to violations of local musical emotion regularity but the absence of a late negativity in response to violations of global emotion regularity in chord sequences. Specifically, similar to the MMN, the N2 is also considered as a mismatch-related component (Patel & Azzam, 2005), which is associated with attentive control (Folstein & Van Petten, 2008). In the present study, comparable to TD participants, ASD participants exhibited an MMN and an N2 to the local regularity of musical emotions, suggesting that they possess the ability to detect the mismatch of local musical emotional deviants. However, for the processing of global musical emotion regularity, a late negativity was observed in TD participants, but not in ASD participants. As discussed aboved, the late negativity reflects the allocation of attention for the inspection of memory traces (Mecklinger et al., 2016).

Therefore, the absence of the late negativity in ASD indicates that their brain cannot consciously allocate attentional resources to evaluate the violations of global emotion regularity.

Across Experiments 1 and 2, ASD participants showed similar neural responses to emotion regularities in facial and musical sequences. However, there was a slight difference in the patterns of response to these two kinds of sequences, suggesting a distinction between visual and auditory emotion regularity processing. In particular, for violations of local emotion regularity, individuals with ASD only showed an MMN for facial expressive sequences, but exhibited both an MMN and an N2 for chord sequences. This might be due to the difference in processing between auditory and visual oddball tasks. Specifically, when comparing auditory and visual oddball tasks, the N2 is more easily evoked by the auditory than the visual modality in typically developing individuals (Halgren et al., 1998). Together, despite this slight difference, our findings indicate that the processing of local and global emotion regularities in ASD is independent of the stimulus domain such as faces and music.

Implications for the global deficit hypothesis in ASD

There is an ongoing debate on whether ASD is associated with a global processing deficit, and such a debate cannot be separated from the hypothesis of a local bias in ASD. Given that global integration requires extraction of regularity across various timescales, we investigated how the autistic brain responds to local and global emotion regularities in facial and musical sequences. At the local level, individuals with ASD exhibited preserved neural responses to local emotion regularity. Given that regularity extraction is based upon the perception of each facial expression, this finding extends EPF theory (Mottron & Burack, 2001; Mottron et al., 2006) to suggests that the local bias may facilitate the local emotion regularity processing in ASD. On the other hand, consistent with previous findings of atypical neural responses to statistical relations (Jeste et al., 2015; Marin et al., 2020; Scott-Van Zeeland et al., 2010), our study showed that the autistic brain was unable to respond to global emotion regularity at the global level. These findings suggest that the autistic brain responses to emotion regularity are modulated by the timescale of sequential stimuli.

In the present study, the absence of brain responses to global regularities suggest that individuals with ASD are unable to detect violations of global emotion regularities at the conscious level, which may be attributed to attention deficits in ASD. Indeed, ASD is associated with deficits in focus/concentration (Keehn et al. 2013), attention span (Eaves, Ho, & Eaves, 1994), and shifting/orienting attention (Corbett et al., 2009; Keehn et al. 2010). Using local-global processing tasks, previous studies suggested that attentional shifting deficits could lead to difficulties for individuals with ASD to switch from attending to local details to global aspects rather than vice versa (Plaisted et al., 1999; Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2001; Soriano et al., 2018). On the other hand, given that individuals with ASD take more time to process global information (Soriano et al., 2018; Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015; Wang, Mottron, Peng, Berthiaume, & Dawson, 2007), and local and global regularities in the present study differed in the timescale at which they were extracted, it is possible that attention deficits in ASD increase the risk of global processing difficulties by making it more difficult to learn emotional regularity from large-scale than small-scale time series. However, future studies are needed to test this hypothesis.

Regarding the debate on whether ASD is associated with a global processing deficit, some studies suggested that global processing is not impaired but less preferred in ASD, because whether the processing is impaired or enhanced depends on a default preference to processing local information, or instruction of allocation of attention (Happé & Booth, 2008; Plaisted et al., 1999). Evidence shows that individuals with ASD exhibited better performance on the local than the global information when they were instructed to attend to both the local and global levels (Plaisted et al., 1999), or given a free-choice (Koldewyn, Jiang, Weigelt, & Kanwisher, 2013); however, when they were instructed to attend to either local or global information, they showed comparable performance on attentive information, no matter what level it is (Plaisted et al., 1999; Van der Hallen et al., 2017). Therefore, the global deficit is interpreted as a disinclination, rather than a disability in ASD (Koldewyn et al., 2013).

However, our findings on how individuals with ASD process local versus global emotion regularities do not provide evidence for the disinclination view. In particular, participants in our study were instructed to count the number of global deviant sequences that violated the regularity of the majority of the sequences. That is, participants were instructed to attend to the global regularity. Despite this requirement, ASD participants did not show typical neural responses to violations of global emotion regularities in either facial or musical sequences. This finding is inconsistent with previous studies (Happé & Booth, 2008; Plaisted et al., 1999) that reported intact global performance by individuals with ASD who were instructed to attend to the global information. The different stimuli used across studies may account for this discrepancy. In particular, previous studies used either a global shape (e.g., a global triangle made of small squares) (Hayward et al., 2012), or a large letter (e.g., a large H made up of small Ss) (Plaisted et al., 1999). Unlike the static graphs used by these studies, our study used the dynamic sequences as stimuli. Such a design allows us to explore local versus global processing separately by excluding the interference of one over the other, which might have led to different results than previous studies. However, future studies are needed to investigate this hypothesis by comparing ASD participants' performance on both types of tasks.

It is worth noting that the processing of local regularity in the present study also reflects global processing, although such processing occurs at a sequence level. For the local emotion regularity task, neither local attention nor perception was explicitly required. Instead, our participants were instructed to attend to the global information. However, results showed that the autistic brain was able to respond to violations of the local emotion regularities in both facial and musical sequences at a preattentive level. Therefore, intact early neural response to local emotion regularity may be due to the local bias in ASD. That is, if individuals with ASD indeed had a bias towards local elements/details, then this processing style would facilitate the extraction of regularity from these discrete elements in short sequences. Together, given that the local and global regularities differed in the timescale at which they were extracted in the present study, our findings indicate that the processing of emotion regularity depends upon the timescale of sequences in individuals with ASD.

Limitations and future directions

One limitation of the present study is that our sample size is relatively small, although power analysis had suggested that this sample size was large enough to reveal an effect. Moreover, although most of our participants were adolescents, we did include participants with a wider age range in order to increase our overall sample size. To examine the potential impact of participant age on our results, we reanalyzed the data by including age as a covariate. The results showed the same patterns as in the ANOVAs (see supplementary text for details), suggesting that our findings were not significantly influenced by participants' age ranges. However, future studies should use a larger sample size and focus on specific age ranges (e.g., children or adults) to further confirm the neural alternation in processing global emotion regularity in ASD.

Another caveat is that we did not include neutral emotion as a control condition in the present study. This is because the goal of the present study was to investigate neural responses to local and global emotion *regularities*, rather than the processing of *emotions* per se, in facial and musical sequences. Therefore, we did not examine the processing of discrete emotions using neutral emotion as a perceptual control condition. Indeed, although neutral facial emotions are relatively common, it is almost impossible to find a single chord that is completely neutral. In order to investigate the processing of local and global emotion regularities across modalities, we selected pleasant and unpleasant faces/chords as stimuli. However, it would be interesting for future studies to investigate group differences in processing negative/positive versus neural emotions at local and global levels across visual and other auditory (e.g., speech) domains.

Conclusion

The present study reveals for the first time that the autistic brain can process local but not global emotion regularity in facial and musical sequences. Given that there is a great deal of heterogeneity in results regarding the deficit of ASD, our findings may contribute to a better understanding of the characteristics of ASD. First, our study showed that the autistic brain exhibited similar patterns of neural anomaly in processing global emotion regularities in faces and music. This finding suggests a domain-general global processing deficit in ASD. Second, considering that emotion processing in visual and auditory domains is equally important to social communication, our findings indicated that the processing of emotion regularities at both local and global levels in ASD may be independent of the stimulus domain such as faces and music. This suggests that the global processing deficit in ASD may be domain-general, contributing to social-communication difficulties among individuals with ASD. Finally, regarding the debate over whether ASD is associated with a global processing deficit, our findings demonstrated that the processing of global emotion regularity in ASD is modulated by the timescale of the facial and musical sequences. Together, these findings may contribute to a better understanding of the neural mechanisms underlying regularity processing, as well as the processing of local versus global information in ASD.

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Tables

Table 1

Demographic characteristics of participants in ASD and TD groups

	ASD group (*N* = 20)	TD group (*N* = 21)	*t*	*p*
Sex	3F, 17M	3F, 18M		
Age in years	13.50 (3.76)	13.19 (4.12)	0.25	.803
Education in years	6.60 (2.50)	7.91 (3.63)	1.33	.190
Musical training in years	1.90 (2.45)	1.57 (2.31)	0.44	.661
ADOS-2 Module 3 (*N* = 16)	14.94 (6.52)	-		
ADOS-2 Module 4 (*N* = 4)	17.25 (0.96)	-		
IQ (RPM)	96.81 (18.45)	105.37 (15.53) †	1.56	.127

Note. Sixteen participants (nine ASD and seven TD participants) have received music training. Of these, nine of the participants (five ASD and four TD participants) took piano lessons, five (two ASD and three TD participants) studied wind music, such as the saxophone and the Sheng, a traditional Chinese instrument, one ASD participant learned the drum set, and one ASD participant learned vocal music. The education received by the two groups was homogeneous. All of them had received education under China's nine-year compulsory education system in ordinary primary and secondary schools.

F = female; M = male. The numbers in parentheses are standard deviations (*SD*).

† Data are missing from two participants.

Table 2

ERP results of the local regularity processing of facial emotions in Experiment 1

Variables		$F_{(1, 39)}$	*p*	η_p^2	*BF*
MMN					
Group		6.50	.015	0.14	3.23
Stimulus type		3.92	.055	0.09	0.85
Group × Stimulus type		**5.38**	**.026**	**0.12**	**6.46**
	ASD: Dev < Std	9.02	.005	0.19	
	TD: Dev = Std	0.06	.810	0.002	
N2					
Group		0.08	.785	0.002	0.54
Stimulus type		0.07	.799	0.002	0.24
Group × Stimulus type		4.09	.050	0.10	1.49
	ASD: Dev = Std	1.52	.225	0.04	
	TD: Dev = Std	2.66	.111	0.06	
P3b					
Group		0.12	.732	0.003	0.36
Stimulus type		2.83	.101	0.07	0.66
Group × Stimulus type		**10.05**	**.003**	**0.21**	**13.57**
	ASD: Dev = Std	1.08	.304	0.03	
	TD: Dev > Std	12.06	.001	0.24	
LPC/Late negativity					
Group		5.08	.030	0.12	2.25
Stimulus type		2.81	.102	0.07	0.67
Group × Stimulus type		**6.09**	**.018**	**0.14**	**3.24**
	ASD: Dev = Std	0.31	.583	0.01	
	TD: Dev > Std	8.80	.005	0.18	

Note. Significant interactions between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.

Table 3

ERP results of the global regularity processing of facial emotions in Experiment 1

Variables		$F_{(1, 39)}$	p	η_p^2	BF
MMN					
Group		12.41	.001	0.24	28.74
Stimulus type		0.21	.648	0.01	0.29
Group × Stimulus type		0.50	.482	0.01	0.32
N2					
Group		0.52	.475	0.01	0.41
Stimulus type		0.17	.679	0.004	0.26
Group × Stimulus type		1.03	.316	0.03	0.41
P3b					
Group		6.14	.018	0.14	3.19
Stimulus type		4.87	.033	0.11	1.61
Group × Stimulus type		**5.60**	**.023**	**0.13**	**3.09**
	ASD: Dev = Std	0.01	.913	< .001	
	TD: Dev > Std	10.72	.002	0.22	
LPC/Late negativity					
Group		20.06	< .001	0.34	333.13
Stimulus type		14.02	.001	0.26	17.92
Group × Stimulus type		**15.12**	**<.001**	**0.28**	**61.56**
	ASD: Dev = Std	0.01	.920	< .001	
	TD: Dev > Std	29.85	< .001	0.43	

Note. Significant interactions between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.

Table 4

ERP results of the local regularity processing of musical emotions in Experiment 2

Variables	$F_{(1, 39)}$	p	η_p^2	*BF*
MMN				
Group	3.15	.084	0.08	1.24
Stimulus type	10.35	.003	0.21	15.27
Group × Stimulus type	1.02	.319	0.03	0.25
N2				
Group	0.14	.707	0.004	0.53
Stimulus type	10.62	.002	0.21	14.35
Group × Stimulus type	0.59	.448	0.02	0.35
P3b				
Group	2.35	.133	0.06	0.93
Stimulus type	2.81	.102	0.07	0.76
Group × Stimulus type	0.01	.931	< .001	0.31
LPC/Late negativity				
Group	0.004	.950	< 0.001	0.46
Stimulus type	0.62	.437	0.02	0.30
Group × Stimulus type	1.02	.320	0.03	0.43

Table 5

ERP results of the global regularity processing of musical emotions in Experiment 2

Variables		$F_{(1, 39)}$	p	η_p^2	BF
MMN					
Group		1.51	.227	0.04	0.72
Stimulus type		0.17	.680	0.004	0.24
Group × Stimulus type		< 0.001	.997	< 0.001	0.29
N2					
Group		0.24	.627	0.01	0.32
Stimulus type		0.10	.757	0.002	0.25
Group × Stimulus type		1.86	.180	0.05	0.64
P3b					
Group		0.27	.607	0.01	0.35
Stimulus type		0.49	.490	0.01	0.29
Group × Stimulus type		3.58	.066	0.08	1.28
LPC/Late negativity					
Group		0.50	.483	0.01	0.39
Stimulus type		8.01	.007	0.17	5.25
Group × Stimulus type		**5.27**	**.027**	**0.12**	**29.19**
	ASD: Dev = Std	0.14	.711	0.004	
	TD: Dev < Std	13.46	.001	0.26	

Note. Significant interaction between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.

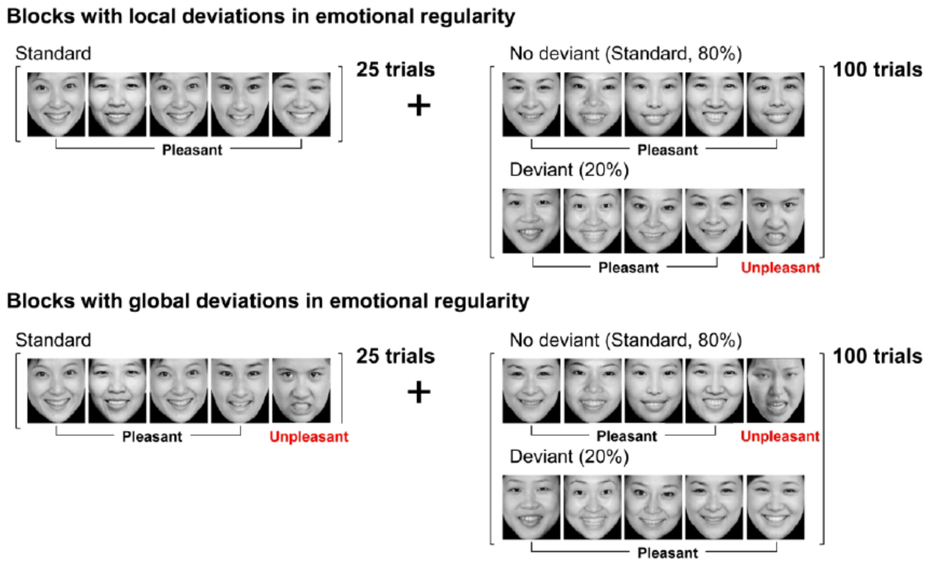
Figure legends

Figure 1. Emotional oddball paradigm of facial images in Experiment 1. Five-image sequences were presented in blocks with local or global deviations. Each block consisted of 125 trials, where the first 25 trials consisted of the frequent sequences in order to establish the regularity. The following 100 trials consisted of 80 frequent sequences and 20 rare sequences in random order. By doing so, a facial image with a different emotional type following the first four images with the same type of emotion represents a local deviant in the blocks with local deviations (within trial), while the five-image sequences with the same emotional type represents global deviants in the blocks with global deviations (across trials). Photos reproduced with permission from Yuejia Luo.

Figure 2. Grand mean waveforms elicited by local and global facial emotional regularities at representative electrode sites for ASD and TD participants. Bottom: Scalp distribution of the deviant-minus-standard difference waves in four-time windows for ASD and TD participants.

Figure 3. Emotional oddball paradigm of chords in Experiment 2. Five-chord sequences were presented in blocks with local or global deviations. Each block consisted of 125 trials, where the first 25 trials consisted of the frequent sequences in order to establish the regularity. The following 100 trials consisted of 80 frequent sequences and 20 rare sequences in random order.

Figure 4. Grand mean waveforms elicited by local and global musical emotional regularities at representative electrode sites for ASD and TD participants. Bottom: Scalp distribution of the deviant-minus-standard difference waves in four-time windows for ASD and TD participants.



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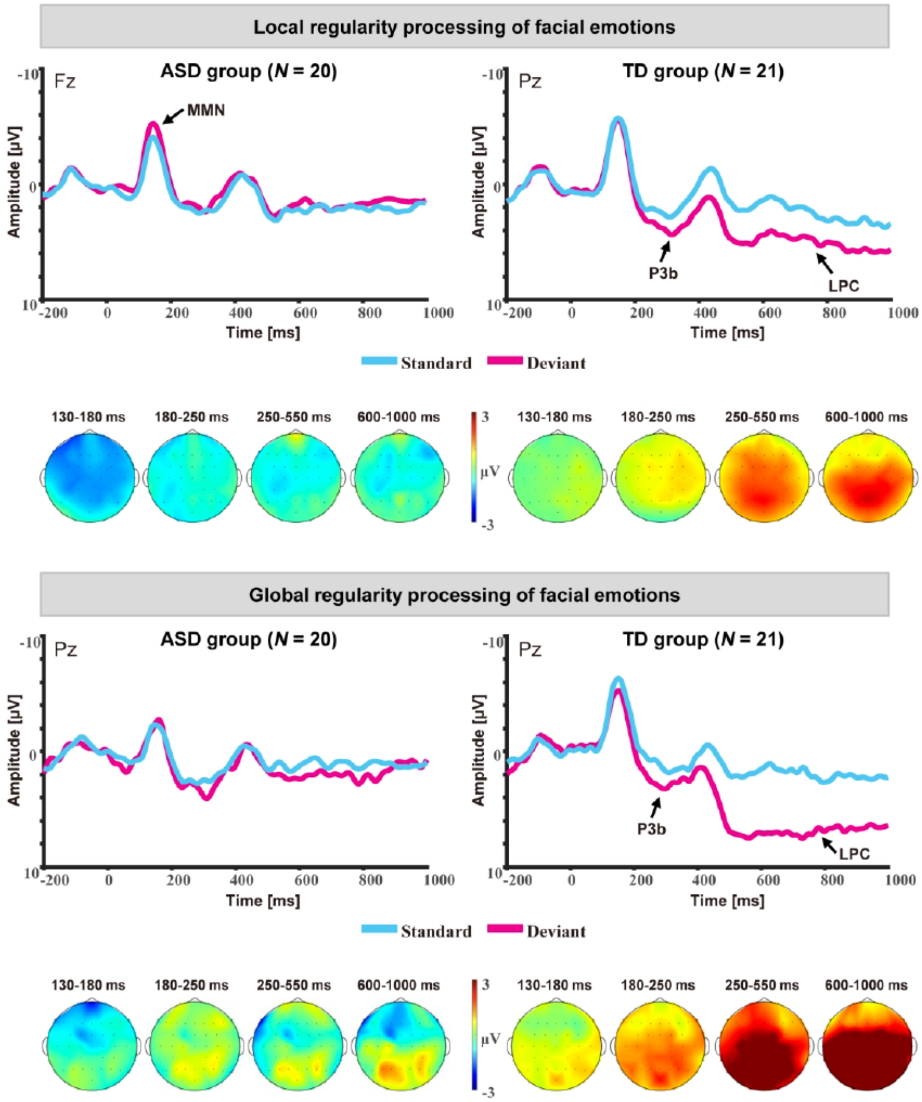

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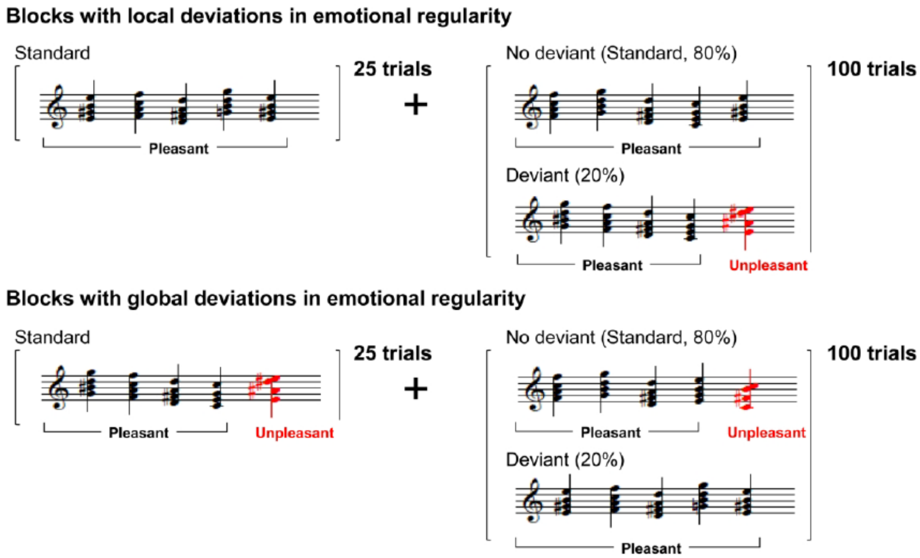

Figure 3. Emotional oddball paradigm of chords in Experiment 2. Five-chord sequences were presented in blocks with local or global deviations. Each block consisted of 125 trials, where the first 25 trials consisted of the frequent sequences in order to establish the regularity. The following 100 trials consisted of 80 frequent sequences and 20 rare sequences in random order.

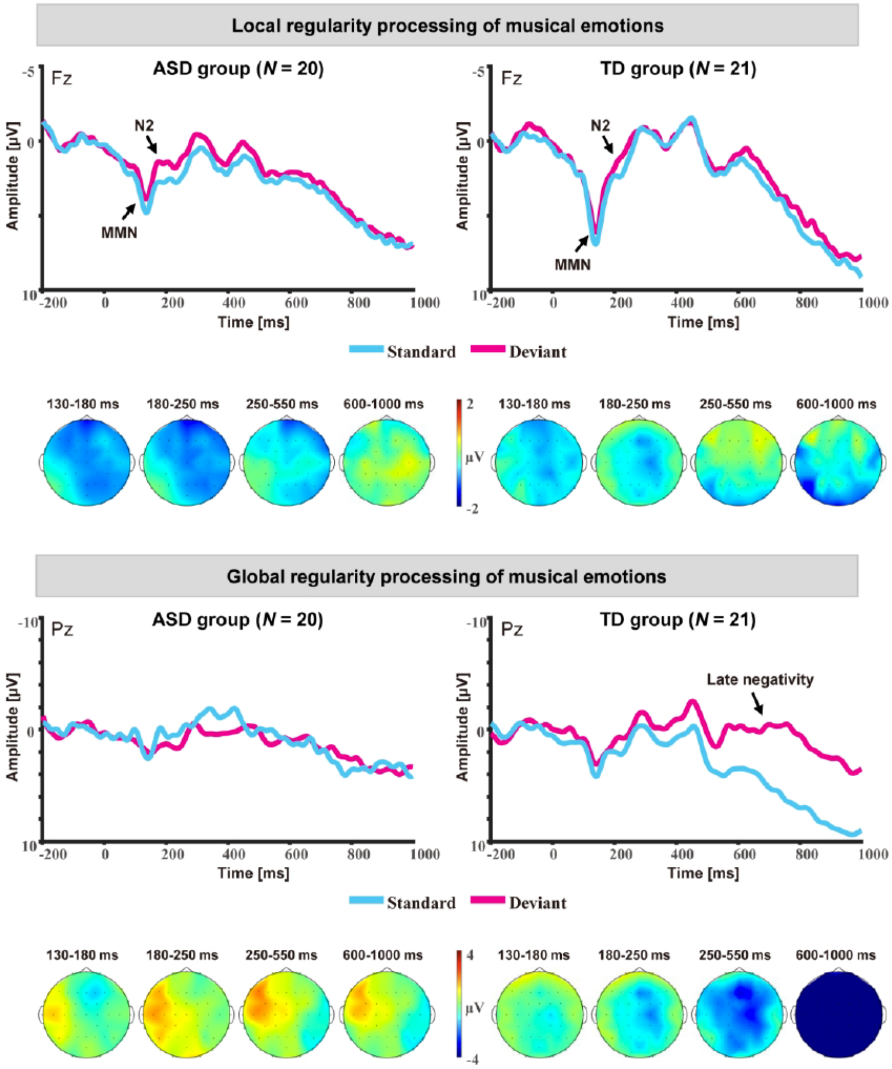

Figure 4. Grand mean waveforms elicited by local and global musical emotional regularities at representative electrode sites for ASD and TD participants. Bottom: Scalp distribution of the deviant-minus-standard difference waves in four-time windows for ASD and TD participants.

Supplementary text

Experiment 1

Stimuli

In order to assess the emotional valence of these images, 18 healthy participants who did not participate in the formal experiment were asked to rate each image with regard to perceived pleasantness on a 7-point scale (7 = very pleasant to 1 = very unpleasant). Paired samples *t*-tests showed that happy facial images ($M = 5.64$, $SD = 0.48$) received significantly higher ratings than angry facial images ($M = 2.11$, $SD = 0.44$) in perceived pleasantness [$t_{(17)} = 23.64$, $p < .001$].

Behavioral results

For the blocks with local deviants, an independent *t* test showed no difference on the self-reported number of deviant trials counted by the ASD ($M = 17.81$, $SD = 4.50$) and TD ($M = 17.94$, $SD = 3.52$) participants, $t_{(40)} = 0.11$, $p = .917$. Similar, for the blocks with local deviants, there was no difference on the self-reported number of deviant trials between the ASD ($M = 26.06$, $SD = 13.92$) and TD ($M = 21.64$, $SD = 17.06$) groups, $t_{(40)} = 0.92$, $p = .364$. These findings suggesting that both ASD and TD participants attended to the global regularity of facial emotions.

EEG results

To examine the potential effect of age on the current results, we also analyzed our EEG data using ANCOVAs by including age as a covariate. As demonstrated in Tables S1 and S2, the results showed the same patterns as the ANOVAs reported in the main paper.

Table S1. *ERP results of the local regularity processing of facial emotions in Experiment 1*

Variables		$F_{(1, 39)}$	*p*	η_p^2	*BF*
MMN					
Group		6.81	.013	0.15	3.70
Stimulus type		3.86	.057	0.09	0.80
Group × Stimulus type		**5.81**	**.021**	**0.13**	**2.96**
	ASD: Dev < Std	9.54	.004	0.20	
	TD: Dev = Std	0.08	.776	0.002	
N2					
Group		0.08	.785	0.002	0.54
Stimulus type		0.73	.399	0.02	0.25
Group × Stimulus type		**4.23**	**.047**	**0.10**	**1.45**
	ASD: Dev = Std	1.59	.216	0.04	
	TD: Dev = Std	2.74	.106	0.07	
P3b					
Group		0.11	.742	0.003	0.36
Stimulus type		0.10	.752	0.003	0.66
Group × Stimulus type		**10.16**	**.003**	**0.21**	**14.02**
	ASD: Dev = Std	1.12	.296	0.03	
	TD: Dev > Std	12.11	.001	0.24	
LPC/Late negativity					
Group		4.91	.033	0.11	2.14
Stimulus type		0.01	.912	< 0.001	0.72
Group × Stimulus type		**6.02**	**.019**	**0.14**	**3.27**
	ASD: Dev = Std	0.31	.580	0.01	
	TD: Dev > Std	8.66	.006	0.19	

Note. Significant interactions between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.

Table S2. *ERP results of the global regularity processing of facial emotions in Experiment 1*

Variables		$F_{(1, 39)}$	*p*	η_p^2	*BF*
MMN					
Group		13.77	.001	0.27	41.61
Stimulus type		0.43	.518	0.01	0.26
Group × Stimulus type		0.53	.473	0.01	0.32
N2					
Group		0.47	.498	0.01	0.42
Stimulus type		0.08	.774	0.002	0.27
Group × Stimulus type		1.04	.314	0.03	0.35
P3b					
Group		5.99	.019	0.14	3.07
Stimulus type		0.05	.825	0.001	1.64
Group × Stimulus type		**5.54**	**.024**	**0.13**	**2.97**
	ASD: Dev = Std	0.02	.905	< .001	
	TD: Dev > Std	10.55	.002	0.22	
LPC/Late negativity					
Group		19.82	< .001	0.34	330.54
Stimulus type		0.46	.504	0.01	16.58
Group × Stimulus type		**14.87**	**<.001**	**0.28**	**62.45**
	ASD: Dev = Std	0.01	.913	< .001	
	TD: Dev > Std	29.28	< .001	0.44	

Note. Significant interactions between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.

Experiment 2

Stimuli

All chords were created using Cubase 7.0 (Steinberg Media Technologies GmbH, Hamburg, Germany), exported with the piano timbre and edited using Adobe Audition CS6 software (Adobe Systems Incorporated, San Jose, CA, USA) with 44.1 kHz sampling rate and 16-bit resolution. The loudness was normalized with Adobe Audition CS6 at an approximate intensity of 68 dB SPL.

In order to assess the emotional valence of these chords, 16 healthy participants who did not participate in the formal experiment were asked to rate each chord with regard to perceived pleasantness on a 7-point scale (7 = very pleasant to 1 = very unpleasant). Paired samples *t*-tests showed that consonant chords (M = 4.45, SD = 0.47) received significantly higher ratings than dissonant chords (M = 3.54, SD = 1.04) in perceived pleasantness [$t_{(15)} = 3.09$, $p = .007$].

Behavioral results

For the blocks with local deviants, an independent *t* test showed no difference on the self-reported number of deviant trials counted by the ASD (M = 25.37, SD = 16.06) and TD (M = 18.39, SD = 10.68) participants, $t_{(40)} = 1.66$, $p = .105$. Similar, for the blocks with local deviants, there was no difference on the self-reported number of deviant trials between the ASD (M = 30.15, SD = 35.26) and TD (M = 18.49, SD = 9.02) groups, $t_{(40)} = 1.47$, $p = .150$. These findings suggesting that both ASD and TD participants paid attention to the global regularity of musical emotions.

EEG results

To examine the potential effect of age on the current results, we also analyzed our EEG data using ANCOVAs by including age as a covariate. As demonstrated in Tables S3 and S4, the results showed the same patterns as the ANOVAs reported in the main paper.

Table S3. *ERP results of the local regularity processing of musical emotions in Experiment 2*

Variables	$F_{(1, 39)}$	p	η_p^2	*BF*
MMN				
Group	4.00	.053	0.10	1.02
Stimulus type	5.59	.023	0.13	8.39
Group × Stimulus type	0.40	.530	0.01	0.37
N2				
Group	0.11	.741	0.003	0.52
Stimulus type	4.22	.047	0.10	14.59
Group × Stimulus type	0.70	.409	0.02	0.38
P3b				
Group	2.24	.143	0.06	0.99
Stimulus type	0.37	.546	0.01	0.75
Group × Stimulus type	0.01	.937	< .001	0.30
LPC/Late negativity				
Group	0.001	.975	< 0.001	0.45
Stimulus type	0.36	.555	0.01	0.31
Group × Stimulus type	0.96	.333	0.03	0.44

Table S4. *ERP results of the global regularity processing of musical emotions in Experiment 2*

Variables		$F_{(1, 39)}$	p	η_p^2	*BF*
MMN					
Group		1.41	.243	0.04	0.66
Stimulus type		1.40	.244	0.04	0.24
Group × Stimulus type		0.003	.960	< 0.001	0.31
N2					
Group		0.23	.633	0.01	0.32
Stimulus type		0.77	.385	0.02	0.25
Group × Stimulus type		1.97	.168	0.05	0.58
P3b					
Group		0.31	.582	0.01	0.36
Stimulus type		0.04	.849	0.001	0.28
Group × Stimulus type		3.48	.070	0.08	1.31
LPC/Late negativity					
Group		0.56	.458	0.02	0.39
Stimulus type		0.40	.533	0.01	5.37
Group × Stimulus type		**5.16**	**.029**	**0.12**	**2.52**
	ASD: Dev = Std	0.13	.718	0.003	
	TD: Dev < Std	13.15	.001	0.26	

Note. Significant interaction between group and stimulus type ($p < .05$) are marked in bold. Dev = Deviant; Std = Standard.