

## Multilevel alterations in the processing of audio–visual emotion expressions in autism spectrum disorders

Geneviève Charbonneau<sup>a</sup>, Armando Bertone<sup>b,c</sup>, Franco Lepore<sup>a,d</sup>, Marouane Nassim<sup>c</sup>, Maryse Lassonde<sup>a,d</sup>, Laurent Mottron<sup>c</sup>, Olivier Collignon<sup>a,d,e,\*</sup>

<sup>a</sup> Centre de Recherche en Neuropsychologie et Cognition (CERNEC), Département de psychologie, Université de Montréal, CP 6128, succursale Centre-Ville, Montréal, Québec, Canada H3C 3J7

<sup>b</sup> School/Applied Child Psychology, Department of Education and Counseling Psychology, McGill University, 3700 McTavish St. Montreal, Québec, Canada H3A 1Y2

<sup>c</sup> Centre d'excellence en Troubles envahissants du développement de l'Université de Montréal (CETEDUM), Hôpital Rivière-des-Prairies, 7070 boul. Perras, Montréal, Québec, Canada H1E 1A4

<sup>d</sup> Centre de Recherche CHU Sainte-Justine, 3175, Chemin de la Côte-Sainte-Catherine, Montréal, Québec, Canada H3T 1C5

<sup>e</sup> Centre for Mind/Brain Sciences (CIMeC), University of Trento, via delle Regole, 101, Mattarello (TN), Italy.

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### ABSTRACT

The abilities to recognize and integrate emotions from another person's facial and vocal expressions are fundamental cognitive skills involved in the effective regulation of social interactions. Deficits in such abilities have been suggested as a possible source for certain atypical social behaviors manifested by persons with autism spectrum disorders (ASD). In the present study, we assessed the recognition and integration of emotional expressions in ASD using a validated set of ecological stimuli comprised of dynamic visual and auditory (non-verbal) vocal clips. Autistic participants and typically developing controls (TD) were asked to discriminate between clips depicting expressions of disgust and fear presented either visually, auditorily or audio-visually. The group of autistic participants was less efficient to discriminate emotional expressions across all conditions (unimodal and bimodal). Moreover, they necessitated a higher signal-to-noise ratio for the discrimination of visual or auditory presentations of disgust versus fear expressions. These results suggest an altered sensitivity to emotion expressions in this population that is not modality-specific. In addition, the group of autistic participants benefited from exposure to bimodal information to a lesser extent than did the TD group, indicative of a decreased multisensory gain in this population. These results are the first to compellingly demonstrate joint alterations for both the perception and the integration of multisensory emotion expressions in ASD.

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### 1. Introduction

The ability to recognize emotional expressions is a fundamental cognitive ability for the regulation of interpersonal interactions (Adolph, 2002; Custrini & Feldman, 1989; Izard et al., 2001). The tone of the voice and the facial expression are two crucial cues that we constantly use to predict others' actions and to react appropriately in a social situation. An important aspect of affect perception in everyday life is that it usually involves, like

speech, the activation of several sensory channels simultaneously. Therefore, the combination of information from facial expression (visual signal) and prosody (auditory signal) usually results in a unified and more optimal representation of the expressed emotion (de Gelder, Bocker, Tuomainen, Hensen, & Vroomen, 1999; de Gelder & Vroomen, 2000; de Gelder et al., 2005). For example, it has been shown that the multisensory integration (MSI) of these two types of information typically allows for faster and more accurate recognition of emotion expressions in human observers (Collignon et al., 2008, 2010; de Gelder & Vroomen, 2000; Dolan, Morris, & de Gelder, 2001; Kreifelts, Ethofer, Grodd, Erb, & Wildgruber, 2007; Massaro & Egan, 1996) and in human-machine interfaces (Busso et al., 2004).

Deficits in the perception of emotion expressions have been suggested as possible causes of atypical social and communicative interactions that are a striking part of the behavioral phenotype of autistic spectrum disorders (ASD) (Bachevalier & Loveland, 2006; Monk et al., 2010; Sigman, Dijamco, Gratier, & Rozga, 2004).

\* Corresponding author at: CIMeC—Center for Mind/Brain Sciences, University of Trento, via delle Regole, 101, Mattarello (TN), Italy. Tel.: +39 461 282778; fax: +39 461 883066.

E-mail addresses: genevieve.charbonneau.1@umontreal.ca (G. Charbonneau), armando.bertone@mcgill.ca (A. Bertone), franco.lepore@umontreal.ca (F. Lepore), marouane.nassim.hrdp@sss.gouv.qc.ca (M. Nassim), maryse.lassonde@umontreal.ca (M. Lassonde), motttron@istar.ca (L. Mottron), olivier.collignon@unitn.it (O. Collignon).

However, a majority of the empirical investigations in the field have focused on the facial expression of emotions using static stimuli such as photographs (Bal et al., 2010), with only a few studies using video representing dynamic facial movements (Golan, Baron-Cohen, & Golan, 2008; Loveland, Steinberg, Pearson, Mansour, & Reddoch, 2008; Loveland et al., 1997). The former static stimuli have limited ecological validity and neglect the intrinsic dynamic nature of facial expressions. Indeed, facial movements have been shown to enrich emotional expression, contributing to its identification and playing an important role in the perception of its intensity (Ambadar, Schooler, & Cohn, 2005; Biele & Grabowska, 2006). Also, neuroimaging studies have shown that the brain regions involved in the processing of facial affect, such as the posterior superior temporal sulcus (pSTS), the amygdala and the insula, respond differently to dynamic than to static emotional expressions (Haxby, Hoffman, & Gobbini, 2000, 2002; LaBar, Crupain, Voyvodic, & McCarthy, 2003; Miki, Takeshima, Watanabe, Honda, & Kakigi, 2011). Moreover, only a few studies explored the processing of affective vocalizations in ASD (Baker, Montgomery, & Abramson, 2010; Hall, Szechtman, & Nahmias, 2003; Loveland et al., 2008; Wang, Lee, Sigman, & Dapretto, 2007). In most cases, these studies included semantic or lexical confounds in the tasks (Lindner & Rosen, 2006) raising the possibility that the results were influenced by differences in language comprehension (Haviland, Walker-Andrews, Huffman, Toci, & Alton, 1996; Paul, Augustyn, Klin, & Volkmar, 2005). Finally, most studies investigating the recognition of emotions in autistic individuals explored a single sensory modality at a time, whereas in natural settings, emotions are expressed both facially and vocally, allowing the combination of these sources of information by human observers for optimal recognition (Collignon et al., 2008; de Gelder et al., 1999; de Gelder & Vroomen, 2000; de Gelder et al., 2005). The use of multisensory conditions to explore the recognition of emotional expressions in ASD is of particular interest since differences in multisensory processing between ASD and typically developing controls (TD) has recently been demonstrated (Collignon et al., 2012; Magnee, de Gelder, van Engeland, & Kemner, 2007; 2008; Russo et al., 2010; Russo, Mottron, Burack, & Jemel, 2012).

An additional challenge associated with the processing of emotional expressions in natural settings is related to the fact that the saliency of emotional information in faces and voices is often reduced by environmental noise. In signal processing, noise can be considered unwanted data that is not being used to transmit a signal, but is simply a by-product of other activities. For example, the voice of an individual can be masked by noise from other human voices or from objects surrounding him. Similarly, a person's facial expression can be partially hidden by an object or because of the angle in which the observer is positioned. Therefore, the ability of the observer to extract efficiently emotional information from noise appears crucial for effective social interactions and therefore it is relevant to evaluate the perception of emotional expressions in noisy situations (Pelli & Farell, 1999). Some studies have suggested that ASD have a specific difficulty in perceiving speech when presented in a noisy background compared to TD (Alcantara, Weisblatt, Moore, & Bolton, 2004; Smith & Bennetto, 2007). To our knowledge, no study has investigated the perception of visual or auditory emotional expressions in noise in ASD.

The goal of the present study was therefore to explore the perception and the integration of emotion expressions in ASD by using ecological and validated sets of dynamic visual and non-verbal vocal clips of emotional expressions (Belin, Fillion-Bilodeau, & Gosselin, 2008; Simon, Craig, Gosselin, Belin, & Rainville, 2008). Participants were asked to categorize expressions of fear or disgust as quickly and accurately as possible when

presented with auditory, visual and audio-visual stimuli. This task allowed us to compare recognition and MSI performance of emotional expressions between ASD and TD. We also compared unisensory performance of ASD and TD participants by measuring their ability to discriminate emotional expressions when presented auditorily and visually in individually adapted levels of noise. Similar paradigms have been previously successfully used to demonstrate that the perception of emotional expressions is a robust multisensory situation which follows rules that have been observed in other perceptual domains (Collignon et al., 2008) and to illustrate gender differences in the processing of emotion expressions (Collignon et al., 2010).

## 2. Material and methods

### 2.1. Subjects

Thirty-two autistic participants (30 males; mean age 21 years  $\pm$  6; range 14–32 years) and 18 TD controls (18 males; mean age 21 years  $\pm$  4; range 15–27 years) participated in this study. Participants were recruited from the database of the Rivière-des-Prairies Hospital's autism clinic (Montreal, Canada). ASD participants were defined using DSM-IV-TR diagnostic criteria, as operationalized by the Autism Diagnostic Interview – Revised (ADI-R) (Lord, Rutter, & Le Couteur, 1994) and the Autistic Diagnostic Observation Schedule-Generic (ADOS-G) (Lord et al., 2000) algorithms. Control participants and their first-degree relatives were screened with a questionnaire for any history of neurological or psychiatric disorders. The groups were closely matched in terms of laterality and Wechsler IQ ([Full-scale=ASD: 105  $\pm$  15; TD 111  $\pm$  9]; [Performance=ASD: 102  $\pm$  13; TD 108  $\pm$  10]; [Verbal=ASD: 106  $\pm$  16; TD 112  $\pm$  11]). All participants had a global Wechsler score of 80 or more. They all had normal or corrected to normal far and near vision assessed before testing using near and far Snellen acuity charts. The ethics board of both the Rivière-des-Prairies Hospital and University of Montreal approved the study.

Autism lies on a spectrum, and comprises two major subgroups: individuals with classic autism and those with Asperger's syndrome. These groups share the combination of social-communication difficulties, repetitive behaviors and restricted interests. In classic autism, language development in children is also delayed and their intelligence level range from intellectual disability to superior intelligence, while criteria for Asperger excludes cognitive impairment. Following the DSM-5 decision to adopt a dimensional view of heterogeneity in autism spectrum, we subsequently merged the subgroups in a common sample of ASD. However, since previous experiments suggested that classic autism and Asperger's syndrome might differ in terms of perceptual abilities (Brochu-Barbeau, Soulières, Dawson, Zeffiro, & Mottron, 2013; Bonnel et al., 2010; Jones et al., 2009), we also analyzed the data by separating the two subgroups and no significant difference was observed between them (see supplemental analyses; S Figs. 2–5).

### 2.2. Stimuli

As in our previous experiments, fear and disgust expressions were used because, from an evolutionary perspective, these emotions may be more important for survival than other basic emotions. Indeed, in the multisensory domain, Dolan et al. (2001) suggested that the rapid integration across modalities is not as automatic for happy expressions as it is for fear signals. More specifically, the goal of fear would be to augment sensory vigilance (Davis & Whalen, 2001) whereas disgust is associated with sensory rejection (Rozin & Fallon, 1987). Consistent with this idea, it has been demonstrated that fear enhances sensory acquisition and perception, whereas disgust dampens it (Susskind et al., 2008), therefore giving empirical support to the Darwinian hypothesis that some basic emotion expressions may have originated in altering the sensory interface with the physical world (Darwin, 1972/1998). Furthermore, disgust and fear expressions convey highly discriminable signals (Belin et al., 2008; Ekman & Friesen, 1976; Simon et al., 2008; Susskind et al., 2008) and serve as a model to study the existence of separate neural substrates underlying the processing of individual emotion expressions (Calder, Lawrence, & Young, 2001).

The *visual stimuli* used in this study were selected from a standardized set of dynamic color stimuli of actors and actresses displaying prototypical facial expressions (Simon et al., 2008). One actor and one actress who best depicts facial expressions of fear and disgust based on a previous control study (Collignon et al., 2008) were selected. The facial expressions were "prototypical" and "natural" insofar as they possessed the key features (identified using the Facial Action Coding System: FACS) identified by Ekman and Friesen (1976) as being representative of everyday facial expressions (Simon et al., 2008). The same actor and actress portrayed the two emotions. The selected clips were edited in short segments of 500 msec with a size of 350  $\times$  430 pixels using Adobe Premiere and

Adobe Aftereffect (Adobe Systems Inc., San Jose, US). The clips always started with a neutral face, which then continuously evolves into full expression (Fig. 1).

The auditory stimuli used were selected from the “Montreal affective voices”, a standardized set of emotional vocal expressions designed for research on auditory affective processing with the avoidance of potential confound from linguistic content (Belin et al., 2008). Among this set, we selected fear and disgust vocalizations portrayed by one actor and one actress producing the stimuli with the highest level of distinctiveness. Again, each actor portrayed both emotions. The selected affective interjections were then edited in short meaningful segments of 500 ms (10 ms sinusoidal rise/fall ramp time) and normalized peak values (90%) using Adobe Audition 2.0 (Adobe Systems Inc., San Jose, US) (see the Supplementary material section for further details about the selection of the stimuli).

### 2.3. Procedure

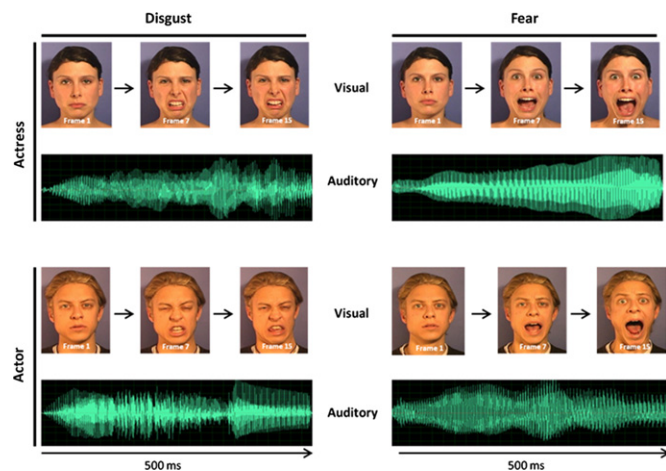
Participants sat in a silent and darkened room with their head supported by a chinrest in front of a computer screen at a viewing distance of 57 cm. Visual stimuli (width=10° and height=12.5° of visual angle) were presented in the centre of the screen over a constant gray background. Auditory stimuli were presented binaurally through headphones (Philips HJ030) at a self-adjusted comfort level.

#### 2.3.1. Task 1: Discrimination of emotional expressions and multisensory integration

Participants were asked to discriminate fear and disgust stimuli presented auditorily, visually, or audio-visually. The bimodal (audio-visual) stimuli consisted in the synchronous presentation of visual and auditory clips depicting the same emotion (e.g. fearful face/fearful voice). Each actor or actress in the visual clips has been associated with a specific voice, and these pairs remained the same for all experimental conditions. Participants were asked to respond as quickly and as accurately as possible in a forced two-choice discrimination paradigm, by pressing the appropriate keyboard keys with the index (left key) and the middle finger (right key) of their right hand. The response keys were counterbalanced across subjects so that for half of the participants the left key corresponded to fear and the right key to disgust and for the other half the opposite was true. The participants were presented a total of 120 stimuli randomly interleaved (2 [emotions: fear, disgust] × 2 [actors: 1 actor, 1 actress] × 3 [modalities: visual, auditory, audio-visual] × 10 repetitions). These stimuli were displayed in 4 separate blocks of 30 stimuli lasting approximately 10 min. Each stimulus presentation was followed by a 2000 ms gray background (the response period), and then a central cross appeared for 500–1500 ms (uniformly distributed random duration) prior to the next stimulus (Mean ISI 3000 ms; range 2500–3500 ms, uniformly distributed).

#### 2.3.2. Task 2: Signal/noise ratio for auditory and visual emotional expressions recognition

The participants had to discriminate between fear and disgust stimuli presented visually or auditorily. They were asked to respond as accurately as possible, without time constraint, by pressing the appropriate keyboard keys with the index (left key) and the middle finger (right key) of their right hand. The response keys were counterbalanced across subjects, so that for half of the participants the left key corresponded to fear and the right key to disgust and for the other half the left key corresponded to disgust and the right key to fear.



**Fig. 1.** Schematic representation of the stimuli. Participants were required to discriminate between affective expressions of fear and disgust displayed either by an actress or an actor. Stimuli consisted in video and non-linguistic vocal clips and were either displayed alone or together (bimodal condition).

Each stimulus presentation lasted until the participant pressed one of the response keys. The next stimulus appeared immediately after the participant's response. After each correct response, white Gaussian noise was randomly added to the presented audio (sequence of normally distributed random numbers at a sample rate of 44.1 kHz) or video (Gaussian noise in each of the three color channels) clips. Similarly, noise was removed from the following stimulus each time the participant made a wrong choice. This individual adjustment was carried out using the QUEST adaptive staircase (Watson & Pelli, 1983) implemented in the Psychtoolbox (Brainard, 1997; Pelli, 1997) for Matlab (The MathWorks, Inc.). The signal-to-noise ratio of the video and audio clips was adjusted in order to target a 80% accuracy rate in each participant. The participants viewed a total of 320 stimuli (2 [emotions: fear, disgust] × 2 [actors: 1 actor, 1 actress] × 2 [modalities: visual, auditory] × 40 repetitions). These stimuli were separated in 4 “visual blocks” each including 40 video clips and 4 “auditory blocks” each comprising 40 audio clips. The blocks were counterbalanced between modalities.

### 2.4. Data analysis

#### 2.4.1. Task 1

Task accuracy was estimated by the calculation of the  $d'$  sensitivity index computed following Snodgrass and Corwin (1988). Only latencies of correct responses were considered in the analysis of reaction times (RTs). In experiments equally emphasizing accuracy and processing speed, it is, in principle, possible that each subject (group) may adopt different response strategies, by varying RT inversely with accuracy (and thus show speed-accuracy trade-off). Therefore, overall performance (and variance) may best be reflected by a single variable that simultaneously takes into account speed and accuracy. We recently introduced the “speed-accuracy composite score (SACS)”, which is an extension of the widely used “inverse efficiency” scores (Townsend & Ashby, 1983), and demonstrated its utility in investigating between-groups differences in performance (Collignon et al., 2010). With SACS, in order to attribute the same weight to accuracy and reaction time (RT) performances across the participants, we normalized the  $d'$  and the RT scores obtained across all conditions and we subtracted the normalized RTs from the normalized  $d'$  [ $Z(d')$ – $Z(\text{RTs})$ ]. Differences in performance were then analyzed by submitting the  $d'$ , RTs and SACS to a repeated measures ANOVA. Based on significant  $F$ -values, Bonferroni post-hoc analyses were performed when appropriate. Percentage of correct responses (HIT) and of false alarms (and related statistics) are illustrated separately in a supporting figure (Fig. S1).

#### 2.4.2. Multisensory integration

We first calculated separately in each participant the redundancy gain (RG) as defined by the decrease (in percent) of the mean RT obtained in the multisensory condition when compared with the mean RT obtained in the best unisensory condition (Girard, Collignon, & Lepore, 2011). The RG was then submitted to an independent samples  $t$ -test to test for a statistical difference between ASD and TD. Different explanations have been put forward to account for the observation of the RG. The most common are the race and the coactivation models. The race model proposes that each individual stimulus elicits an independent detection process. For a given trial, the fastest stimulus determines the observable RT. On average, the time to detect the fastest of several redundant signals is faster than the detection time for a single signal. Therefore, the speeding up of reaction time is attributable to statistical facilitation (Raab, 1962). When the race model's prediction is violated, the speeding up of RTs cannot be attributed to a statistical effect alone but some kind of coactivation must have occurred. To account for violations of the race model's prediction, the coactivation model (Miller, 1982) proposes that the neural activations of both stimuli combine to induce faster responses. Testing the race model inequality is widely used as an indirect behavioral measure of neurophysiological integrative processes underlying RT facilitation (see for example Girard, Pelland, Lepore, and Collignon (2013); but see Otto and Mamassian (2012)). To further investigate multisensory integration differences between ASD and TD, the race model inequality was evaluated (Miller, 1982) using the RMITest software, which implements the algorithm described at length in Ulrich, Miller, and Schröter (2007). This procedure involves several steps. First, cumulative distribution functions (CDFs) of the RT distributions were estimated for every participant and for each condition (visual, auditory and audio-visual conditions). Second, the bounding sum of the two CDFs obtained from the two unimodal conditions (visual and auditory) were computed for each participant. This measure provided an estimate of the boundary at which the race model is violated, given by Boole's inequality. Third, percentile points were determined for every distribution of RT, including the estimated bound for each participant. In the present study, the race model inequality was evaluated at the 5th, 15th, 25th... 95th percentile points of the RT distributions. Fourth, for each percentile, mean RTs from redundant conditions were subtracted from the mean RTs from the bound. If these scores were above 0, it exceeded the race model prediction and therefore supported the existence of an integrative process (Miller, 1982; but see Otto and Mamassian (2012)).



### 2.4.3. Task 2

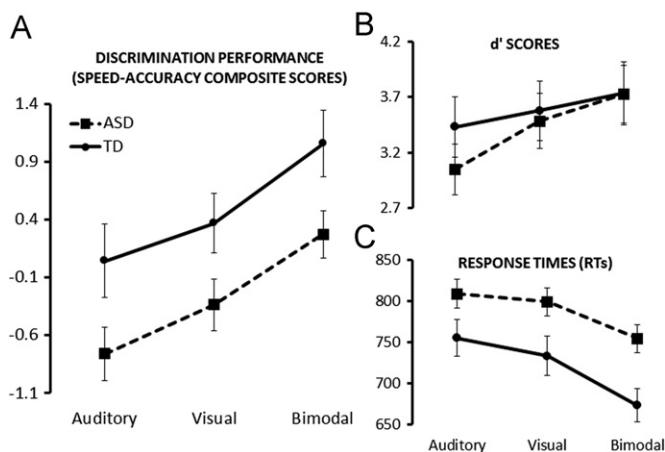
The signal-to-noise ratios, corresponding to the detection thresholds, were analyzed using a repeated measures ANOVA (2 [groups: ASD, TD; between subjects factor]  $\times$  2 [modalities: auditory, visual; within subject factor]). Based on significant *F*-values, Bonferroni post-hoc analyses were performed when appropriate.

## 3. Results

In all the analyses presented in the main manuscript, data obtained for fear and disgust stimuli are collapsed. Results (and related statistics) obtained for each emotion separately are presented in Supplementary material (S Figs. 6–8).

### 3.1. Task 1

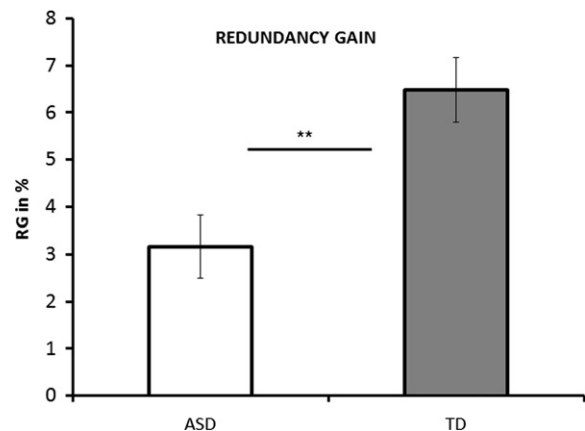
For the SACS (Fig. 2A), we observed a main effect of the factor “group” ( $F(1,48)=5.27$ ,  $p \leq .05$ ,  $\eta^2_{\text{partial}}=.10$ ), revealing superior general performance in the TD group compared to the ASD group. The analysis also yielded a main effect of the factor “modality” ( $F(2,96)=31.82$ ,  $p \leq .0005$ ,  $\eta^2_{\text{partial}}=.61$ ). Post-hoc comparisons demonstrated superior performance with bimodal stimuli compared to visual ( $p \leq .0005$ ) and auditory ( $p \leq .0005$ ) stimuli alone, and superior performance with visual stimuli compared to auditory stimuli ( $p \leq .05$ ). A “modality” by “group” interaction was not evidenced ( $F(2,96)=.082$ ,  $p=.92$ ,  $\eta^2_{\text{partial}}=.002$ ), suggesting that lower performance in the ASD group was generalized across stimulus presentation conditions. For  $d'$  scores (Fig. 2B), we did not observe any significant difference in performance between TD and ASD ( $F(1,48) = .21$ ,  $p=.65$ ,  $\eta^2_{\text{partial}}=.004$ ). However, we observed a main effect of the factor “modality” ( $F(1,48)=12.18$ ,  $p \leq .005$ ,  $\eta^2_{\text{partial}}=.20$ ) with superior performance for bimodal stimuli compared to auditory ( $p \leq .005$ ) but not visual ( $p=.56$ ) stimuli and no difference between visual and auditory ( $p=.1$ ) stimuli. There was no interaction between “group” and “modality” factors ( $F(2,96)=.97$ ,  $p=.38$ ,  $\eta^2_{\text{partial}}=.02$ ). For RTs (Fig. 2C), we observed a main effect of the factor “group” ( $F(1,48)=6.12$ ,  $p \leq .05$ ,  $\eta^2_{\text{partial}}=.11$ ), revealing superior general performance (faster RTs) in TD compared to ASD. It also yielded a main effect of the factor “modality” ( $F(1,48)=70.66$ ,  $p \leq .005$ ,  $\eta^2_{\text{partial}}=.60$ ), with superior performance for bimodal stimuli compared to visual ( $p \leq .0005$ ) and auditory ( $p \leq .0005$ ) stimuli alone and no difference between visual and auditory ( $p=.32$ ) stimuli. There was no interaction between “group” and “modality” factors ( $F(2,96)=1.54$ ,  $p=.22$ ,  $\eta^2_{\text{partial}}=.03$ ).



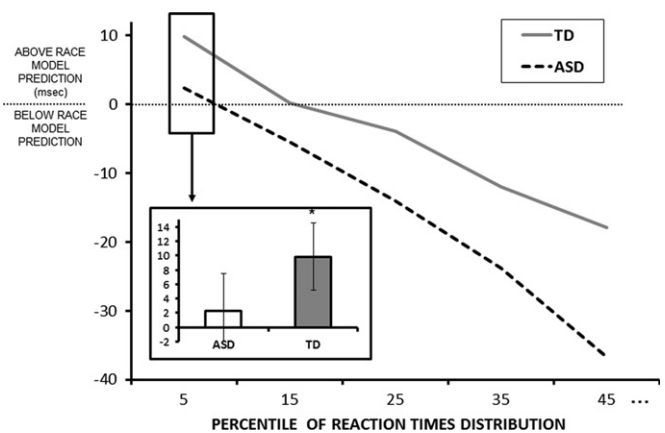
**Fig. 2.** Speed-accuracy composite scores ((A) see Material and methods),  $d'$  scores (B) and mean reaction times (C) for the discrimination of emotional expressions presented auditorily, visually and audio-visually in ASD and TD. In all the figures, error bars denote the standard error of the group.

### 3.2. Multisensory integration

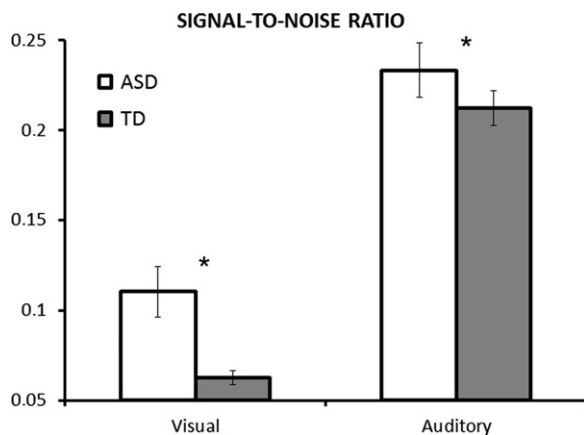
Although ASD ( $t(31)=4.73$ ,  $p \leq .001$ ,  $\eta^2=.42$ ) and TD ( $t(17)=9.43$ ,  $p \leq .001$ ,  $\eta^2=.84$ ) showed a reliable RG, there was a superior multisensory gain in the TD group compared to the ASD group ( $t(48)=-3.21$ ,  $p \leq .005$ ,  $\eta^2=.18$ ) (Fig. 3). To further test for differences in multisensory integration abilities in ASD and TD, we used a one-sampled *t*-test against ‘0’ in order to investigate whether the positive difference between the redundant condition and the probabilistic bound was significant (meaning a violation of the race model prediction) in TD and ASD. For TD, the difference was significant for the fastest 5th percentiles of the RTs distribution ( $t(17)=2.1$ ,  $p \leq .05$ ,  $\eta^2=.21$ ) whereas for ASD, no violation of the race model inequality was found ( $t(31)=.44$ ,  $p=.66$ ,  $\eta^2=.01$ ) (Fig. 4).



**Fig. 3.** Redundancy gain (in percent; see material and methods) for ASD and TD. Error bars denote the standard error of the group. The figure illustrates a superior redundancy gain in TD than in ASD (\*\*:  $p \leq .005$ ).



**Fig. 4.** Race model inequality. Test for violation of the race model inequality (Miller, 1982; Ulrich, Miller & Schröter, 2007). The graph represents the difference in milliseconds (on the Y axis) between the model prediction computed from the RTs of each unisensory counterpart (the model bound) and the RTs obtained in the redundant conditions. Positive values on the graph refer to RTs that were faster than the race model prediction. Negative values on the graph refer to RTs that were slower than the race model prediction. The difference between the bound and the RTs of the redundant condition are computed for each percentile of the RT distribution (on the X axis). For TD, the difference significantly exceeded the race model inequality for the 5th percentiles of the RTs distribution. For ASD, no violation of the race model inequality was found (\*:  $p \leq .05$ ).



**Fig. 5.** Signal-to-noise ratio for an 80% accuracy rate in the discrimination of emotional expressions presented auditorily and visually in ASD and TD. This graphic illustrates the main effect of the factor “group”, suggesting inferior detection thresholds in TD than ASD for both modalities (\*:  $p \leq .05$ ).

### 3.3. Task 2

We observed a main effect of the factor “group” ( $F(1,48)=3.93$ ,  $p \leq .05$ ,  $\eta^2_{\text{partial}}=.08$ ), with lower detection thresholds for the TD group. There was also a main effect for the factor “modality” ( $F(1,48)=159.58$ ,  $p \leq .0005$ ,  $\eta^2_{\text{partial}}=.77$ ), with lower detection thresholds for visual than for auditory stimuli (Fig. 5). A “modality” by “group” interaction was not found ( $F(1,48)=1.54$ ,  $p=.22$ ,  $\eta^2_{\text{partial}}=.003$ ), suggesting lower detection thresholds in the TD group for both visual and auditory modalities.

## 4. Discussion

Alterations in the ability to recognize emotional expressions in ASD is often suggested as a possible source for certain atypical social and communicative behaviors that characterize this population. The first aim of this study was to empirically test this hypothesis by exploring the perception of emotion in autistic individuals using ecological and validated sets of dynamic visual and non-verbal vocal clips of emotional expressions. We found a decreased performance in ASD compared to TD for the recognition of emotion expressions in every condition of stimulus presentation (auditory, visual, bimodal; see Fig. 2). These results suggest the existence of a generalized alteration in the perception of emotion expressions in ASD that is apparent in different sensory channels. Group differences are mainly (but not only) noticeable in their response speed (Fig. 2C). Perceptual decisions involve the accumulation of sensory evidence over time, a process that is corrupted by noise (Gold & Shadlen, 2007). The basic principle is that noisy evidence for a sensory signal is accumulated over time until a criterion is reached and a decision is made (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010). It is possible that auditory and visual estimates of emotional expressions are noisier in ASD leading to the necessity to accumulate more evidence before taking a perceptual decision on the emotional expression displayed. This is partly supported by the observation that ASD also necessitate a higher signal-to-noise ratio than TD for the recognition of unimodal auditory and visual emotion expressions in noise. Pellicano and Burr (2012) recently relied on a Bayesian framework to suggest that altered autistic perception might result from attenuated priors resulting in fewer internal constraints on perception (hypo-priors). The authors suggested that hypo-priors in ASD should impede/improve performance in situations where priors help/bias perceptual

decisions, respectively. It might therefore be hypothesized that in the context of the discrimination of emotion expressions, individuals with ASD might lack priors that typically improve the efficiency of perceptual computations by reducing overall noise or error (e.g. this mouth’s shape means this expression). Overall, this impairment in the extraction of meaningful emotional information might be related to the prominent atypical behavior of ASD in social contexts, by preventing them from engaging in ‘expected’ behaviors, such as quickly and efficiently adjusting to a particular theme in a conversation conveyed by the facial or vocal emotional information originating from the expression of the interlocutor, particularly in situation when the environment is noisy. Our experiment however focused on a subset of emotional expressions, which do not preclude the possibility that the results might be different with other emotional expressions (e.g. happiness, anger). Also, because the present study does not indicate what specific features of the facial and vocal expressions are processed abnormally in ASD during the perception of emotion expression (i.e. changes in the shapes of the eyes for facial expressions or changes in the pitch of the voice for vocal expressions), further research is needed to investigate in more details which are the specific underlying mechanisms of this impairment (Neumann, Spezio, Piven, & Adolphs, 2006; Spezio, Adolphs, Hurley, & Piven, 2007; Song, Kawabe, Hakoda, & Du, 2012).

Our results agree with previous studies pointing toward inferior performance by ASD for the recognition of emotional expressions. Deficits in the recognition of visual emotional expressions were previously found in ASD (Celani, Battacchi, & Arcidiacono, 1999; Kuusikko et al., 2009; Pelphrey et al., 2002; Teunisse & de Gelder, 2001). It was also demonstrated that ASD were markedly impaired in selecting the appropriated facial expression of emotions associated with a vocalization (Hobson, 1986a, 1986b). In addition, ASD were found to have lower performance than TD when asked to match faces on the basis of emotional expressions (Hobson, Ouston, & Lee, 1988), and were shown to be much better for matching corresponding objects than facial expressions (Braverman, Fein, Lucci, & Waterhouse, 1989). These results are also consistent with a recent study by Hubert, Wicker, Monfardini, and Deruelle (2009) measuring electro-dermal response during perception of emotional expressions in ASD. The authors found that autistic persons, unlike TD, do not present any variation of the skin conductance response (SCR) when presented with facial emotional expressions. Because of the important role of the amygdala in the modulation of autonomic response (Bagshaw & Benzie, 1968; Lang, Tuovinen, & Valleala, 1964; Mangina & Beuzeron-Mangina, 1996) and in the processing of emotions expressions (Adolph, 2002; Critchley et al., 2000; LeDoux, 2000), Hubert et al. (2009) attributed their results to a putative dysfunction of this brain region in ASD. This hypothesis is coherent with several studies that have reported structural, functional and connectivity alterations of the amygdala in ASD (Baron-Cohen et al., 1999; Corbett et al., 2009; Critchley et al., 2000; Kleinhans et al., 2008; Monk et al., 2010; Munson et al., 2006; Murphy et al., 2012; Nacewicz et al., 2006; Pelphrey, Morris, McCarthy, & Labar, 2007; Schumann, Barnes, Lord, & Courchesne, 2009; Schumann et al., 2004; Shalom, 2009; Stanfield et al., 2008; Weng et al., 2011). Such alteration in the function of the amygdala may also, at least in part, explain the generalized (amodal) deficit observed in ASD in the current study, since this core brain structure in affective processing receives input from all sensory modalities (LeDoux, 2007; Macdonald, 1998) and has been demonstrated to be involved in the processing of both visual (Costafreda, Brammer, David, & Fu, 2008) and auditory (Fecteau, Belin, Joanne, & Armony, 2007) emotional expressions. This hypothesis of a general alteration in the

processing of emotional expressions may also relate to the observation that individuals with ASD show reduced processing of affective meaning of actions (Grezes, Wicker, Berthoz, & de Gelder, 2009) and body postures (Hadjikhani et al., 2009).

Aside from atypicalities in emotional brain centers, some neuroimaging studies in ASD also showed alterations in sensory-specific brain regions dedicated to the processing of facial or vocal information. For example, a reduction of activity of the fusiform face area (FFA) has been found in ASD during the discrimination of different faces (Critchley et al., 2000; Hubl et al., 2003; Pierce, Muller, Ambrose, Allen, & Courchesne, 2001; Schultz, 2005). However, a recent meta-analysis (Samson, Mottron, Soulieres, & Zeffiro, 2012) suggested that these results depend on particular task characteristics and are not explained by a generalized disruption of the mechanisms of the fusiform gyrus or by a reduced face expertise (Hadjikhani et al., 2004; Hadjikhani, Joseph, Snyder, & Tager-Flusberg, 2007; Pierce, Haist, Sedaghat, & Courchesne, 2004). It has also been hypothesized that this hypoactivation of FFA results from diminished gaze fixation during face processing in autism (Dalton et al., 2005) or from a slight displacement of the face activation region (Scherf, Luna, Minshew, & Behrmann, 2010). A study involving only five ASD individuals has also suggested that ASD failed to activate superior temporal sulcus (STS), a voice-selective region, in response to vocal sounds, whereas a normal pattern of brain activation is present in response to non-vocal sounds (Gervais et al., 2004). Altogether, these results suggest atypical cortical processing of socially relevant visual and auditory information in ASD and again may be related to our observation of a generalized alteration in the processing of emotional expression irrespective of the sensory modality conveying such information.

One might wonder if the alteration observed here for the discrimination of emotional expressions reflect a general deficit in the processing of any sensory/perceptual information in ASD. Previous results from our team and from several other groups strongly argue against such interpretation. Brochu-Barbeau et al. (2013) recently suggested that when ASD are matched with control participants on the basis of Wechsler scores (like here), this might result in the ASD being superior in various perceptual domains. Actually, several participants from the present study were enrolled in a recent experiment demonstrating faster visual-search abilities in ASD, despite reduced multisensory integration (Collignon et al., 2012). Therefore, such dissociation between the presence (in comparison with a Wechsler matched control group) of diminished processing of social information and preserved or even enhanced processing of non-social stimuli (Bertone, Mottron, Jelenic, & Faubert, 2005; Caron, Mottron, Berthiaume, & Dawson, 2006), which is especially evident for visuo-spatial processing (Collignon et al., 2012; Jolliffe & Baron-Cohen, 1997; Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Pellicano, Gibson, Maybery, Durkin, & Badcock, 2005; Shah & Frith, 1983) and for pitch perception (Bonnell et al., 2010; Jones et al., 2009), may represent a behavioral marker for ASD and may explain the classical observation of an avoidance of socially complex environment concomitant with an enhanced investment in restricted domain of expertise in ASD.

It is worth noting here that all the participants of the current study were late adolescents and young adults, between 15 and 27 years. Many studies suggested an improvement in emotional recognition during the course of development in TD and ASD children (Lindner & Rosen, 2006; Wright et al., 2008). Moreover, Smith, Montagne, Perrett, Gill and Gallagher (2010) reported a significant relationship between age and accuracy at identifying the emotional expression of disgust in ASD. A meta-analysis by Stanfield et al. (2008) also demonstrated that as age increased the

volume difference of the amygdala between ASD and TD decreased. Therefore, it would be interesting to carry out further research to investigate whether differences in the perception of multisensory emotion expressions between ASD and TD are amplified during childhood and reduced in older adults.

The second main objective of the present experiment was to investigate the ability to integrate audio-visual emotional expressions in ASD. The results obtained in the present study support our previous findings (Collignon et al., 2008, 2010) by showing that the information from the visual and auditory sensory modalities interact to produce a redundancy gain, which is expressed by a significant reduction in RTs in the bimodal condition when compared to the best modality. However, even if a RG was found in both groups, it was reduced in the ASD compared to TD group. Consistently with previous studies (Collignon et al., 2008, 2010), we found that in TD, for the fastest latencies (percentiles) of the RT distributions, the RT probability in the bimodal condition exceeded the probabilistic sum of the RT observed in the auditory or visual unisensory conditions, suggesting that signal integration occurred (Fig. 4; Miller, 1982; but see Otto and Mamassian (2012)). This was however not observed in ASD. These results therefore indicate that in addition to a general alteration in the recognition of emotions, individuals with ASD also present altered ability to integrate separate sensory representations of the emotional expressions. It is important here to understand that this result is not a direct outcome of the unimodal inferiority in ASD. In contrast, according to the "inverse effectiveness" principle, a basic concept in multisensory integration stating that the multisensory gain is inversely proportional to the saliency of unisensory signals (Stein & Meredith, 1993), one may have predicted greater integration in ASD on the basis of their inferior performance in unisensory conditions. We therefore postulate that ASD might present a specific alteration in the integration of socially-contingent information coming from separate auditory and visual modalities.

Because the combination of multiple sensory inputs into a single percept requires the integration of different sensory areas of the brain, the reduced MSI in ASD is coherent with models suggesting reduced communication between functionally specialized brain regions (Belmonte et al., 2004; Brock, Brown, Boucher, & Rippon, 2002; Liu, Cherkassky, Minshew, & Just, 2011; Rippon, Brock, Brown, & Boucher, 2007; Schipul, Keller, & Just, 2011), as exemplified by altered anatomical and functional inter-regional connectivity (Cherkassky, Kana, Keller, & Just, 2006; Thomas, Humphreys, Jung, Minshew, & Behrmann, 2011; Weinstein et al., 2011). Supporting this hypothesis, Hall et al. (2003) found a decrease in the activity of the right fusiform region and a reduced frontal activation in ASD when congruent prosodic content was added to emotional facial stimuli. Also, an electroencephalographic study, measuring event related potentials (ERPs) in response to cross-modal presentation of emotional expressions in ASD, suggested impaired functional connectivity between the fusiform gyrus and STS, which is involved in MSI (Magnée, de Gelder, van Engeland, & Kemner, 2008). Finally, several evoked potential studies have demonstrated that ASD present delayed latencies of the N170 face-sensitive component to faces compared to TD (McPartland, Dawson, Webb, Panagiotides, & Carver, 2004; O'Connor, Hamm, & Kirk, 2005). This delay in processing facial information during social interactions could lead to an inaccurate association between facial expressions and the auditory information coming from a person's voice (O'Connor, 2007).

Interestingly, MSI deficit in ASD does not appear to be selective to complex social stimuli. In a recent study, we showed that ASD do not benefit from the presence of a typically advantageous temporally relevant tone during a complex visual search task



(Collignon et al., 2012). Along the same lines, a recent electroencephalographic study demonstrated that ASD children do not automatically combine sensory inputs early in the processing hierarchy as efficiently as TD individuals (Russo et al., 2010; but see Russo et al. (2012)). Also, Brandwein et al. (2012) recorded high-density electrophysiology during a simple audio–visual task and showed reduced behavioral facilitation and altered early neurophysiological processing of multisensory stimuli in children with ASD when compared to TD. Reduced MSI abilities might therefore be grounded on impairments in neural communication across distant brain systems that generalize across cognitive domains (i.e. social versus non-social).

Previous studies reported that persons with classic autism (AUT) and Asperger's syndrome (ASP), two sub-populations in the broad ASD, might differ in terms of perceptual skills (Bonnel et al., 2010; Mazefsky & Oswald, 2007; Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2000; Sahyoun, Soulières, Belliveau, Mottron, & Mody, 2009). As individuals with AUT have developmental communication/language impairments whereas persons with ASP do not exhibit language delay or disruption during development (see Section 2.1), one might have expected that AUT might be associated with more detrimental effects when perceiving emotions (Mazefsky & Oswald, 2007). Interestingly, we did not find any significant differences between the AUT and ASP sub-groups for the perception and MSI of emotion expressions (see SFigs. 2–5). In contrast, our results suggest that the history of language development in the ASD population has no significant impact on the atypical perception of emotional expressions observed in this population.

In conclusion, the data presented here provides strong evidence that alterations in the processing of emotion expressions is a prominent perceptual feature of ASD and that such disruption is not associated to a specific sensory modality. This difficulty was manifested during the perception of visual and auditory emotional expressions and suggests noisier amodal perceptual estimates of emotional expressions in ASD. Finally, these results compellingly demonstrate joint alteration in the perception and the integration of multisensory emotion expression in ASD.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.neuropsychologia.2013.02.009>.

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