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# What Makes the Detection of Movement Different Within the Autistic Traits Spectrum? Evidence From the Audiovisual Depth Paradigm

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## Abstract

Atypical sensory processing is now considered a diagnostic feature of autism. Although multisensory integration (MSI) may have cascading effects on the development of higher-level skills such as socio-communicative functioning, there is a clear lack of understanding of how autistic individuals integrate multiple sensory inputs. Multisensory dynamic information is a more ecological construct than static stimuli, reflecting naturalistic sensory experiences given that our environment involves moving stimulation of more than one sensory modality at a time. In particular, depth movement informs about crucial social (approaching to interact) and non-social (avoiding threats/collisions) information. As autistic characteristics are distributed on a spectrum over clinical and general populations, our work aimed to explore the multisensory integration of depth cues in the autistic personality spectrum, using a go/no-go detection task. The autistic profile of 38 participants from the general population was assessed using questionnaires extensively used in the literature. Participants performed a detection task of auditory and/or visual depth moving stimuli compared to static stimuli. We found that subjects with high-autistic traits overreacted to depth movement and exhibited faster reaction times to audiovisual cues, particularly when the audiovisual stimuli were looming and/or were presented at a fast speed. These results provide evidence of sensory particularities in people with high-autistic traits and suggest that low-level stages of multisensory integration could operate differently all along the autistic personality spectrum.

**Keywords**

multisensoriality, depth movement, personality traits, autism spectrum disorder, psychophysics

**1. Introduction**

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by (i) deficits in social communication/interaction and by (ii) repetitive and restricted behaviors. Within this second group of symptoms, atypical sensory processing is now considered a diagnostic feature of ASD (APA, 2013). This is typically the case when individuals avoid certain sensory stimuli (e.g., averting certain noises or textures) and seek out sensory experiences through stimulatory behaviors (e.g., stimulating their eyes with their hands). Reports estimate that atypical reactivity to sensory inputs is prevalent in 69–95% of the ASD population (Hazen *et al.*, 2014), confirming that sensory abnormalities concern the vast majority of individuals with ASD. Given the significance of sensory symptoms, growing evidence suggests that these may have detrimental effects on higher-order processes such as social interaction and communication (Ayres and Tickle, 1980; Robertson and Baron-Cohen, 2017). Thus, disturbance in the processing of basic visual or auditory information may contribute to the emergence and/or to the intensity of deficits found at the higher level, such as socio-communicative functioning (Marco *et al.*, 2011). Along this line, previous studies highlighted a relationship between sensory-processing particularities and communication difficulties (Lane *et al.*, 2010), social responsiveness (Baker *et al.*, 2008; Hilton *et al.*, 2007), and maladaptive behaviors (Chen *et al.*, 2009).

Although unisensory processing has been extensively studied in ASD and is increasingly characterized (for a review, see Ben-Sasson *et al.*, 2009), there is a lack of understanding regarding the processing of multisensory stimuli within the ASD (for a review, see Feldman *et al.*, 2018). Multisensory integration (MSI) provides the merging of sensory inputs originating from multiple sensory modalities to build a unified and coherent internal representation of our external environment. MSI provides a crucial behavioral benefit by enabling incoming information to be processed more quickly and effectively. This performance enhancement has been referred to as ‘multisensory facilitation’ (Stein, 2012; Stein and Meredith, 1993). Given the predominant socio-communicative difficulties in ASD, most research investigations have used complex social stimuli to explore multisensory integration in the disorder. By assessing the responses of ASD participants to auditory (voice), visual (face), or audiovisual speech (voice and face) stimuli, alterations in MSI have been revealed. Studies reported difficulties in unifying voices and faces to the same emotion (e.g., Loveland *et al.*, 1995; O’Connor, 2007), and

reduced multisensory facilitation in recognition tasks of emotions within the ASD (Xavier *et al.*, 2015). In addition, ASD participants demonstrated atypical sensitivity to the McGurk illusion (Fuxe *et al.*, 2015; Woynaroski *et al.*, 2013), and a reduced benefit from lipreading in auditory speech discrimination tasks (Newman *et al.*, 2021; Smith and Bennetto, 2007). However, to ascertain whether impairment of MSI within ASD is related to a basic perceptual difference and not to differences in social abilities, stimuli void of social content must be used. Three approaches to study the MSI of nonsocial information in ASD have been used and have produced mixed results. First, in the temporal processing approach, the temporal range within which stimuli from different sensory modalities are perceived as simultaneous has been investigated as a ‘Temporal Binding Window’ (TBW). This TBW was found to be either significantly larger in ASD participants (Kwakye *et al.*, 2011; Noel *et al.*, 2018; Woynaroski *et al.*, 2013) or similar to that of control participants (Stevenson *et al.*, 2018). Second, the ‘fusion illusion’ refers to the perception of multiple flashes when the display of a single flash is associated to multiple auditory tones. This illusion was reported to be either weakened in ASD (Foss-Feig *et al.*, 2010; Stevenson *et al.*, 2014) or similar to that of control participants (Keane *et al.*, 2010; Stevenson *et al.*, 2018). Third, controversial results can also be found regarding multisensory facilitation, which has been demonstrated to be either intact (e.g., de Boer-Schellekens *et al.*, 2013; Stefanou *et al.*, 2020) or degraded in ASD (e.g., Ainsworth *et al.*, 2021; Brandwein *et al.*, 2013).

Most of the previous studies focused on static sensory inputs. The stimuli to which our everyday activities expose us, however, are mainly dynamic. Multisensory moving information may therefore be a more ecological construct, reflecting naturalistic sensory experiences given that our environment involves moving stimulation of more than one sensory modality at a time. Depth movement in particular is a crucial signal, as it informs about a distancing (receding) object which one must decide to pursue or to stay away from for safety. More importantly, it informs about potential threats such as approaching (looming) objects which one must decide either to avoid or confront. Thus, unsurprisingly, preferential responsiveness to looming signals has been previously demonstrated in the general population (e.g., Maier *et al.*, 2008; Neuhoff, 1998, 2001). In addition, multisensory facilitation increased specifically for looming signals (Cappe *et al.*, 2009). Depth movement is commonly involved in social interactions in which a person approaches another one to interact or avoids social contact by distancing themselves from others, rendering this movement interesting within ASD where social functioning is one of the main areas of difficulty. The biological motion represents human actions using displays of moving light points (Blake and Shiffrar, 2007; Johansson,

1973). It transmits the information of a body in walking motion facing the participants, which in real life is expressed by a looming or receding movement. At an early age, a preference for human biological movement is not observed in ASD compared to control subjects (Annaz *et al.*, 2012; Falck-Ytter *et al.*, 2013). In addition, the recent meta-analysis by Todorova *et al.* (2019) based on 52 studies confirmed the presence of difficulties in recognizing biological movement in ASD (this includes global body movement, facial or eye movement displayed with light points). Centelles *et al.* (2013) studied the recognition abilities of a ‘social movement’ which involves interaction with other individuals (e.g., playing football), to a ‘non-social movement’ which constituted any human movement without social interaction. (e.g., walking, stepping forward or backward). Results showed that ASD subjects are less successful at categorizing both types of movement and exhibited a slower response speed for social movement. It therefore seems that there are difficulties for ASD subjects perceiving movement that transmits social information, either directly (movement involving social interaction) or indirectly (movement involving at least one person).

However, to our knowledge, only one study focused on depth movement in ASD and used exclusively looming complex visual stimuli (Hu *et al.*, 2017). The authors found a lack of behavioral reactivity to aversive looming signals in ASD participants associated with abnormality (weak connectivity) in a neuronal pathway involved in looming-evoked defensive responses (superior colliculus–pulvinar–amygdala). Other studies focused on visual radial movements (expansion/contraction) and demonstrated identification difficulties in ASD (Bertone *et al.*, 2003). Using an immersive installation to focus on visuo-postural tuning in ASD, postural hyporeactivity to expansion movement was also found (Gepner and Mestre, 2002; Greffou *et al.*, 2012). According to the temporospatial processing hypothesis (Gepner and Féron, 2009), such difficulties in movement processing observed in ASD are the consequence of impairment in integrating information across time and space, leading to the perception of the environment changing too rapidly. In support of this hypothesis, previous studies demonstrated that ASD participants recognize and spontaneously imitate emotional and non-emotional facial expressions better when the presentation speed is slowed down (Lainé *et al.*, 2008, 2011; Meiss *et al.*, 2015; Tardif *et al.*, 2007). In addition, autobiographical reports from individuals with ASD describe a world that is ‘moving too fast’ (Grandin, 1995; Williams, 1999).

The dimensional model of ASD proposes that autistic characteristics are distributed on a continuum over clinical and general populations (Baron-Cohen, 1995; Hobson, 1992). Thus, as a spectrum disorder, specific traits associated with ASD are not only found in individuals with a clinical diagnosis but are also found in the general population. In order to assess the degree

of autistic traits in any individual adult, psychometric tools were developed such as the ‘Autism Spectrum Quotient’ (AQ; Baron-Cohen *et al.*, 2001). In addition, the sensory profile of an individual can be assessed using the Adolescent/Adult Sensory Profile (AASP; Brown and Dunn, 2002). Several similarities were demonstrated between ASD and the high-autistic personality, such as cognitive processing (e.g., Almeida *et al.*, 2010; Bayliss and Tipper, 2005; Grinter *et al.*, 2009a, b), sensory processing in several modalities (e.g., Clark *et al.*, 2013; Mayer, 2017; Takayama *et al.*, 2014), multisensory integration (e.g., Donohue *et al.*, 2012; van Laarhoven *et al.*, 2019; Yaguchi and Hidaka, 2018) and impaired responses to social information (e.g., Stewart and Ota, 2008; Voos *et al.*, 2013). Moreover, recent studies reported similar neurobiological, neuroanatomical, and neurofunctional issues between subjects with ASD and those without ASD but with high-autistic traits (Alemany *et al.*, 2021; Kondo and Lin, 2020; von dem Hagen *et al.*, 2013).

Given the predominance of moving multisensory information in our environment and the continuum distribution of autistic particularities in the general population, it remains crucial to characterize the MSI of dynamic information within the autistic spectrum. According to growing evidence in the literature, sensory atypicalities could have a cascade influence and contribute to overall difficulties within the autistic spectrum, encouraging the use of simple non-social stimuli in present and future studies. In this framework, the present study aimed to explore the multisensory integration of depth cues in the autistic traits spectrum, using a go/no-go detection task.

## 2. Material and Method

### 2.1. Participants

Forty-three young adults (10 males) between the ages of 18 and 25 years (mean = 22.21 years, SD = 1.9) participated in this study. All participants had normal hearing and normal or corrected-to-normal vision and had no history of neurological or psychiatric illness. Of these 43 participants, five were excluded for having insufficient correct responses in the behavioral experiment (see section 2.5. *Data Analysis*), leaving 38 participants (10 males) with a mean age of 22.23 (SD = 1.95). According to a standardized handedness questionnaire (Oldfield, 1971), the majority ( $n = 34$ ) were right-handed. The study conformed with the Code of Ethics of the World Medical Associations (Declaration of Helsinki) and was approved by the local research ethics committee (Comité de Protection des Personnes Sud Méditerranée III, Avis N° 2020-A03056-33). All participants provided written informed consent and received monetary compensation. Participants took part in the study in a single two-hour session. First, the autistic traits and sensory profiles of the participants

were measured using two questionnaires in a paper–pencil format. Second, they performed a computerized behavioral experiment.

## 2.2. *Autistic Traits and Sensory Profiles*

The AQ is a validated 50-item self-report questionnaire for identifying the degree to which an adult presents autistic traits. The instrument measures five dimensions (10 items each): Social skill (e.g., “I find it hard to make new friends”), Attention switching (e.g., “I frequently get so strongly absorbed in one thing that I lose sight of other things”), Attention to detail (e.g., “I often notice small sounds when others do not”), Communication (e.g., “I enjoy social chit-chat”) and Imagination (e.g., “I find making up stories easy”) (Baron-Cohen *et al.*, 2001). Each response is scored 0 or 1, a higher score indicates higher levels of autistic behavior. Previous studies found a high internal consistency for the overall AQ score with a Cronbach’s alpha between 0.72 and 0.79 (Hoekstra *et al.*, 2008; Ruzich *et al.*, 2015; Stevenson and Hart, 2017). We used the French version of the AQ (Kempnaers *et al.*, 2017).

In order to obtain an assessment of the sensory processing of the participants, AASP (Brown and Dunn, 2002) was administered. This self-reported questionnaire includes 60 items, each describing a behavior related to an everyday sensory experience that is assessed with a five-point Likert scale. Items are scored by sensory factor: taste/smell, movement, visual, tactile, activity level and auditory processing (e.g., “I stay away from noisy settings”); and behavior profile: low registration, sensory sensitivity, sensation-avoiding and sensation-seeking (e.g., “I work on two or more tasks at the same time”). The total score ranges from 60 to 300 with higher scores indicating a higher sensory sensitivity. Brown and Dunn (2002) found that the questionnaire presented a moderate Cronbach’s alpha ( $\alpha = 0.64$ ). We used the French version of the AASP (Brown and Dunn, 2006).

## 2.3. *Behavioral Experiment*

The stimuli and procedure were adapted from the previous study by Cappe *et al.* (2009). The stimuli were visual, auditory, or audiovisual and could be dynamic or static. In dynamic conditions, stimuli varied in movement (looming or receding) and in presentation speed (fast or slow). To induce the perception of movement, auditory stimuli changed in volume and visual stimuli changed in size to give the impression of either looming or receding. The slow presentation was based on the original stimuli from Cappe *et al.* (2009). The speed presentation of the stimuli was multiplied by 2 for the fast condition. Static information was added at the end of each fast stimulus so that all stimuli had the same duration of 500 ms. All stimuli were initially of the same size/intensity to ensure that participants used dynamic information to perform the task (see Fig. 1). The audiovisual condition consisted of the auditory and

visual stimuli presented simultaneously and was always congruent in speed and in movement. In static conditions, the size and volume of static stimuli were constant.

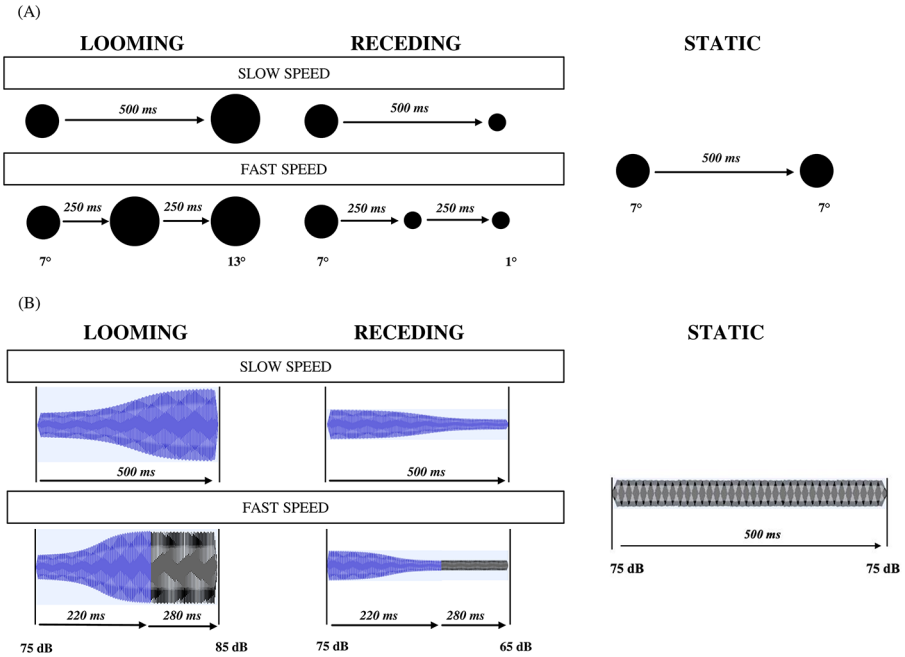
The visual stimuli were presented in the center of the screen at a viewing distance of  $\sim 80$  cm from the eyes of the participants and were generated with MATLAB Version: 9.13.0 (R2022b) (MathWorks, 2022) and the Psychophysics Toolbox (Brainard, 1997). The stimuli consisted of a disk that was either white on a black background or black on a white background, randomized across blocks of trials, and were presented with a 50% contrast. They were symmetrically expanded from  $7^\circ$  to  $13^\circ$  diameter (looming condition) or contracted from  $7^\circ$  to  $1^\circ$  diameter (receding condition). In the slow condition, the expansion and contraction lasted for 500 ms. In the fast condition, the movement lasted for 250 ms (i.e., acceleration  $\times 2$  of the slow condition). Then static visual information was added at the end of each visual fast stimulus for the other 250 ms. In static conditions, the size of visual stimuli was constant (see Fig. 1A).

The auditory stimuli differed by 2 dB of those used in the original study of Cappe *et al.* (2009). They were presented binaurally over insert earphones (Etymotic model ER3XR; Etymotic, 2023), were 1000-Hz tones composed of a triangular waveform and generated with Adobe Audition software (Adobe Systems Inc., San Jose, CA, USA). To prevent the occurrence of clicks, 10 ms onset and offset ramps composed the auditory stimuli which were sampled at 44.1 kHz. The intensity of the tones either increased (looming condition) or decreased (receding condition) by 10 dB approximately linearly during 500 ms in the slow condition. In the fast condition, an acceleration  $\times 2$  was not effective in perceiving faster movement. In order to enhance perception of fast stimuli, the movement duration was set to 220 ms for auditory conditions. Static auditory information was added at the end of each fast auditory stimulus. In static conditions, the volume of auditory stimuli was constant (see Fig. 1B).

#### 2.4. Procedure

Participants sat in a silent and dimly lit room to complete a go/no-go detection task validated in a sample of young adults (Cappe *et al.*, 2009). When a moving stimulus appeared (go condition), participants were instructed to press a response button with their dominant hand, and conversely, when a static stimulus (no-go condition) was presented, participants were told not to press it. Participants had to respond to the stimulus as fast and as accurately as they could. Reaction times in go conditions and accuracy in go as well as in no-go conditions were recorded and analyzed.

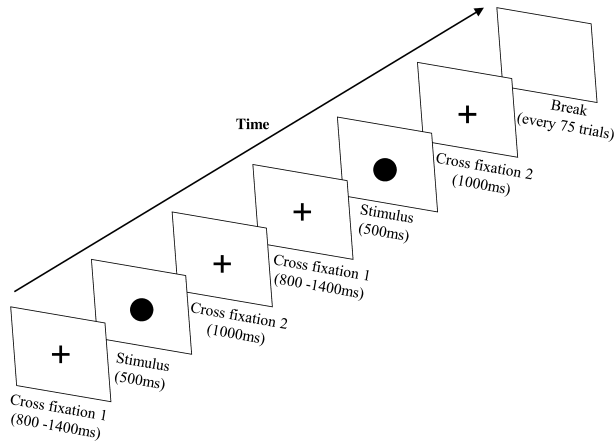




**Figure 1.** Experimental stimuli. (A) The movement of visual stimuli symmetrically expanded (looming) or contracted (receding) over the duration of 500 ms in the slow speed and 250 ms in the fast speed conditions. (B) In the auditory modality, the perception of movement was induced by rising-intensity (looming) or falling-intensity (receding) complex tones during 500 ms in the slow speed and 220 ms in the fast speed. Static information was added at the end of fast visual and auditory stimuli so that all experimental conditions had a duration of 500 ms.

There were 15 experimental stimulations varying in modality, movement and speed. Each stimulus was presented 50 times and was randomly intermixed within 10 blocks of 75 trials each. After a cross fixation time (cross fixation 1) varying between 800 and 1400 ms (randomly assigned in each trial), a stimulus was presented for 500 ms during which participants' responses were recorded. Another period of cross fixation of 1000 ms (cross fixation 2) was added to record participants' responses after the stimulus presentation (see Fig. 2). Thus, participants could respond both during the stimulus presentation and the fixation cross 2, leading to the recording of responses from the presentation of stimuli to 1500 ms post stimulus.

All stimuli were presented using EventIDE software version 2017.1.2 (Okazolab, London, UK). Go conditions (i.e., dynamic stimuli) occurred 80% of the time.



**Figure 2.** Experimental paradigm. Example of two successive trials.

## 2.5. Data Analysis

### 2.5.1. Autistic Traits and Sensory Profiles

We examined the relationship between the AASP and the AQ scores using Pearson correlations. As the scores of the two questionnaires correlated positively (see section 3.1. *Autistic Traits and Sensory Profiles*), we used the AQ only to explore the relationship between autistic traits and responses to the behavioral experiment. To do so, we split our population into two groups according to the median score of the AQ, resulting in a high-AQ group (AQ+,  $n = 19$ , male = 7) and a low-AQ group (AQ-,  $n = 19$ , male = 3). As no gender effect was found on reaction times (males: mean = 526.99 ms, SD = 159.56 ms; females: mean = 535.27 ms, SD = 171.31 ms;  $Z = -1.52$ ,  $p = 0.129$ ), on percentage of correct responses in go conditions (males: mean = 0.86%, SD = 0.17%; females: mean = 0.87%, SD = 0.15%;  $Z = -1.19$ ,  $p = 0.235$ ), as well as on percentage of correct responses in no-go conditions (males: mean = 0.87%, SD = 0.12%; females: mean = 0.85%, SD = 0.14%;  $Z = 0.612$ ,  $p = 0.541$ ), this variable was not included in the analysis.

### 2.5.2. Outlier Rejection Process

In the analysis of reaction times (RTs), RTs occurring earlier than 150 ms post stimulus onset were considered as anticipated. RTs occurring later than 1000 ms post stimulus onset were interpreted as misses. Thus, only responses with RTs between 150 ms and 1000 ms were included. The accuracy analysis (incorrect and correct responses, see below) was based on the overall responses, including responses with RTs earlier than 150 ms and later than 1000 ms post stimulus. For both the analysis of RTs and accuracy, participants with less than 10 responses per go condition were excluded. This criterion led

to the exclusion of the data of five participants, giving a final analyzed sample of 38 participants. In total, the mean and the standard deviation of trial numbers per condition included in the RT analysis were 40.94 ( $\pm 6.05$ ) for the AQ- group and 43.67 ( $\pm 4.7$ ) for the AQ+ group. The accuracy analysis was based on 43.04 trials ( $\pm 8.05$ ) per condition for the AQ- group and 45.06 trials ( $\pm 6.29$ ) per condition for the AQ+ group.

2.5.3. *Generalized Linear Mixed-Effects Models*

Accuracy and RTs for go conditions were analyzed using generalized linear mixed-effects models (GLMMs) where the modality (A: auditory vs V: visual vs AV: audiovisual), the movement (L: looming vs R: receding), the speed (F: fast vs S: slow) and the AQ group (AQ+ vs AQ-) were considered as fixed effects while the subject parameter was considered as a random effect. Accuracy for no-go conditions was analyzed using another GLMM where the modality (A: auditory vs V: visual vs AV: audiovisual) and the autistic personality group (AQ+ vs AQ-) were considered as fixed effects while the subject parameter was considered as a random effect.

While the GLMM of RTs was computed using a gamma distribution family and an identity link function, as implemented in the *lme4* library in R software, the GLMMs of correct responses (for go and no-go conditions) were computed with a binomial family and a logit link function, as also established in the *lme4* library in R software (Bates *et al.*, 2015). The binary response variable was the accuracy of the response whereby 1 = correct response and 0 = incorrect response. Mixed models provide more accurate estimates than those based on second-level statistics (the scores of each subject) because they take into account the number of trials used to compute each score.

Nakagawa’s  $R^2$  was used to assess the model’s goodness of fit (see Table 1). To test the GLMM statistically, Wald chi-squared tests were used and *post-hoc* tests were subsequently conducted using Wilcoxon rank tests with a False Discovery Rate correction (FDR; Benjamini and Hochberg, 1995). Results were considered significant at  $p < 0.05$ . Because the quality of the model of no-go conditions was weak ( $R^2 = 0.05$ , see Table 1), results focused on models of go conditions.

**Table 1.** Generalized linear mixed-effects models for go conditions and no go conditions

| Conditions       | Models  | R2   |
|------------------|---|------|
| Go conditions    | Reaction times ~ Modality × Movement × Speed × AQ Group | 0.89 |
|                  | Accuracy ~ Modality × Movement × Speed × AQ Group       | 0.17 |
| No go conditions | Accuracy ~ Modality × AQ Group                          | 0.05 |

#### 2.5.4. Race Model Analysis

Our psychophysical index of MSI was based on Miller's Race Model (Miller, 1982), a stringent and established behavioral metric of MSI based on RTs. According to this model, a behavior benefit can occur because the multisensory stimulus is composed of two signals to trigger a response (e.g., auditory and visual), and the fastest signal wins. This race between the two unisensory signals can lead to faster RT to multisensory stimuli because of probability summation. The model is tested as follows: for any latency  $t$ , predicted cumulative probability (CP) values of multisensory stimuli ( $TR_{AV}$ ) are calculated by summing the CP of each unisensory stimulus ( $TR_A$  and  $TR_V$ ) from which the expression of their joint probabilities is subtracted:

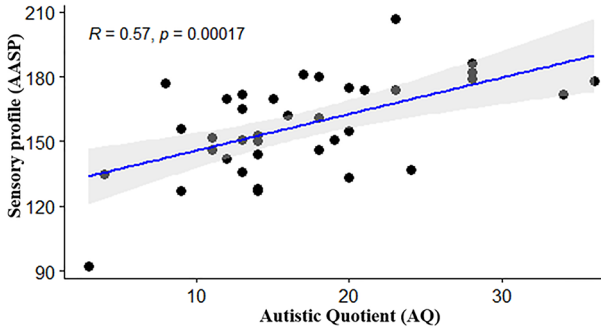
$$\text{Predicted CP} \cdot (TR_{AV} \leq t) = \text{CP} \cdot (TR_A \leq t) + \text{CP} \cdot (TR_V \leq t) - \text{CP} \cdot (TR_A \leq t) * \text{CP} \cdot (TR_V \leq t)$$

A 'Miller Inequality' value is calculated by subtracting the value predicted by the race model from the CP of the participants' RTs to the AV stimulus. Positive values represent the violation of the race model and suggest that sensory inputs interacted during processing to facilitate RT. To compare the Miller inequality values between AQ groups, non-parametric permutation tests (10 000 permutations) based on the  $t$ -statistic were computed. The same statistical tests were used to test the significance of the model violation in each AQ group.

### 3. Results

#### 3.1. Autistic Traits and Sensory Profiles

The global score of the AQ ranged from 3 to 36 with a mean of 16.94 (SD = 7.41) and a median of 14. The mean score of the AASP was 157.62 (SD = 21.93) with a range from 92 to 207 and a median of 155. In agreement with the literature (Horder *et al.*, 2014; Mayer, 2017), the global scores of these two questionnaires were positively correlated ( $r = 0.57$ ,  $p < 0.001$ ; see Fig. 3), meaning that the more the participants present autistic characteristics, the more they have sensory particularities. These results support the dimensional model of ASD which proposes that both spheres of autistic characteristics (impairment in social interaction and atypical behaviors including sensory peculiarities) extend in the general population. Because the AQ has been extensively used in the literature to study autistic personality traits and assesses more specific personality dimensions of ASD than the AASP does, which only focuses on sensory functioning, we decided to use only the AQ to explore the relationship between autistic traits and responses to the behavioral experiment. Additional analysis with the AASP is explored in the Supplementary Material.



**Figure 3.** Correlation representation between the Autism Spectrum Quotient (AQ) and the sensory profile (AASP). The regression line and the confidence intervals are represented by the solid line and shaded, respectively.

### 3.2. Generalized Linear Mixed-Effects Models

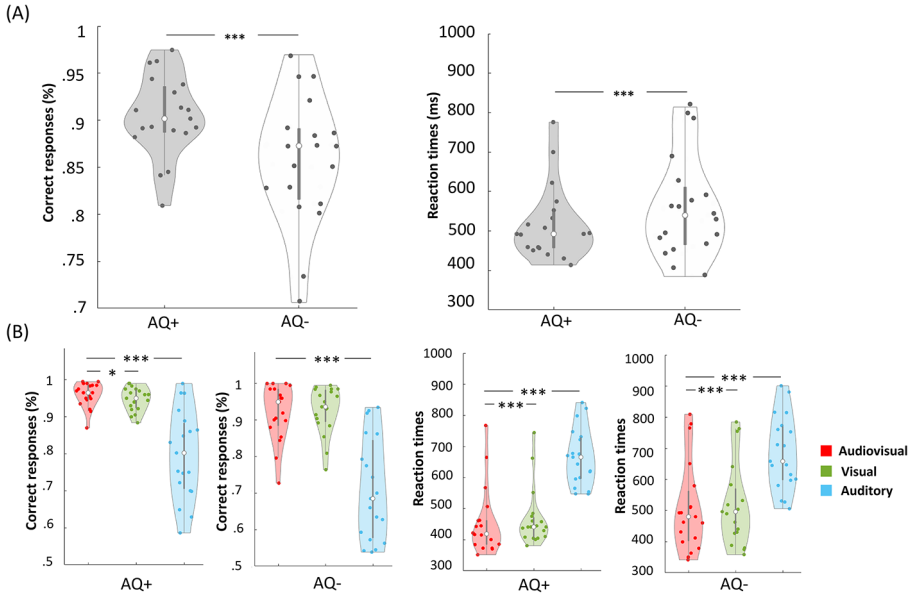
#### 3.2.1. Accuracy

The mean performance reached 88% in the go conditions (SEM = 0.008%) and 85% in the no-go conditions (SEM = 0.02%).

A significant main effect of the group was found, owing to the higher accuracy in the AQ+ compared to the AQ- group ( $Z = 10.41$ ,  $p < 0.0001$ ; see Fig. 4A). A significant main effect of the modality,  $\chi^2(2) = 1141.88$ ,  $p < 0.001$ , showed a lower accuracy in the auditory modality than in either the audiovisual ( $Z = -29.24$ ,  $p < 0.0001$ ) or the visual ( $Z = -28.47$ ,  $p < 0.0001$ ) modality.

A significant Modality  $\times$  Group interaction,  $\chi^2(2) = 6.58$ ,  $p < 0.05$ , revealed that only the AQ+ group had a higher accuracy in the audiovisual modality compared to the visual modality ( $Z = 2.54$ ,  $p = 0.01$ ; see Fig. 4B).

A significant main effect of the movement revealed a higher accuracy in the looming conditions compared to the receding conditions ( $Z = 19$ ,  $p < 0.0001$ ). This result is possibly attributable to a significant Modality  $\times$  Movement interaction,  $\chi^2(2) = 198.85$ ,  $p < 0.001$ , showing a higher accuracy in the looming condition than in the receding condition only within the auditory modality ( $Z = 22.34$ ,  $p < 0.0001$ ). The Modality  $\times$  Speed  $\times$  Group interaction was significant,  $\chi^2(2) = 10.21$ ,  $p < 0.01$  and revealed that the AQ- group had a lower accuracy in the auditory slow condition than the AQ+ group, whatever the condition ( $A^F$ :  $Z = -10.12$ ,  $p < 0.0001$ ;  $A^S$ :  $Z = -9.75$ ,  $p < 0.0001$ ;  $V^F$ :  $Z = -3.75$ ,  $p < 0.0001$ ;  $V^S$ :  $Z = -2.45$ ,  $p < 0.0001$ ;  $AV^F$ :  $Z = -5.08$ ,  $p < 0.0001$ ;  $AV^S$ :  $Z = -4.61$ ,  $p < 0.0001$ ). No other significant interactions were found ( $p > 0.11$ ).



**Figure 4.** Accuracy and reaction times (RTs) across Autism Spectrum Quotient (AQ) groups and sensory modalities. To represent the results of the binomial generalized linear mixed-effects models (GLMMs) (1 = correct response; 0 = incorrect response), binary values of the model were transformed into a rate of correct responses. (A) Individual transformed binary values (left) and Individual RTs (right) for the high and low AQ group. (B) Individual transformed binary values (left) and Individual RTs (right) for the AQ groups across the sensory modalities (audiovisual, visual and auditory respectively). In each plot, the median, the interquartile range, and the density are represented. \*\*\*,  $p < 0.0001$ ; \*,  $p < 0.05$ .

### 3.2.2. Reaction Times (RTs)

A significant main effect of the group revealed that the AQ+ group detected depth movement faster than the AQ- group ( $Z = -14.76$ ,  $p < 0.0001$ ; see Fig. 4A).

A significant main effect of the modality was found,  $\chi^2(2) = 18578.62$ ,  $p < 0.001$ , RT was shorter in the audiovisual modality than in either the visual ( $Z = -8.27$ ,  $p < 0.0001$ ) or the auditory ( $Z = 60.83$ ,  $p < 0.0001$ ) modality (see Fig. 4B). A significant Modality  $\times$  Group interaction,  $\chi^2(2) = 401.13$ ,  $p < 0.0001$ , revealed that the AQ+ group were particularly faster in the audiovisual modality compared to the AQ- group whatever the modality (A:  $Z = -48.8$ ,  $p < 0.0001$ ; V:  $Z = -18.47$ ,  $p < 0.0001$ ; AV:  $Z = -13.15$ ,  $p < 0.0001$ ).

A significant main effect of movement revealed shorter RTs in looming conditions compared to receding conditions ( $Z = -2.81$ ,  $p < 0.01$ ). As revealed by a significant Movement  $\times$  Group interaction,  $\chi^2(1) = 21.66$ ,  $p < 0.0001$ , the AQ+ group was faster in the looming conditions compared to the AQ-

group whatever the movement condition (looming:  $Z = -8.42$ ,  $p < 0.0001$ ; receding:  $Z = -12.8$ ;  $p < 0.0001$ ).

A significant Movement  $\times$  Modality interaction,  $\chi^2(3) = 598.511$ ,  $p < 0.001$ , showed that RTs were significantly shorter when an audiovisual looming stimulus was presented compared to unisensory looming stimuli (AL:  $Z = -44.5$ ,  $p < 0.0001$ ; VL:  $Z = -6.79$ ,  $p < 0.0001$ ), unisensory receding stimuli (AR:  $Z = -43.81$ ,  $p < 0.0001$ ; VR:  $Z = -10.88$ ,  $p < 0.0001$ ) and audiovisual receding stimuli ( $Z = -5.3$ ,  $p < 0.0001$ ). A Movement  $\times$  Modality  $\times$  Group interaction,  $\chi^2(2) = 79.63$ ,  $p < 0.0001$ , showed interestingly that the AQ+ group was particularly faster in the audiovisual looming condition compared to the AQ- group, (AL:  $Z = -35.93$ ,  $p < 0.0001$ ; AR:  $Z = -34.17$ ,  $p < 0.0001$ ; VL:  $Z = -13.93$ ,  $p < 0.0001$ ; VR:  $Z = -15.95$ ,  $p < 0.0001$ ; AVR:  $Z = -12.78$ ,  $p < 0.0001$ ; see Fig. 5A).

A main effect of the speed revealed shorter RTs to fast stimuli relative to slow stimuli ( $Z = -9.15$ ,  $p < 0.0001$ ). As revealed by the Speed  $\times$  Group interaction,  $\chi^2(1) = 8.62$ ,  $p < 0.01$ , the AQ+ group presented shorter RTs in fast conditions compared to the AQ- group, whatever the speed condition (slow:  $Z = -8.4$ ,  $p < 0.0001$ ; fast:  $Z = -6.78$ ,  $p < 0.0001$ ).

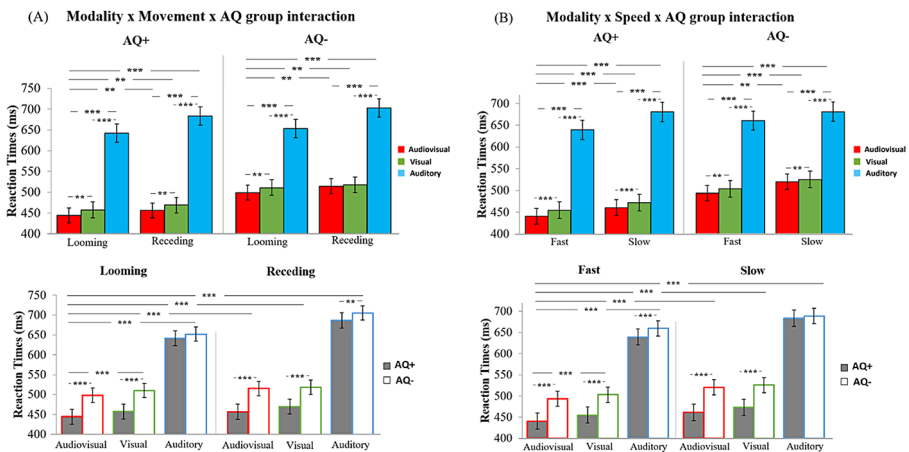
A Speed  $\times$  Modality interaction,  $\chi^2(2) = 335.98$ ,  $p < 0.001$ , showed that RTs were significantly shorter in the audiovisual fast condition compared to unisensory fast ( $V^F$ :  $Z = -6.73$ ,  $p < 0.0001$ ;  $A^F$ :  $Z = -44.29$ ,  $p < 0.0001$ ), unisensory slow ( $V^S$ :  $Z = -12.82$ ,  $p < 0.0001$ ;  $A^S$ :  $Z = -46.22$ ,  $p < 0.0001$ ) and audiovisual slow ( $Z = -7.18$ ,  $p < 0.0001$ ) conditions. A Speed  $\times$  Modality  $\times$  Group interaction,  $\chi^2(2) = 106.61$ ,  $p < 0.0001$ , revealed that the AQ+ group presented particularly shorter RT in the audiovisual fast condition compared to the AQ- group, whatever the condition ( $A^F$ :  $Z = -35.93$ ,  $p < 0.0001$ ;  $A^S$ :  $Z = -35.55$ ,  $p < 0.0001$ ;  $V^F$ :  $Z = -13.53$ ,  $p < 0.0001$ ;  $V^S$ :  $Z = -17.69$ ,  $p < 0.0001$ ;  $AV^S$ :  $Z = -14.25$ ,  $p < 0.0001$ ; see Fig. 5B).

There was a significant Speed  $\times$  Movement interaction,  $\chi^2(1) = 26.83$ ,  $p < 0.001$ , demonstrating that RTs were shorter in the fast looming condition compared to slow movements ( $L^S$ :  $Z = -7.44$ ,  $p < 0.0001$ ;  $R^S$ :  $Z = -8.32$ ,  $p < 0.0001$ ) and fast receding ( $Z = -2.81$ ,  $p < 0.01$ ) condition.

Interestingly, a significant Speed  $\times$  Modality  $\times$  Movement interaction,  $\chi^2(1) = 26.83$ ,  $p < 0.001$ , revealed particularly shorter RT when an audiovisual fast looming stimulus was presented compared to all other conditions (AL<sup>F</sup>:  $Z = -32.02$ ,  $p < 0.0001$ ; AL<sup>S</sup>:  $Z = -34.24$ ,  $p < 0.0001$ ; VL<sup>F</sup>:  $Z = -5.29$ ,  $p < 0.0001$ ; VL<sup>S</sup>:  $Z = -10.03$ ,  $p < 0.0001$ ; AR<sup>F</sup>:  $Z = -32.23$ ,  $p < 0.0001$ ; AR<sup>S</sup>:  $Z = -32.1$ ,  $p < 0.0001$ ; VR<sup>F</sup>:  $Z = -8.65$ ,  $p < 0.0001$ ; VR<sup>S</sup>:  $Z = -12.46$ ,  $p < 0.0001$ ; AVR<sup>F</sup>:  $Z = -3.94$ ,  $p < 0.0001$ ; AVR<sup>S</sup>:

$Z = -8.7, p < 0.0001$ ;  $AVL^S: Z = -5.3, p < 0.0001$ ). It is important to add that shorter RTs in the audiovisual looming condition compared to unisensory conditions, as well as the audiovisual receding condition, were found in each speed presentation ( $AL^S: Z = -31.22, p < 0.0001$ ;  $VL^S: Z = -4.31, p < 0.0001$ ;  $AR^S: Z = -29.95, p < 0.0001$ ;  $VR^S: Z = -6.86, p < 0.0001$ ;  $ARVR^S: Z = -3.62, p < 0.001$ . For fast speed,  $Z < -3.94, p < 0.0001$ , see above).

Moreover, as indicated by a significant Speed  $\times$  Modality  $\times$  Movement  $\times$  Group interaction,  $\chi^2(2) = 33.76, p = 0.0001$ , the RTs of the AQ+ group in the audiovisual fast-looming condition were shorter than those of the AQ- group, whatever the condition ( $AL^F: Z = -26.26, p < 0.0001$ ;  $VL^F: Z = -10.37, p < 0.0001$ ;  $AVL^F: Z = -6.27, p < 0.0001$ ;  $AR^F: Z = -25.36, p < 0.0001$ ;  $VR^F: Z = -11.51, p < 0.0001$ ;  $AVR^F: Z = -8.99, p < 0.0001$ ;  $AL^S: Z = -26.53, p < 0.0001$ ;  $VL^S: Z = -13.01, p < 0.0001$ ;  $AVL^S: Z = -10.28, p < 0.0001$ ;  $AR^S: Z = -24.22, p < 0.0001$ ;  $VR^S: Z = -14.62, p < 0.0001$ ;  $AVR^S: Z = -12.23, p < 0.0001$ ). Interestingly, the AQ+ group were faster in each experimental condition ( $Z < -5.28, p < 0.0001$ ) compared to the AQ- group, except in auditory conditions.



**Figure 5.** (A) Mean of reaction times (RTs) in looming and receding conditions across sensory modalities according to intragroup differences (at the top) and intergroup differences (at the bottom). Both Autism Spectrum Quotient (AQ) groups were faster in the audiovisual looming condition, and the AQ+ group presented particularly shorter RTs in such a condition. (B) Mean RTs in fast and slow conditions across sensory modalities according to intragroup differences (at the top) and intergroup differences (at the bottom). Participants' RTs were shorter in the audiovisual fast condition, and the AQ+ group was significantly faster in this condition. Error bars represent the standard error of the mean (SEM). \*\*\*,  $p < 0.0001$ ; \*\*,  $p < 0.001$ .



### 3.3. Race Model Analysis

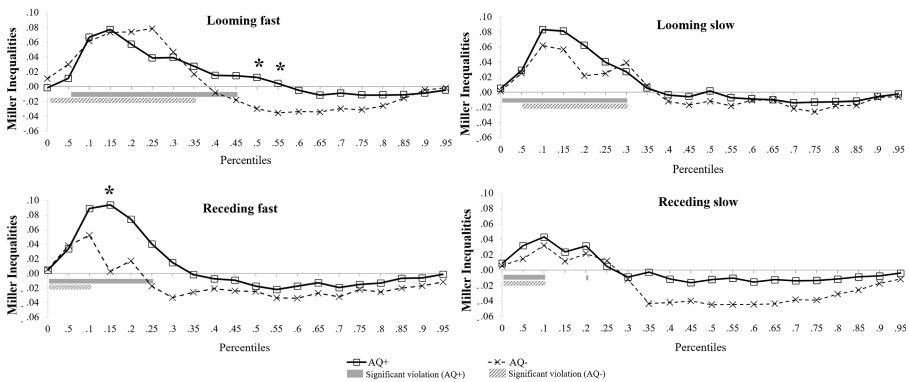
A race model analysis was applied to the RTs of all participants to determine whether shorter RTs in the multisensory condition exceeded the values predicted by the statistical summation of the fastest unisensory responses (see section 2.5.4. *Race Model Analysis*).

#### 3.3.1. Intergroup Analysis

Permutation tests were computed to statistically compare the Miller inequalities between AQ groups. Significant group differences were found in the receding fast condition at the 15th percentile ( $p < 0.01$ ), as well as in the looming fast condition from the 50th to the 55th percentile ( $p < 0.05$ ; see Fig. 6).

#### 3.3.2. Intragroup Analysis

Moreover, the reliability of the race model violations in each AQ group was computed. In both groups, significant violations of the model were found in the slow conditions — from the 0th to 10th percentile in the receding slow condition and from the ~5th to the 30th in the looming slow condition ( $p < 0.05$ ). Interestingly, in fast conditions, the violation of the model occurred in a greater range of RTs in AQ+ than AQ- ( $p < 0.05$ ; see Fig. 6).



**Figure 6.** Results of applying Miller’s race model inequality to the cumulative probability distributions of the reaction time (RT). The model is the arithmetic sum of the cumulative probabilities from unisensory and multisensory trials. The  $x$ -axis indicates the percentile of the RT distribution. \*, significant differences of Miller inequalities between Autism Spectrum Quotient (AQ) groups ( $p < 0.05$ ). Significant violations of the race model in each AQ group are also indicated.

## 4. Discussion

Because autism is a spectrum disorder that extends into the general population, working on autistic personality traits could allow a better understanding of sensory particularities all along the spectrum. This study aimed at exploring the multisensory integration of depth cues across different speeds in the autistic personality spectrum, using a go/no-go detection task. Participants with a high-autistic personality (AQ+) were faster and better at discriminating moving information than participants with a low-autistic personality (AQ-). All participants presented multisensory facilitation in their RTs but this phenomenon was extended to the number of correct responses only for the AQ+ group. Moreover, the AQ+ group were particularly fast to detect audiovisual looming stimuli, as well as high-speed audiovisual stimuli. The application of a specific model of MSI highlighted different integrative interactions of high-speed stimuli in the AQ+ group.

The present study sample was mainly composed of females (73.68%). Any gender effect was found in participants' responses (RTs and accuracy). No study, to our knowledge, has explored the gender effect in multisensory integration using a simple detection paradigm with non-social stimuli, so gender was not further considered in the present study. More precisely, the gender effect on multisensory integration has only been demonstrated in paradigms exploring the integration of multisensory emotion expressions (Collignon *et al.*, 2010; Lin *et al.*, 2021). Other studies have shown controversial results regarding the McGurk effect (Mallick *et al.*, 2015; Traunmüller and Öhrström, 2007).

### 4.1. The Group Effect: Hypersensitivity to Sensory Events

As commonly found in the literature (e.g., Horder *et al.*, 2014; Mayer, 2017), AQ correlated with the sensory profile (AASP). Specifically, the more participants manifested autistic traits, the more they avoided sensations, presented higher sensory sensitivity, and inattention to certain stimuli (low registration). A hypersensitive individual will seek to protect himself from external stimuli by avoiding them and will manifest a poor attention span through being overloaded by sensory stimuli. Because our data highlighted a higher global sensory sensitivity in the AQ+ group compared to the AQ- group, it might be possible that the group effects observed in the behavioral task rely on a higher responsiveness to sensory stimulation. This is in line with sensory theories proposing hypersensitivity to sensory events as the core of ASD functioning.

Specifically, the intense world theory (Markram and Markram, 2010) showed evidence of hyperreactivity, hyperconnectivity, as well as hyperplasticity at the cortical (notably sensory cortex) and subcortical levels in ASD. These dysfunctions probably involve an imbalance in the excitatory (glutamate) and inhibition (GABA) systems which was highlighted in ASD (the

theory of E/I: Rubenstein and Merzenich, 2003) and the high-autistic personality (Kondo and Lin, 2020). According to Markram and Markram (2010), this cortical hyperfunctioning leads to hypersensitivity to sensory events, causing atypical sensory responses. A higher sensory sensitivity in AQ+ participants may have caused hyperreactivity to the stimuli displayed and consequently generated shorter RTs and a higher number of correct responses compared to AQ- participants. In addition, the study by Thillay *et al.* (2016) revealed an overanticipation in ASD participants when stimuli are randomly presented, i.e., in an unpredictable way, leading to overdetected. More concretely, the authors reported shorter RTs to detect a target in a random design associated with an amplitude increase in a cerebral component preceding the presentation of the stimulus (Contingent Negative Variation) in ASD. These results have been suggested to reflect enhanced preparatory mechanisms in ASD. In this vein, our experimental paradigm consisted of 15 different stimuli presented in random order, leading to a high variability of the information displayed which might have led to an overanticipation and a faster reactivity in AQ+. Clinically, overanticipation in subjects with ASD when the context is less predictable could be linked to their difficulties handling changes in everyday life. In EEG studies, change detection in ASD has been investigated based on the mismatch negativity component (MMN). In ASD, differences in this component were found when using complex social stimuli (Kovarski *et al.*, 2021), and simple visual and auditory stimuli (e.g., Cléry *et al.*, 2013; Green *et al.*, 2020). Atypical MMN was also reported in subjects without ASD but with high-autistic traits (Gayle *et al.*, 2012).

#### 4.2. *The Sensory Modality Effects*

In line with previous studies using stationary/moving discrimination tasks of multisensory information (Cappe *et al.*, 2009; Harrison *et al.*, 2010), participants were slower in the auditory modality. This is inconsistent with the current understanding of the auditory system, which exhibits a faster information processing time than the visual system, generally leading to shorter RTs (Shelton and Kumar, 2010). A tentative explanation of our results is related to the well-established expertise of the visual system for processing movement. Indeed, visual movement provides crucial information, such as locating a target and establishing the precise movements to catch it or avoid danger. In particular, correctly detecting depth movement allows us to avoid a threat or pursue a target, and may foster social interactions (Cappe *et al.*, 2009). Thus, spatial characteristics are fundamentally processed differently in the visual and auditory systems. More concretely, while the direction of movement within the visual system is explicitly represented at the level of the single cell, the vast majority of neurons in the auditory system respond to specific ranges of acoustic frequencies once they have inputs from specific regions of the cochlea. At

the cortical level, the specificity of the visual system to process motion is identified from V1 and spreads in many other cortical areas and mainly in the MT and MST areas (for a review, see Ilg, 2008). At the auditory level, while there is some evidence for motion sensitivity and direction selectivity in the A1 and the planum temporale (e.g., Alink *et al.*, 2012; Lewis, 2000), no specific auditory cortical region has been identified for processing motion. Thus, it is quite possible that the auditory information reaches the cortical networks of the auditory system more quickly but that the processing of moving information is less efficient than in the visual system, resulting at the behavioral level in a slower RT in the auditory modality.

Furthermore, as classically reported in detection tasks of unisensory and multisensory information, participants presented multisensory facilitation of their RTs, but interestingly, only AQ+ showed higher correct responses in the audiovisual condition relative to unisensory ones. In addition, AQ+ presented particularly short RTs to detect audiovisual stimuli. Some research investigating the multisensory integration of simple stimuli according to autistic traits in non-ASD subjects used the simultaneity judgment task (Donohue *et al.*, 2012), or the flash-beep illusion task (Yaguchi and Hidaka, 2018) to study the TBW. Their results indicated that the more autistic traits the participant had, the larger his TBW. The use of different approaches (temporal processing *vs* multisensory facilitation) to assess MSI does not make a direct comparison with our results relevant. However, it is possible that subjects with high-autistic traits present a widening of the TBW that facilitates MSI and consequently maximizes multisensory facilitation. Furthermore, one recent study (van Laarhoven *et al.*, 2019) using social stimuli (audiovisual speech) in a multitask paradigm to assess MSI in the autistic personality, revealed that a high AQ score was related to a reduced sensitivity to the McGurk illusion and a reduced visual enhancement of speech comprehensibility in noise. This is in line with results in the literature proposing alterations of MSI in ASD when using social information (for a review, see Feldman *et al.*, 2018). Moreover, studies using a multisensory detection task of simple non-social information are clinical comparative studies (ASD *vs* Control subjects) and have demonstrated either equal multisensory facilitation to controls (Brandwein *et al.*, 2015; de Boer-Schellekens *et al.*, 2013; Stefanou *et al.*, 2020; Stewart *et al.*, 2016) or degraded multisensory facilitation in subjects with ASD (Ainsworth *et al.*, 2021; Brandwein *et al.*, 2013; Collignon *et al.*, 2013; Molholm *et al.*, 2020; Ostrolenk *et al.*, 2019). Thus, our study is the first to investigate the mechanism of multisensory facilitation according to autistic traits and propose it as being improved in subjects with high-autistic traits. This heterogeneity at the behavioral level could be the consequence of a distinct cortical network of MSI, as all studies using neuroimaging techniques demonstrated that sensory merging in ASD occurred at different topographies and latencies compared

to control participants (Brandwein *et al.*, 2013, 2015; Molholm *et al.*, 2020; Russo *et al.*, 2010; Stefanou *et al.*, 2020). In addition, structural, anatomic, and functional differences in the superior temporal sulcus, an important site of audiovisual multisensory integration (for a review, see Beauchamp, 2010), have been demonstrated in participants with ASD compared to control participants (for a review, see Zilbovicius *et al.*, 2013). We can add that the authors of the enhanced perceptual functioning model, a well-established ASD model (Mottron and Burack, 2001; Mottron *et al.*, 2006), proposed that cerebral plasticity in low-level brain areas in ASD leads to enhanced activation in these specific brain areas, referred to as ‘areas of strength’, generating a preference toward a low level of processing. MSI implicates interactions of the primary cortexes between different areas of sensory processing (Cappe and Barone, 2005), meaning that the merging of the senses occurs in the early stages of sensory processing. Thus, it is quite possible that the merging of sensory information may be the core of a ‘surfunctioning’ mechanism leading to differences in brain integration of multisensory information.

#### 4.3. *The Speed Effect in Our Experimental Paradigm*

Participants with high-autistic traits (AQ+) manifested particularly shorter RTs in the fast-speed audiovisual conditions. In addition, a widely used MSI model (the race model) revealed a higher number of cues supporting integrative processes (model violations) in the fast-speed conditions for AQ+. Contrary to our results, many studies exploring the effect of speed on the perception of ASD showed response enhancement in slow-speed conditions, whether the stimuli used were unisensory (Lainé *et al.*, 2009; Tardif *et al.*, 2007) or multisensory (Lainé *et al.*, 2008; Meiss *et al.*, 2015; Tardif *et al.*, 2007). A tentative explanation for these discrepant results is that the effect of speed on participants’ responses differs depending on the level of processing required in the experimental paradigm. More concretely, the methodological differences with the studies cited above may have led to these divergent results. The latter used complex social stimuli in behavioral imitation and emotion or word recognition paradigms. Considering the difficulties with tasks demanding high-level processing commonly highlighted in ASD (Mottron and Burack, 2001; Mottron *et al.*, 2006), a slower speed of presentation generates beneficial effects in processing information and establishing adapted behaviors in such complex tasks. This is in line with the current knowledge in ASD of an oversensitivity to simple, non-social stimuli; for example, in clinical observations: the sound of “[...] alarms in general [...] caused a sensation inside my skull like the pain from a dentist’s drill” and, conversely, difficulties in processing social material: “When grownups talked fast, I heard only the vowel sounds [...]. But by speaking slowly, the speech therapist

helped me to hear the hard consonant sounds [. . .]” (Grandin, 1995). Beyond using simple, nonsocial stimuli, we used a simple detection task. A particularly well-documented finding is the excellence of subjects with ASD in such tasks. For instance, in visual search (e.g., Joseph *et al.*, 2009; Plaisted *et al.*, 1998), subjects with ASD manifest shorter RTs than control subjects. This superiority in visual search was also found in subjects without ASD but with high-autistic traits (Almeida *et al.*, 2010). It would be interesting to set up a study using tasks with progressive complexity to identify the level of processing that generates difficulties in ASD, which seems to be the focus of some current research (e.g., Ainsworth *et al.*, 2019, 2021; Stevenson *et al.*, 2018). Using a different population from the studies that worked on the effect of speed could also explain the inconsistency in the results.

An alternative explanation is associated with the linearity of motion processing particularities in the autistic spectrum. The present research focused on autistic traits in the general population, whereas the literature used participants with ASD. According to the dimensional model of ASD, the more autistic traits the person presents, the more the person suffers from sensory particularities. In this context, if we consider a linear expression of sensory particularities throughout the autistic spectrum, ASD individuals are at the extreme of the spectrum with a more severe impairment than autistic personality individuals. Thus, as overresponsiveness to sensory moving events was found in the high-autistic personality in this study, exacerbated with fast speed, the expression of such sensory particularities at the other extreme of the ASD spectrum is likely to be even more severe. In other words, if we find sensory particularities in people with high-autistic traits, these particularities will be more intensely expressed in ASD and thus lead to impairments. This could explain the pronounced difficulties in ASD in processing information at a fast speed and, consequently, the beneficial effect of slowing down the speed of presentation. This is in line with previous studies finding atypia in sensory processing in subjects without ASD but with high-autistic traits that were exacerbated in ASD subjects (e.g., Mayer, 2017; Takayama *et al.*, 2014).

In addition, we should mention that the characteristics of the stimuli differed according to the speed of presentation (the movement lasted 500 ms in slow-speed conditions and 250 ms in fast-speed conditions, after which the participant did not receive any information on the motion aspect of the stimulation). Consequently, the characteristics of the fast speed stimulations induced the speed effect. Future investigations could investigate this effect by developing an experimental paradigm consisting of stimulation with different presentation durations.

#### 4.4. *The Specific Integration of Looming Signals*

Participants manifested shorter RTs in the looming audiovisual conditions, whatever the presentation speed. We thus replicated the robust behavioral effect of multisensory integration of looming movement (Cappe *et al.*, 2009) and extended this result by using different speeds. According to the theory of the intense world (Markram and Markram, 2010), sensory hypersensitivity in ASD generates strategies such as preference selection and active avoidance of stimuli. Hyperpreference processing in the sensory domain could lead to exaggerated selectivity, sensitivity, and specialization of sensory features and hence hyperperception. Because looming signals are involved in social interaction, such social cues can be anxiety-inducing for ASD people and high-autistic personalities. Thus, the infant faced with looming movements during development could learn to actively avoid such high arousal level stimuli and to over-react to them. Indeed, Hu *et al.* (2017) found in a very young ASD sample (3–4 years), a lack of behavioral reactivity to aversive looming signals associated with weak connectivity in a structural pathway involved in looming-evoked defensive responses. Similar results showed postural hyporeactivity to expansion movement in children of 7–11 years (Gepner and Mestre, 2002) and in an adolescent sample (12–15 years; Greffou *et al.*, 2012) but not in older participants (16–33 years; Greffou *et al.*, 2012). Taken together, these results suggest that sensitivity to looming movement could be dependent on social experience in the autistic spectrum. In addition, because the multisensory signal is all the more informative (auditory looming + visual looming), it is expected that people with high-autistic traits reacted faster to this one. As a speed effect was found in the present study, an adaptation to the speed presentation could be applied to react efficiently to the stimuli. Longitudinal studies would be useful to better define the developmental trajectory of looming movement integration within the autistic spectrum.

### 5. Summary

In conclusion, this study supports the presence of sensory particularities in people with high-autistic traits, particularly regarding the multisensory integration of looming cues and fast-moving stimuli. As our environment is predominantly dynamic and multisensory, studying such information is essential. This study contributes to better defining the difficulties experienced on a daily basis throughout the spectrum and supports evidence that low-level stages of multisensory integration may operate differently all along the autistic personality spectrum. These findings extend to the whole autistic spectrum the growing discussion about the subsequential effect of basic perceptual particularities on the development of social abilities.

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## Supplementary Material

Supplementary material is available online at:  
<https://doi.org/10.6084/m9.figshare.23152049>

## References

- Ainsworth, K., Falagiarda, F., Collignon, O. and Bertone, A. (2019). Time-resolved discrimination of audiovisual expressions of emotion in children with and without autism, *J. Vis.* **19**, 20a. DOI:10.1167/19.10.20a.
- Ainsworth, K., Ostrolenk, A., Irion, C. and Bertone, A. (2021). Reduced multisensory facilitation exists at different periods of development in autism, *Cortex* **134**, 195–206. DOI:10.1016/j.cortex.2020.09.031.
- Aleman, S., Blok, E., Jansen, P. R., Muetzel, R. L. and White, T. (2021). Brain morphology, autistic traits, and polygenic risk for autism: a population-based neuroimaging study, *Autism Res.* **14**, 2085–2099. DOI:10.1002/aur.2576.
- Alink, A., Euler, F., Kriegeskorte, N., Singer, W. and Kohler, A. (2012). Auditory motion direction encoding in auditory cortex and high-level visual cortex, *Hum. Brain Mapp.* **33**, 969–978. DOI:10.1002/hbm.21263.
- Almeida, R. A., Dickinson, J. E., Maybery, M. T., Badcock, J. C. and Badcock, D. R. (2010). Visual search performance in the autism spectrum II: the radial frequency search task with additional segmentation cues, *Neuropsychologia* **48**, 4117–4124. DOI:10.1016/j.neuropsychologia.2010.10.009.
- Annaz, D., Campbell, R., Coleman, M., Milne, E. and Swettenham, J. (2012). Young children with autism spectrum disorder do not preferentially attend to biological motion, *J. Autism Dev. Disord.* **42**, 401–408. DOI:10.1007/s10803-011-1256-3.
- APA (2013). *Diagnostic and Statistical Manual of Mental Disorders, Fifth ed/ (DSM-5)*. American Psychiatric Association, Washington, DC, USA. DOI:10.1176/appi.books.9780890425596.
- Ayres, A. J. and Tickle, L. S. (1980). Hyper-responsivity to touch and vestibular stimuli as a predictor of positive response to sensory integration procedures by autistic children, *Am. J. Occup. Ther.* **34**, 375–381. DOI:10.5014/ajot.34.6.375.
- Baker, A. E. Z., Lane, A., Angley, M. T. and Young, R. L. (2008). The relationship between sensory processing patterns and behavioural responsiveness in autistic disorder: a pilot study, *J. Autism Dev. Disord.* **38**, 867–875. DOI:10.1007/s10803-007-0459-0.
- Baron-Cohen, S. (1995). *Mindblindness: an Essay on Autism and Theory of Mind*. The MIT Press, Cambridge, MA, USA. DOI:10.7551/mitpress/4635.001.0001.



- Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J. and Clubley, E. (2001). The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians, *J. Autism Dev. Disord.* **31**, 5–17. DOI:10.1023/A:1005653411471.
- Bates, D., Mächler, M., Bolker, B. and Walker, S. (2015). Fitting linear mixed-effects models using lme4, *J. Stat. Softw.* **67**, 1–48. DOI:10.18637/jss.v067.i01.
- Bayliss, A. P. and Tipper, S. P. (2005). Gaze and arrow cueing of attention reveals individual differences along the autism spectrum as a function of target context, *Br. J. Psychol.* **96**, 95–114. DOI:10.1348/000712604X15626.
- Beauchamp, M. S. (2010). Biological motion and multisensory integration: the role of the superior temporal sulcus, in: *The Science of Social Vision*, R. B. Adams, N. Ambady, K. Nakayama and S. Shimojo (Eds), pp. 409–420. Oxford University Press, Oxford, UK. DOI:10.1093/acprof:oso/9780195333176.003.0024.
- Ben-Sasson, A., Hen, L., Fluss, R., Cermak, S. A., Engel-Yeger, B. and Gal, E. (2009). A meta-analysis of sensory modulation symptoms in individuals with autism spectrum disorders, *J. Autism Dev. Disord.* **39**, 1–11. DOI:10.1007/s10803-008-0593-3.
- Benjamini, Y. and Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing, *J. R. Stat. Soc. Series B Methodol.* **57**, 289–300. DOI:10.1111/j.2517-6161.1995.tb02031.x.
- Bertone, A., Mottron, L., Jelenic, P. and Faubert, J. (2003). Motion perception in autism: a “complex” issue, *J. Cogn. Neurosci.* **15**, 218–225. DOI:10.1162/089892903321208150.
- Blake, R. and Shiffrar, M. (2007). Perception of human motion, *Annu. Rev. Psychol.* **58**, 47–73. DOI:10.1146/annurev.psych.57.102904.190152.
- Brainard, D. H. (1997). *The Psychophysics Toolbox*, *Spat. Vis.* **10**, 433–436. DOI:10.1163/156856897X00357.
- Brandwein, A. B., Foxe, J. J., Butler, J. S., Russo, N. N., Altschuler, T. S., Gomes, H. and Molholm, S. (2013). The development of multisensory integration in high-functioning autism: high-density electrical mapping and psychophysical measures reveal impairments in the processing of audiovisual inputs, *Cereb. Cortex* **23**, 1329–1341. DOI:10.1093/cercor/bhs109.
- Brandwein, A. B., Foxe, J. J., Butler, J. S., Frey, H.-P., Bates, J. C., Shulman, L. H. and Molholm, S. (2015). Neurophysiological indices of atypical auditory processing and multisensory integration are associated with symptom severity in autism, *J. Autism Dev. Disord.* **45**, 230–244. DOI:10.1007/s10803-014-2212-9.
- Brown, C. and Dunn, W. (2002). *Adolescent/Adult Sensory Profile Manual*. Psychological Corporation, San Antonio, TX, USA.
- Brown, C. and Dunn, W. (2006). *Sensory Profile™ Adolescent/Adult Sensory Profile® Adolescent/Adult Sensory Profile Summary Report*. Pearson, San Antonio, TX, USA.
- Cappe, C. and Barone, P. (2005). Heteromodal connections supporting multisensory integration at low levels of cortical processing in the monkey, *Eur. J. Neurosci.* **22**, 2886–2902. DOI:10.1111/j.1460-9568.2005.04462.x.
- Cappe, C., Thut, G., Romei, V. and Murray, M. M. (2009). Selective integration of auditory-visual looming cues by humans, *Neuropsychologia* **47**, 1045–1052. DOI:10.1016/j.neuropsychologia.2008.11.003.
- Centelles, L., Assaiante, C., Etchegoyhen, K., Bouvard, M. and Schmitz, C. (2013). From action to interaction: exploring the contribution of body motion cues to social understanding in

- typical development and in autism spectrum disorders, *J. Autism Dev. Disord.* **43**, 1140–1150. DOI:10.1007/s10803-012-1655-0.
- Chen, Y.-H., Rodgers, J. and McConachie, H. (2009). Restricted and repetitive behaviours, sensory processing and cognitive style in children with autism spectrum disorders, *J. Autism Dev. Disord.* **39**, 635–642. DOI:10.1007/s10803-008-0663-6.
- Clark, A. I., Hughes, P. S., Grube, M. and Stewart, M. E. (2013). Autistic traits and sensitivity to interference with flavour identification, *Autism Res.* **6**, 332–336. DOI:10.1002/aur.1293.
- Cléry, H., Bonnet-Brilhault, F., Lenoir, P., Barthelemy, C., Bruneau, N. and Gomot, M. (2013). Atypical visual change processing in children with autism: an electrophysiological study, *Psychophysiology* **50**, 240–252. DOI:10.1111/psyp.12006.
- Collignon, O., Girard, S., Gosselin, F., Saint-Amour, D., Lepore, F. and Lassonde, M. (2010). Women process multisensory emotion expressions more efficiently than men, *Neuropsychologia* **48**, 220225. DOI:10.1016/j.neuropsychologia.2009.09.007.
- Collignon, O., Charbonneau, G., Peters, F., Nassim, M., Lassonde, M., Lepore, F., Mottron, L. and Bertone, A. (2013). Reduced multisensory facilitation in persons with autism, *Cortex* **49**, 1704–1710. DOI:10.1016/j.cortex.2012.06.001.
- de Boer-Schellekens, L., Eussen, M. and Vroomen, J. (2013). Diminished sensitivity of audio-visual temporal order in autism spectrum disorder, *Front. Integr. Neurosci.* **7**, 8. DOI:10.3389/fnint.2013.00008.
- Donohue, S. E., Darling, E. F. and Mitroff, S. R. (2012). Links between multisensory processing and autism, *Exp. Brain Res.* **222**, 377–387. DOI:10.1007/s00221-012-3223-4.
- Falck-Ytter, T., Bölte, S. and Gredebäck, G. (2013). Eye tracking in early autism research, *J. Neurodev. Disord.* **5**, 28. DOI:10.1186/1866-1955-5-28.
- Feldman, J. I., Dunham, K., Cassidy, M., Wallace, M. T., Liu, Y. and Woynarowski, T. G. (2018). Audiovisual multisensory integration in individuals with autism spectrum disorder: a systematic review and meta-analysis, *Neurosci. Biobehav. Rev.* **95**, 220–234. DOI:10.1016/j.neubiorev.2018.09.020.
- Foss-Feig, J. H., Kwakye, L. D., Cascio, C. J., Burnette, C. P., Kadivar, H., Stone, W. L. and Wallace, M. T. (2010). An extended multisensory temporal binding window in autism spectrum disorders, *Exp. Brain Res.* **203**, 381–389. DOI:10.1007/s00221-010-2240-4.
- Foxe, J. J., Molholm, S., Del Bene, V. A., Frey, H.-P., Russo, N. N., Blanco, D., Saint-Amour, D. and Ross, L. A. (2015). Severe multisensory speech integration deficits in high-functioning school-aged children with autism spectrum disorder (ASD) and their resolution during early adolescence, *Cereb. Cortex* **25**, 298–312. DOI:10.1093/cercor/bht213.
- Gayle, L. C., Gal, D. E. and Kieffaber, P. D. (2012). Measuring affective reactivity in individuals with autism spectrum personality traits using the visual mismatch negativity event-related brain potential, *Front. Hum. Neurosci.* **6**, 334. DOI:10.3389/fnhum.2012.00334.
- Gepner, B. and Féron, F. (2009). Autism: a world changing too fast for a mis-wired brain?, *Neurosci. Biobehav. Rev.* **33**, 1227–1242. DOI:10.1016/j.neubiorev.2009.06.006.
- Gepner, B. and Mestre, D. (2002). Rapid visual-motion integration deficit in autism, *Trends Cogn. Sci.* **6**, 455. DOI:10.1016/s1364-6613(02)02004-1.
- Grandin, T. (1995). *Ma Vie d'Autiste*. Odile Jacob, Paris, France.
- Green, H. L., Shuffrey, L. C., Levinson, L., Shen, G., Avery, T., Randazzo Wagner, M., Sepulveda, D. M., Garcia, P., Maddox, C., Garcia, F., Hassan, S. and Froud, K. (2020). Evaluation

- of mismatch negativity as a marker for language impairment in autism spectrum disorder, *J. Commun. Disord.* **87**, 105997. DOI:10.1016/j.jcomdis.2020.105997.
- Greffou, S., Bertone, A., Hahler, E.-M., Hanssens, J.-M., Mottron, L. and Faubert, J. (2012). Postural hypo-reactivity in autism is contingent on development and visual environment: a fully immersive virtual reality study, *J. Autism Dev. Disord.* **42**, 961–970. DOI:10.1007/s10803-011-1326-6.
- Grinter, E. J., Van Beek, P. L., Maybery, M. T. and Badcock, D. R. (2009a). Brief report: visuospatial analysis and self-rated autistic-like traits, *J. Autism Dev. Disord.* **39**, 670–677. DOI:10.1007/s10803-008-0658-3.
- Grinter, E. J., Maybery, M. T., Van Beek, P. L., Pellicano, E., Badcock, J. C. and Badcock, D. R. (2009b). Global visual processing and self-rated autistic-like traits, *J. Autism Dev. Disord.* **39**, 1278–1290. DOI:10.1007/s10803-009-0740-5.
- Harrison, N. R., Wuerger, S. M. and Meyer, G. F. (2010). Reaction time facilitation for horizontally moving auditory–visual stimuli, *J. Vis.* **10**, 16. DOI:10.1167/10.14.16.
- Hazen, E. P., Stornelli, J. L., O'Rourke, J. A., Koesterer, K. and McDougle, C. J. (2014). Sensory symptoms in autism spectrum disorders, *Harv. Rev. Psychiatry* **22**, 112–124. DOI:10.1097/01.HRP.0000445143.08773.58.
- Hilton, C., Graver, K. and LaVesser, P. (2007). Relationship between social competence and sensory processing in children with high functioning autism spectrum disorders, *Res. Autism Spectrum Disord.* **1**, 164–173. DOI:10.1016/j.rasd.2006.10.002.
- Hobson, R. (1992). Autism and Asperger's Syndrome. U. Frith (Ed.), 1991. Cambridge University Press, Cambridge, UK [book review]. *cry* **161**, 872. DOI:10.1192/S0007125000131381.
- Hoekstra, R. A., Bartels, M., Cath, D. C. and Boomsma, D. I. (2008). Factor structure, reliability and criterion validity of the autism-spectrum quotient (AQ): a study in Dutch population and patient groups, *J. Autism Dev. Disord.* **38**, 1555–1566. DOI:10.1007/s10803-008-0538-x.
- Holder, J., Wilson, C. E., Mendez, M. A. and Murphy, D. G. (2014). Autistic traits and abnormal sensory experiences in adults, *J. Autism Dev. Disord.* **44**, 1461–1469. DOI:10.1007/s10803-013-2012-7.
- Hu, Y., Chen, Z., Huang, L., Xi, Y., Li, B., Wang, H., Yan, J., Lee, T. M. C., Tao, Q., So, K.-F. and Ren, C. (2017). A translational study on looming-evoked defensive response and the underlying subcortical pathway in autism, *Sci. Rep.* **7**, 14755. DOI:10.1038/s41598-017-15349-x.
- Ilg, U. J. (2008). The role of areas MT and MST in coding of visual motion underlying the execution of smooth pursuit, *Vis. Res.* **48**, 2062–2069. DOI:10.1016/j.visres.2008.04.015.
- Johansson, G. (1973). Visual perception of biological motion and a model for its analysis, *Percept. Psychophys.* **14**, 201–211. DOI:10.3758/BF03212378.
- Joseph, R. M., Keehn, B., Connolly, C., Wolfe, J. M. and Horowitz, T. S. (2009). Why is visual search superior in autism spectrum disorder?, *Dev. Sci.* **12**, 1083–1096. DOI:10.1111/j.1467-7687.2009.00855.x.
- Keane, B. P., Rosenthal, O., Chun, N. H. and Shams, L. (2010). Audiovisual integration in high functioning adults with autism, *Res. Autism Spectrum Disord.* **4**, 276–289. DOI:10.1016/j.rasd.2009.09.015.
- Kempenaers, C., Braun, S., Delvaux, N. and Linkowski, P. (2017). The assessment of autistic traits with the autism spectrum quotient: contribution of the French version to its construct validity, *Eur. Rev. Appl. Psychol.* **67**, 299–306. DOI:10.1016/j.erap.2017.09.001.

- Kondo, H. M. and Lin, I.-F. (2020). Excitation-inhibition balance and auditory multistable perception are correlated with autistic traits and schizotypy in a non-clinical population, *Sci. Rep.* **10**, 8171. DOI:10.1038/s41598-020-65126-6.
- Kovarski, K., Charpentier, J., Roux, S., Batty, M., Houy-Durand, E. and Gomot, M. (2021). Emotional visual mismatch negativity: a joint investigation of social and non-social dimensions in adults with autism, *Translat. Psychiatry* **11**, 10. DOI:10.1038/s41398-020-01133-5.
- Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L. and Wallace, M. T. (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders, *Front. Integr. Neurosci.* **4**, 129. DOI:10.3389/fnint.2010.00129.
- Lainé, F., Tardif, C. and Gepner, B. (2008). Amélioration de la reconnaissance et de l'imitation d'expressions faciales chez des enfants autistes grâce à une présentation visuelle et sonore ralentie, *Ann. Med.-Psychol.* **166**, 533–538. DOI:10.1016/j.amp.2005.09.032.
- Lainé, F., Rauzy, S., Gepner, B. and Tardif, C. (2009). Prise en compte des difficultés de traitement des informations visuelles et auditives rapides dans le cadre de l'évaluation diagnostique de l'autisme, *Enfance* **2009**, 133–141. DOI:10.4074/S0013754509001153.
- Lainé, F., Rauzy, S., Tardif, C. and Gepner, B. (2011). Slowing down the presentation of facial and body movements enhances imitation performance in children with severe autism, *J. Autism Dev. Disord.* **41**, 983–996. DOI:10.1007/s10803-010-1123-7.
- Lane, A. E., Young, R. L., Baker, A. E. Z. and Angley, M. T. (2010). Sensory processing subtypes in autism: association with adaptive behavior, *J. Autism Dev. Disord.* **40**, 112–122. DOI:10.1007/s10803-009-0840-2.
- Lewis, J. W. (2000). A comparison of visual and auditory motion processing in human cerebral cortex, *Cereb. Cortex* **10**, 873–888. DOI:10.1093/cercor/10.9.873.
- Lin, Y., Ding, H. and Zhang, Y. (2021). Unisensory and multisensory Stroop effects modulate gender differences in verbal and nonverbal emotion perception, *J. Speech Lang. Hear. Res.* **64**, 4439–4457. DOI:10.1044/2021\_JSLHR-20-00338.
- Loveland, K. A., Tunali-Kotoski, B., Chen, R., Brelsford, K. A., Ortegon, J. and Pearson, D. A. (1995). Intermodal perception of affect in persons with autism or Down syndrome, *Dev. Psychopathol.* **7**, 409–418. DOI:10.1017/S095457940000660X.
- Maier, J. X., Chandrasekaran, C. and Ghazanfar, A. A. (2008). Integration of bimodal looming signals through neuronal coherence in the temporal lobe, *Curr. Biol.* **18**, 963–968. DOI:10.1016/j.cub.2008.05.043.
- Mallick, D. B., Magnotti, J. F. and Beauchamp, M. S. (2015). Variability and stability in the McGurk effect: contributions of participants, stimuli, time, and response type, *Psychon. Bull. Rev.* **22**, 1299–1307. DOI:10.3758/s13423-015-0817-4.
- Marco, E. J., Hinkley, L. B. N., Hill, S. S. and Nagarajan, S. S. (2011). Sensory processing in autism: a review of neurophysiologic findings, *Pediat. Res.* **69**, 48–54. DOI:10.1203/PDR.0b013e3182130c54.
- Markram, K. and Markram, H. (2010). The intense world theory – a unifying theory of the neurobiology of autism, *Front. Hum. Neurosci.* **4**, 224. DOI:10.3389/fnhum.2010.00224.
- MathWorks (2022). *MATLAB Version: 9.13.0 (R2022b)*. The MathWorks Inc., Natick, MA, USA. <https://www.mathworks.com>.
- Mayer, J. L. (2017). The relationship between autistic traits and atypical sensory functioning in neurotypical and ASD adults: a spectrum approach, *J. Autism Dev. Disord.* **47**, 316–327. DOI:10.1007/s10803-016-2948-5.

- Meiss, E., Tardif, C., Arciszewski, T., Dauvier, B. and Gepner, B. (2015). Effets positifs d'une exposition à des séquences vidéo ralenties sur l'attention, la communication sociale et les troubles du comportement chez 4 enfants autistes sévères: une étude translationnelle pilote, *Neuropsychiatr. Enfance Adolesc.* **63**, 302–309. DOI:10.1016/j.neurenf.2015.01.004.
- Miller, J. (1982). Divided attention: evidence for coactivation with redundant signals, *Cogn. Psychol.* **14**, 247–279. DOI:10.1016/0010-0285(82)90010-X.
- Molholm, S., Murphy, J. W., Bates, J., Ridgway, E. M. and Foxe, J. J. (2020). Multisensory audiovisual processing in children with a sensory processing disorder (I): behavioral and electrophysiological indices under speeded response conditions, *Front. Integr. Neurosci.* **14**, 4. DOI:10.3389/fnint.2020.00004.
- Mottron, L. and Burack, J. A. (2001). Enhanced perceptual functioning in the development of autism, in: *The Development of Autism: Perspectives From Theory and Research*, J. A. Burack, T. Charman, N. Yirmiya and P. R. Zelazo (Eds), pp. 131–148. Lawrence Erlbaum Associates, New York, NY, USA. DOI:10.4324/9781410600196-14.
- Mottron, L., Dawson, M., Soulières, I., Hubert, B. and Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception, *J. Autism Dev. Disord.* **36**(1), 27–43. DOI:10.1007/s10803-005-0040-7.
- Neuhoff, J. G. (1998). Perceptual bias for rising tones!, *Nature* **395**, 123–124. DOI:10.1038/25862.
- Neuhoff, J. G. (2001). An adaptive bias in the perception of looming auditory motion, *Ecol. Psychol.* **13**, 87–110. DOI:10.1207/S15326969ECO1302\_2.
- Newman, R. S., Kirby, L. A., Von Holzen, K. and Redcay, E. (2021). Read my lips! Perception of speech in noise by preschool children with autism and the impact of watching the speaker's face, *J. Neurodev. Disord.* **13**, 4. DOI:10.1186/s11689-020-09348-9.
- Noel, J.-P., Stevenson, R. A. and Wallace, M. T. (2018). Atypical audiovisual temporal function in autism and schizophrenia: similar phenotype, different cause, *Eur. J. Neurosci.* **47**, 1230–1241. DOI:10.1111/ejn.13911.
- O'Connor, K. (2007). Brief report: impaired identification of discrepancies between expressive faces and voices in adults with Asperger's syndrome, *J. Autism Dev. Disord.* **37**, 2008–2013. DOI:10.1007/s10803-006-0345-1.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory, *Neuropsychologia* **9**, 97–113. DOI:10.1016/0028-3932(71)90067-4.
- Ostrolenk, A., Bao, V. A., Mottron, L., Collignon, O. and Bertone, A. (2019). Reduced multisensory facilitation in adolescents and adults on the autism spectrum, *Sci. Rep.* **9**, 11965. DOI:10.1038/s41598-019-48413-9.
- Plaisted, K., O'Riordan, M. and Baron-Cohen, S. (1998). Enhanced visual search for a conjunctive target in autism: a research note, *J. Child Psychol. Psychiatry* **39**, 777–783.
- Robertson, C. E. and Baron-Cohen, S. (2017). Sensory perception in autism, *Nat. Rev. Neurosci.* **18**, 671–684. DOI:10.1038/nrn.2017.112.
- Rubenstein, J. L. R. and Merzenich, M. M. (2003). Model of autism: increased ratio of excitation/inhibition in key neural systems, *Genes Brain Behav.* **2**, 255–267. DOI:10.1034/j.1601-183X.2003.00037.x.
- Russo, N., Foxe, J. J., Brandwein, A. B., Altschuler, T., Gomes, H. and Molholm, S. (2010). Multisensory processing in children with autism: high-density electrical mapping of auditory–somatosensory integration, *Autism Res.* **3**, 253–267. DOI:10.1002/aur.152.

- Ruzich, E., Allison, C., Smith, P., Watson, P., Auyeung, B., Ring, H. and Baron-Cohen, S. (2015). Measuring autistic traits in the general population: a systematic review of the autism-spectrum quotient (AQ) in a nonclinical population sample of 6900 typical adult males and females, *Mol. Autism* **6**, 2. DOI:10.1186/2040-2392-6-2.
- Shelton, J. and Kumar, G. P. (2010). Comparison between auditory and visual simple reaction times, *Neurosci. Med.* **1**, 30–32. DOI:10.4236/nm.2010.11004.
- Smith, E. G. and Bennetto, L. (2007). Audiovisual speech integration and lipreading in autism, *J. Child Psychol. Psychiat.* **48**, 813–821. DOI:10.1111/j.1469-7610.2007.01766.x.
- Stefanou, M. E., Dundon, N. M., Bestelmeyer, P. E. G., Ioannou, C., Bender, S., Biscaldi, M., Smyrnis, N. and Klein, C. (2020). Late attentional processes potentially compensate for early perceptual multisensory integration deficits in children with autism: evidence from evoked potentials, *Sci. Rep.* **10**, 16157. DOI:10.1038/s41598-020-73022-2.
- Stein, B. E. (Ed.) (2012). *The New Handbook of Multisensory Processing*. MIT Press, Cambridge, MA, USA.
- Stein, B. E. and Meredith, M. A. (1993). *The Merging of the Senses*. MIT Press, Cambridge, MA, USA.
- Stevenson, J. L. and Hart, K. R. (2017). Psychometric properties of the autism-spectrum quotient for assessing low and high levels of autistic traits in college students, *J. Autism Dev. Disord.* **47**, 1838–1853. DOI:10.1007/s10803-017-3109-1.
- Stevenson, R. A., Siemann, J. K., Woynaroski, T. G., Schneider, B. C., Eberly, H. E., Camarata, S. M. and Wallace, M. T. (2014). Evidence for diminished multisensory integration in autism spectrum disorders, *J. Autism Dev. Disord.* **44**, 3161–3167. DOI:10.1007/s10803-014-2179-6.
- Stevenson, R. A., Segers, M., Ncube, B. L., Black, K. R., Bebko, J. M., Ferber, S. and Barense, M. D. (2018). The cascading influence of multisensory processing on speech perception in autism, *Autism* **22**, 609–624. DOI:10.1177/1362361317704413.
- Stewart, C. R., Sanchez, S. S., Grenesko, E. L., Brown, C. M., Chen, C. P., Keehn, B., Velasquez, F., Lincoln, A. J. and Müller, R.-A. (2016). Sensory symptoms and processing of nonverbal auditory and visual stimuli in children with autism spectrum disorder, *J. Autism Dev. Disord.* **46**, 1590–1601. DOI:10.1007/s10803-015-2367-z.
- Stewart, M. E. and Ota, M. (2008). Lexical effects on speech perception in individuals with “autistic” traits, *Cognition* **109**, 157–162. DOI:10.1016/j.cognition.2008.07.010.
- Takayama, Y., Hashimoto, R., Tani, M., Kanai, C., Yamada, T., Watanabe, H., Ono, T., Kato, N. and Iwanami, A. (2014). Standardization of the Japanese version of the Glasgow sensory questionnaire (GSQ), *Res. Autism Spectrum Disord.* **8**, 347–353. DOI:10.1016/j.rasd.2013.12.017.
- Tardif, C., Lainé, F., Rodriguez, M. and Gepner, B. (2007). Slowing down presentation of facial movements and vocal sounds enhances facial expression recognition and induces facial-vocal imitation in children with autism, *J. Autism Dev. Disord.* **37**, 1469–1484. DOI:10.1007/s10803-006-0223-x.
- Thillay, A., Lemaire, M., Roux, S., Houy-Durand, E., Barthélémy, C., Knight, R. T., Bidet-Caulet, A. and Bonnet-Brilhault, F. (2016). Atypical brain mechanisms of prediction according to uncertainty in autism, *Front. Neurosci.* **10**, 317. DOI:10.3389/fnins.2016.00317.

- Todorova, G. K., Hatton, R. E. M. and Pollick, F. E. (2019). Biological motion perception in autism spectrum disorder: a meta-analysis, *Mol. Autism* **10**, 49. DOI:10.1186/s13229-019-0299-8.
- Traunmüller, H. and Öhrström, N. (2007). Audiovisual perception of openness and lip rounding in front vowels, *J. Phon.* **35**, 244–258. DOI:10.1016/j.wocn.2006.03.002.
- van Laarhoven, T., Stekelenburg, J. J. and Vroomen, J. (2019). Increased sub-clinical levels of autistic traits are associated with reduced multisensory integration of audiovisual speech, *Sci. Rep.* **9**, 9535. DOI:10.1038/s41598-019-46084-0.
- von dem Hagen, E. A. H., Stoyanova, R. S., Baron-Cohen, S. and Calder, A. J. (2013). Reduced functional connectivity within and between ‘social’ resting state networks in autism spectrum conditions, *Soc. Cogn. Affect. Neurosci.* **8**, 694–701. DOI:10.1093/scan/nss053.
- Voos, A. C., Pelphrey, K. A. and Kaiser, M. D. (2013). Autistic traits are associated with diminished neural response to affective touch, *Soc. Cogn. Affect. Neurosci.* **8**, 378–386. DOI:10.1093/scan/nss009.
- Williams, D. (1999). *Nobody Nowhere: the Remarkable Autobiography of an Autistic Girl*. Jessica Kingsley Publishers, London, UK.
- Woynarowski, T. G., Kwakye, L. D., Foss-Feig, J. H., Stevenson, R. A., Stone, W. L. and Wallace, M. T. (2013). Multisensory speech perception in children with autism spectrum disorders, *J. Autism Dev. Disord.* **43**, 2891–2902. DOI:10.1007/s10803-013-1836-5.
- Xavier, J., Vignaud, V., Ruggiero, R., Bodeau, N., Cohen, D. and Chaby, L. (2015). A multidimensional approach to the study of emotion recognition in autism spectrum disorders, *Front. Psychol.* **6**, 1954. DOI:10.3389/fpsyg.2015.01954.
- Yaguchi, A. and Hidaka, S. (2018). Distinct autistic traits are differentially associated with the width of the multisensory temporal binding window, *Multisens. Res.* **31**, 523–536. DOI:10.1163/22134808-00002612.
- Zilbovicius, M., Saitovitch, A., Popa, T., Rechtman, E., Diamandis, L., Chabane, N., Brunelle, F., Samson, Y. and Boddaert, N. (2013). Autism, social cognition and superior temporal sulcus, *Open J. Psychiatr.* **3**, 46–55. DOI:10.4236/ojpsych.2013.32A008.