Both high and low spatial frequencies are critical for visual consciousness in autism: Evidence of an emotional attentional blink paradigm.

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**Both high and low spatial frequencies are critical for visual consciousness in autism:
Evidence of an emotional attentional blink paradigm.**

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Abstract

High Spatial Frequencies (HSF - conveying local information) may serve a critical role in visual consciousness. Despite an HSF bias during visual perception in autism, autistic individuals demonstrate impairments in face processing. Our aim was to investigate the respective role of HSF and Low Spatial Frequencies (LSF - conveying coarse information) on visual consciousness in autism. Thirty-two autistic adults and 35 typically developing (TD) controls performed an emotional attentional blink paradigm with spatially filtered distractors. TD participants showed reduced T2 accuracy (i.e., accuracy for the second target given the correct report of the first target T1) after unfiltered and HSF distractors compared to LSF distractors. In the autistic group, we observed lower T2 accuracy than controls after HSF and LSF distractors but not after unfiltered distractors. Results suggest the importance of HSF for visual consciousness in TD participants whereas, both LSF and HSF seem important in autism.

Keywords: autism; spatial frequencies ; visual consciousness ; attentional blink ; face processing

Introduction

Efficient face processing play an important role in successful navigation of the social world (see Oruc et al., 2019) and people demonstrate the remarkable ability to process human faces and to identify emotion on faces (Tanaka, 2001). This ability would partly rely on the treatment of low-level information such as orientation and spatial frequencies (Balas and Verdugo, 2018; Oruc et al., 2019). In a visual stimulus, spatial frequency refers to the energy distribution derived from the Fourier transform, and expressed in the number of cycle per degree of visual angle (Park et al., 2012). Coarse information would be conveyed by Low Spatial Frequencies (LSF - below two cycles per degree) mainly by the dorsal stream, while fine information would be conveyed by High Spatial Frequencies (HSF - above six cycles per degree) by the ventral stream (Skottun, 2015). Addressing specifically the question of the interaction between spatial frequency and consciousness during face processing, De Gardelle & Kouider (2010) demonstrated that HSF information, more than LSF, correlates with consciousness. Previous behavioral studies also showed that HSF components would dominate conscious perception when the exposition time is long enough (Schyns and Oliva, 1994), i.e., more than 100 ms. These findings are corroborated by neurobiological evidence from functional magnetic resonance imaging as the processing of HSF information from faces involved the inferior occipital and fusiform gyri (Iidaka et al., 2004; Vuilleumier et al., 2003), regions implied in conscious perception. Indeed, the recording of single neuron response in the medial temporal lobe showed firing related to conscious perception (Quiroga et al., 2008). Electrophysiological studies also demonstrated that conscious face perception correlates with a boost in the activity of the N170 in the occipito-temporal cortex (Navajas et al., 2013). In sum, there is a body of evidence that HSF would be related to visual consciousness of faces due to the cortical structure underlying their processing.

Autistic individuals are characterized by impairments in several aspects of face processing, included face identification and facial emotion recognition (Oruc et al., 2018; for reviews see Dawson et al., 2005; Golarai et al., 2006; Tang et al., 2015; Uljarevic and Hamilton, 2013). These impairments may significantly contribute to impaired social interaction, one of the core symptoms of Autism Spectrum Disorders¹ (ASD). It has been suggested that discrepancy between autistic and typically developing (TD) individuals in face

¹ This term is used in keeping with the *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* (DSM-5) but we want to mention and acknowledge that ‘autistic person’ is usually preferred by people on the spectrum. Both terms are used in the paper.

processing could be partly explained by a different use of LSF and HSF. Autistic persons exhibited a perceptual bias toward local information while processing either non-social (Caplette et al., 2016; Kéïta et al., 2014; Mottron et al., 2006) or social visual stimuli such as emotional faces (Deruelle et al., 2008, 2004; Jemel et al., 2006). Given the HSF bias in autism and the critical role of HSF for visual consciousness of faces, the difficulties encountered by autistic individuals in face processing and emotion recognition are surprising. One explanation could be a reduced sensitivity to HSF in regions associated with consciousness in autism. In line with this hypothesis, Corradi-Dell'Acqua and al. (2014) showed a reduced sensitivity to HSF in a part of the fusiform gyrus (the fusiform face area) in autism compared to control, whereas the response to LSF was intact. Interestingly, this result could also explain that the fusiform face area has often been found hypoactivated in autism during face processing (Golarai et al., 2006). As the fusiform is associated with visual consciousness and belongs to the social brain network, a primary fusiform deficit might disturb several mechanisms relying on face perception, such as emotion recognition (Dawson et al., 2005). However, this result has not been reproduced and moreover, it does not explain the previously reported better use of HSF in autism for categorizing emotional face. Thus, it is unclear which spatial frequencies play a critical role in visual consciousness of emotional faces in autism. Answering this question would help us to understand if there are atypical low-level visual processing that could be linked to atypical visual consciousness of faces in autism and that could explain some difficulties in face processing. We therefore considered that the attentional blink paradigm would be useful for this investigation.

Rapid Serial Visual Presentation paradigms have been utilized to study visual consciousness by manipulating the time course of attention. During this type of tasks, participants are asked to detect two visual targets (T1 and T2) embedded among a stream of distractors presented at a frequency of about 10 items per second (Shapiro et al., 1997). People typically show high accuracy of detecting the first target T1 (Olivers and Meeter, 2008). However, the conscious perception and the subsequent report of the second target T2 is inconsistent depending on the lag between the two targets (Shapiro et al., 1997). When the lag between T1 and T2 is very short (below 200 ms), the detection of the second target T2 is good, often better than the detection of the first target T1, which is called the Lag-1 sparing phenomenon (Olivers and Meeter, 2008). On the contrary, a second target T2 occurring between 200 ms and 500 ms after T1 often escape from conscious perception (Olivers and Meeter, 2008), which is called the attentional blink (AB). The boost and bounce theory of

temporal attention (Olivers and Meeter, 2008) explains both the Lag-1 sparing and the AB. As for the Lag-1 sparing, it was assumed that a target stimulus just following T1 would receive an attentional enhancement (boost) from excitatory feedbacks elicited by the visual input whenever relevant information was processed. T1 opened a gate, which then remained opened for subsequent relevant information, which allowed it to enter into working memory. However, irrelevant stimuli would receive strong inhibitory signal that blocked the gate (bounce), inhibiting the conscious perception of T2, thereby resulting in the AB.

Previous research has shown that different types of tasks and individual differences can influence T1 or T2 reports. For instance, high similarity between targets and distractors increases the AB (Müsch et al., 2012), while emotional stimuli decreases it (De Jong et al., 2009; Maratos et al., 2008). Also, T1 and T2 report could vary according to the category they belong (e.g., animals are more reliably detected than plants - Balas and Momen, 2014) and could be modulated by individual differences such as age (Georgiou-Karistianis et al., 2007), Full Scale Intelligence Quotient (Colzato et al., 2007) or by a diagnosis such as schizophrenia (Mathis et al., 2011), attention deficit disorder (Amador-Campos et al., 2015) or also autism. There was no difference in the AB magnitude between TD and autistic participants when letter stimuli were used (Amirault et al., 2009; Rinehart et al., 2010). However, when T2 were emotional words, compared to neutral words or male names, an enhancement of T2 report was observed in TD controls, i.e., reduced AB, which was attenuated in autistic individuals, i.e., less reduced AB compared to control (Gaigg and Bowler, 2009). Nonetheless, when the effect of emotional faces was explored by using angry and neutral faces as targets, no difference were found between autistic children and the control group: ASD and TD showed better T2 accuracy for angry targets compared to neutral targets, and the magnitude of the effect was similar for both groups (Yerys et al., 2013). Yerys and al. (2013) made several hypotheses to explain different results in their experiment from those of Gaigg and Bowler (2009). First, the arousal levels of the stimuli might differ between the two experiments. Second, Gaigg and Bowler experiment required verbal abilities as stimuli are words, while Yerys and al. pictorial AB task required lower-level abilities. Finally, they hypothesized that low similarity between targets (dog for T1 and emotional or neutral face for T2) and distractors (non-meaningful scrambled faces) in their experiment enhanced salience of targets among distractors. In other words, they supposed that low similarity between targets and distractors facilitated target detection by intensifying the emotional valence of faces, thereby enhancing performances in autistic participants and reducing differences between the groups

on emotional stimuli. On the contrary, high similarity between targets and distractors can account for an increased AB as shown in TD (Müsch et al., 2012; Visser et al., 2004).

The aim of our current study was to investigate the link between visual consciousness of emotional face stimuli, operationally defined by the AB, and fundamental low-level visual processing, operationally defined by using spatial frequencies, in autism compared to TD participants. We created an AB task, where participants had to detect two unfiltered happy faces (T1 and T2) in a stream of angry faces distractors, which were either in LSF, HSF or unfiltered. We chose happy and angry emotions because it is easy to differentiate them. Happiness is not confused with other emotions and the salient and distinctive smile of happy faces is easily identified, probably because the recognition of facial expression relies more on perceptual processing than on affective dimensions (Calvo and Nummenmaa, 2016). Happy faces are usually well recognized by autistic participants (similarly as control; for a meta-analysis, see Uljarevic & Hamilton, 2013), but this might be the result of efficient compensatory strategies based on cognitive and linguistic resources (Harms et al., 2010). Hence, using happy faces enabled us to focus on the role that HSF and LSF played in visual consciousness of emotional faces in autism, while keeping the task feasible by autistic participants. We capitalized on the finding that spatial-frequency filtered distractors would allow us to manipulate similarity between targets and distractors: the more similar the target and the distractors would be, the greater the AB. We reasoned that, manipulating spatial frequency filtering of the distractors, more than targets, was an interesting way to investigate incidentally which type of low-level information is important for visual consciousness, while keeping a target ecologically intact. In this experiment, we tested three main hypotheses. Firstly, we predicted a strong AB effect in both groups, as distractors have a high degree of similarity with targets because they are all faces. Secondly, given a pivotal role that HSF plays in visual consciousness during face processing, we expected a stronger AB after HSF and unfiltered distractors (as it also contains HSF) compared to LSF distractors in both groups. Lastly, due to the HSF bias for emotional face recognition in ASD, autistic participants would be significantly more disturbed by HSF distractors than TD participants.

Similar to other AB studies, we controlled for T1 accuracy. We also assessed the Full Scale Intelligence Quotient (FSIQ), verbal Intelligence Quotient (VIQ), Performance Intelligence Quotient (PIQ), Autism spectrum Quotient (AQ - Baron-Cohen et al., 2001) and age, to control for these variables (Gaigg and Bowler, 2009; Georgiou-Karistianis et al., 2007).

Method

Participants

Sample size was determined according to studies comparing autistic and control groups during an AB task (Gaigg and Bowler, 2009; Yerys et al., 2013), as there was no study investigating spatial frequencies in a AB task allowing a proper power analysis. Thirty-three autistic adults (15 females, 15 males, 2 transgenders female-to-male) and 35 TD control adults (17 females, 17 males, and 1 transgender female-to-male) were recruited for this study. We recruited a similar number of males and females on purpose, as a second task was performed by the participants after the AB task, in which sex differences were investigated. One autistic man was excluded from the analysis as the task was too difficult for him and he skipped all answers. All participants were aged from 19 to 47 years and had a FSIQ > 70 , as estimated using a Wechsler Intelligence Scale (Wechsler Intelligence Scale for Children, 4th Edition - WISC-IV; Wechsler, 2003 - or Wechsler Adult Intelligence Scale, 3rd or 4th Edition - WAIS-III ; Wechsler, 1997 - or WAIS-IV; Wechsler, 2008). They all reported a normal or corrected-to-normal vision.

Autistic participants were recruited through local community, with the help of local Expertise Centers dedicated to autism diagnosis, clinicians specialized in ASD support or associations for the autistic community. We ensured that they previously received a clinical diagnosis based on the DSM-IV-R (American Psychiatric Association, 2003) or DSM-5 (American Psychiatric Association, 2013) criteria or on the International Classification of Disease 10th revision (OMS and Collectif, 1992) by asking them to show us the written report of their diagnosis. We collected the scores of the Autism Diagnostic Observation Schedule (Lord et al., 1989), the Autism Diagnostic Interview-Revised (Lord et al., 1994) and IQ when they were available. Their age at diagnosis was between 10 and 45 years old (mean = 28.5, SD = 10.1). Three of them also received a diagnosis of attention deficit with or without hyperactivity disorder (one of them was treated with methylphenidate); two received a diagnosis of anxiety disorder and two had a history of traumatic brain injury. Two were receiving neuroleptic medication and six were used to take antidepressant when they were enrolled in the study but were stabilized with the treatment. Twenty-one autistic participants had neither other diagnosis nor treatment. For those who could not provide available IQ data (8 individuals), an estimation of their FSIQ, VIQ, and PIQ was performed using four selected subtests (Vocabulary, Similarities, Block Design and Matrix) of the WAIS-IV (Grégoire and Wierzbicki, 2009; Wechsler, 2008). Note that 10 ASD participants scored below the cut-off of

32 on the AQ. We kept them as AQ does not fully capture autism symptoms in autistic persons who have poor insight (Bishop and Seltzer, 2012), showed by a weak correlation with ADOS scores sometimes (Ashwood et al., 2016). Indeed, AQ scores were primary collected to remove TD participants with high AQ but was not aimed to exclude ASD participants as they have been diagnosed by expert professionals. Detailed information and scores for each participant can be found in the following repository :

https://osf.io/maqvz/?view_only=3002780bdf8247ecb3669e9870b4c00d.

TD adults were recruited via advertisements and mailing list. They didn't have any neurological, neurodevelopmental or psychiatric diagnosis. As far as possible, groups were paired on sex, age and education. An estimation of their FSIQ, VIQ, and PIQ was performed.

After having checked assumptions, we performed two-sample t-test. Groups did not differ on age, education, VIQ, and FSIQ. Nevertheless, it is worth noting that differences between groups on FSIQ is approaching the significance threshold and may be related to the significant difference between groups on PIQ. As predicted, groups differed on the AQ. All relevant statistics regarding groups description are set out in *Table 1*.

Table 1: Subject demographics – *Means (M), standard deviations (SD) and ranges*. FSIQ = Full Scale Intelligence Quotient; VIQ = Verbal Intelligence Quotient; PIQ = Performance Intelligence Quotient ; AQ = Autism-Spectrum Quotient.

	TD (n= 35)			ASD (n= 32)			T-test	Effect size
	<i>M</i>	<i>SD</i>	<i>Range</i>	<i>M</i>	<i>SD</i>	<i>Range</i>	<i>p</i>	<i>Cohen's d</i>
Age	31.9	7.6	19 - 44	32.7	8.3	19 - 47	.702	
Education	15.9	2.7	10 - 24	14.6	2.7	9 - 20	.052	
FSIQ	114.5	14.6	74 - 160	122.5	18.2	70 - 155	.051	
VIQ	121.7	15.8	88 - 150	127.6	17.5	72 - 150	.242	
PIQ	103.8	14.4	68 - 150	113.7	15.7	70 - 142	<.01	.66 (medium)
AQ	15.3	6.1	4 - 29	35.3	8.1	18 - 47	<.001***	2.79 (large)
Age at diagnosis				28.8	10.5	10 - 45		

After a verbal instruction, written informed consent was obtained from all individual participants. Participants received a monetary compensation for their participation at the end of the study.

All procedures performed in this study involving human participants were in accordance with the Code of Ethics of the World Medical Association (Declaration of

Helsinki) and approved by the local ethics committee (CER-Grenoble Alps, COMUE University Grenoble Alpes, IRB00010290).

Material

The stimulus set comprised 80 faces on a grey background from the Chicago Faces Database (Ma et al., 2015): 20 females and 20 males, Caucasians, aged between 18 and 40, expressing either happiness with open mouth for targets or anger with closed mouth for distractors. We carefully controlled the gender of stimuli since it may cause gender bias interacting with emotions (Plant et al., 2004; Villepoux et al., 2015). They were high resolution (2444 x 1718 pixels) and cropped to a 2288 x 1716 pixel size (18.4° x 13.8°). All stimuli were converted to 256 gray levels by averaging the red, green, and blue values of each pixel, then exported into a BMP format in order to standardize file size and load speed. Happy faces were the target stimuli and always presented unfiltered (i.e., in Broad Spatial Frequency – BSF). Angry faces were distractors and were presented either in BSF, LSF containing only frequencies below two cycles per degree of visual angle (corresponding to 36.89 cycles per image width, that is 10.78 cycles per face), or HSF containing only frequencies above six cycles per degree of visual angle (corresponding 110.69 cycles per image width, that is, 31.44 cycles per face). We used a pseudo-randomized list of stimuli. This list was constructed so that for each trial all individuals in our sample of the Chicago Face Database were randomly ordered, then assigned an emotional facial expression and an image filtering according to their timing in the RSVP. Four individuals that did not appear in the RSVP were used for the multiple choices at the end of the trial. Individuals' gender was therefore entirely random and the order of appearance of the 180 trials was randomized by E-Prime (Psychology Software Tools Inc., Pittsburgh, PA). Examples of stimuli and distractors can be seen on *Figure 1*. Stimuli were equalized in luminance and contrast (Kauffmann et al., 2015). Filtering and equalizing procedures were performed using MATLAB (Mathworks Inc., Sherborn, MA, USA). Stimuli were displayed in a darkened experimental box of the Psychology and NeuroCognition Laboratory (Grenoble Alpes University), on a 23-inch LCD monitor Dell P2319H (refresh rate = 75 Hz) at a viewing distance of 117 cm. To maintain the distance and central position, participants' head was supported by a chinrest. E-prime version 2.0 (Psychology Software Tools Inc., Pittsburgh, PA) was used to exhibit stimuli and collect behavioral data. As some participants could not easily come many times to the laboratory, on the same day, after the AB task of 30 minutes duration, they also did another 15 minutes study, after a break. If needed, IQ estimation was done after these tasks.

Figure 1. A. Examples of happy and angry stimuli used during the task. B. Examples of distractors used during the task. The left one is in High Spatial Frequencies (HSF), the middle one is unfiltered (BSF) and the right one is in Low Spatial Frequencies (LSF).

Procedure

Instructions were given both orally and on a written form. Each participant performed the task individually. Participants were informed that a stream of angry faces would be displayed, two happy faces would appear among them and should be memorized in order to recognize each of them among three others at the end of the stream. They were informed of the rapid presentation and were instructed to concentrate a lot for the task. A training session of 8 trials was performed by the participant before the experimental session of 180 trials, which included three breaks (every 45 trials) in order to decrease the attentional load required by the task and allow participants to rest their eyes. During the training session, the experimenter stayed with the participant in order to ensure that instructions had been correctly understood and to reassure the participant if the task's difficulty generated anxiety. After this training session, the experimenter left the room. Each trial began with a fixation cross for approximately 1,000 milliseconds (ms), followed by a sequence of four, five, six or seven

unfiltered angry faces followed by T1 (an unfiltered happy face). The second unfiltered happy face T2 appeared after a second serial of two (Lag 3), four (Lag 5) or six (Lag 7) distractors, which were either in BSF, LSF, or HSF. Lag 0 corresponds to the onset of T1. Each stimulus had a duration of 133 ms. Accordingly, stimulus onset asynchrony was either 399 ms (Lag 3), 665 ms (Lag 5), or 931 ms (Lag 7). As emotional faces are complex stimuli, longer presentation times have been required compared to experiments using letters, in order to reduce task difficulty. For each trial, distractors were similarly filtered and five unfiltered distractors remained after T2. After this rapid serial visual presentation, a screen appeared for 4,000 ms with three happy faces on the upper half. Right-handed participants had to choose which of these three faces corresponded to T1 by pressing one of the three corresponding buttons on the right side of the Chronos® device (Psychology Software Tools). Importantly, participants were instructed not to answer randomly and had to press the far-left button if they had no idea about the answer. For left-handed participants, the buttons were situated on the left side to facilitate the motor response. Then, a second screen appeared for the same duration with three unfiltered happy faces displayed on the lower half; this was made to ensure participants would notice the change. Participants were instructed to find T2 among the three faces. The schematic of one trial is shown in *Figure 2*.

Figure 2 Example of a trial with HSF as distractors. Target 1 has to be selected among other faces on the *Answer 1* slide and Target 2 has to be selected among other faces on the *Answer 2* slide.

Results

All figures and analyses were done using R version 3.6.1 and R Studio version 1.2.5019 (R Core Team, 2019).

Analysis on T2 accuracy (given a correct answer on T1)

Figure 3. Mean T2 accuracy (given a correct answer on T1) and standard errors by group for each Lag and in each Distractor condition. Only significant between groups differences for each Distractor type depending on Lag are represented (* = $p < .05$, ** = $p < .005$).

Table 2. Mean T2 accuracy (and standard errors; SE) for each condition.

Distractor	TD			ASD			All			Mean for each Distractor
	Lag 3	Lag 5	Lag7	Lag 3	Lag 5	Lag7	Lag 3	Lag 5	Lag7	
BSF	26.3 % (3.1)	36.8 % (3.2)	47.4 % (3.2)	21.1 % (3.8)	30.7 % (4.3)	41.1 % (4.3)	23.8 % (2.4)	33.9 % (2.7)	44.4 % (2.7)	34.0 % (1.6)
LSF	23.4 % (2.9)	45.9 % (3.1)	57.1 % (2.7)	19.0 % (3.6)	34.0 % (4.3)	41.7 % (4.5)	21.3 % (2.3)	40.2 % (2.7)	49.7 % (2.7)	37.1 % (1.7)
HSF	21.5 % (3.1)	33.8 % (3.0)	44.8 % (3.8)	16.2 % (3.3)	25.4 % (4.2)	33.4 % (4.8)	19.0 % (2.3)	29.8 % (2.6)	39.3 % (3.1)	29.4 % (1.6)
Mean for each Lag	23.7 % (1.7)	38.8 % (1.9)	49.7 % (1.9)	18.8 % (2.0)	24.2 % (2.5)	38.7 % (2.6)	21.4 % (1.3)	34.6 % (1.6)	44.5 % (1.7)	
General mean	37.4 % (1.2)			29.2 % (1.5)			33.5 % (0.9)			

We calculated the correct response rate (accuracy) for T2 given that T1 was correctly reported (Gaigg and Bowler, 2009; Shapiro et al., 1997; Yerys et al., 2013) for each of the experimental conditions. This latter is abbreviated “T2 accuracy” in the following text. *Figure 3* represents the T2 accuracy for each group (ASD, TD) as a function of Lag (3, 5, and 7) and Distractor (BSF, HSF, and LSF). All means and standard errors for T2 accuracy are reported in *Table 2*. We conducted a mixed-design ANOVA with Group (ASD vs TD participants) as a between subject factor, and Lag (3, 5 or 7) and Distractor (BSF, LSF or HSF) as within-subject factors. Assumptions of sphericity were tested with Mauchly Test. As there was no violation of sphericity, no correction was required. The normality assumption on residuals were visually inspected with histogram and qq-plot, and tested with a Shapiro-Wilk test.

The analysis revealed three significant main effects. The main effect of Group ($F(1, 65) = 4.14, p = .04, \eta^2 = .04$), indicated that overall T2 accuracy of ASD participants was significantly lower than overall T2 accuracy of TD participants. A main effect of Lag ($F(1, 85) = 104.8, p < .001, \eta^2 = .17$) was also found. Post-hoc paired t-test with Tukey adjustment showed that T2 accuracy at Lag 3 was worse than T2 accuracy at Lag 5 ($t(130) = -8.27, p < .001, d = -0.65$), which was also worse than T2 accuracy at Lag 7 ($t(130) = -6.15, p < .001, d = -0.43$). These findings demonstrate the expected AB in our paradigm (both groups taken together). Finally, we observed a main effect of Distractor ($F(1, 88) = 17.68, p < .001, \eta^2 = .02$). Post-hoc paired t-test with Tukey adjustment revealed that T2 accuracy after HSF distractors was lower than after BSF distractors ($t(130) = 3.61, p = .001, d = -0.21$), and lower than after LSF distractors ($t(130) = -5.90, p < .001, d = -0.32$). These findings revealed that HSF produced a greater AB than other distractors when groups were taken together. However, the difference between T2 accuracy after BSF distractors and after LSF distractors was not significant.

There was also a significant Lag $\times$ Distractor interaction ($F(3, 85) = 2.96, p = .02, \eta^2 = .007$), attesting that the effects of distractors were different depending on the Lag. Paired t-test with Tukey adjustment revealed that T2 accuracy was lower for HSF than LSF at Lag 5 ($t(390) = -4.66, p < .001, d = -0.48$) and at Lag 7 ($t(390) = -4.61, p < .001, d = -0.43$). This was not observed at Lag 3, suggesting that the greater AB followed by HSF compared to LSF appeared only at longer lags (5 and 7). Moreover, T2 accuracy was significantly lower for BSF than LSF at Lag 5 ($t(390) = -2.79, p < .02, d = -0.29$), but not at Lag 3, and only marginally significant at Lag 7 ($t(390) = -2.29, p = .058, d = -0.24$). Hence, BSF distractors also produced a greater AB than LSF distractors at longer lags.

The data set out in *Figure 3* suggests that the lack of significant difference between BSF and LSF at Lag 7, which was not expected, could be explained by a different pattern in each group. This led us to perform within-group paired t-test with Tukey adjustment although the foregoing analysis provided no interaction involving the group factor (Group $\times$ Distractor: $F(1, 88) = 1.62, p = .20$; Group $\times$ Lag $\times$ Distractor: $F(3, 85) = 0.67, p = .60$). In the TD group, a significant difference in T2 accuracy exists between HSF and LSF at Lag 5 ($t(390) = -3.94, p < .001, d = -0.67$) and at Lag 7 ($t(390) = -3.99, p < .001, d = -0.62$), and between BSF and LSF at Lag 5 ($t(390) = -2.95, p = .009, d = -0.48$) and at Lag 7 ($t(390) = -3.14, p = .005, d = -0.55$). These findings indicate that, as expected, HSF and BSF distractors produce a greater AB than LSF distractors at longer lags (5 and 7) in TD participants. In the ASD group there is a difference in T2 accuracy between HSF and LSF at lag 5 ($t(390) = -2.68, p = .02, d = -0.36$) and at Lag 7 ($t(390) = -2.56, p = .02, d = -0.31$). However, there is no significant difference between BSF and LSF, neither at Lag 5, nor at Lag 7. Hence, in the ASD group, only HSF distractors produced a greater AB than LSF distractors at longer lags (5 and 7). These differences between groups could therefore explain the lack of significance previously found at Lag 7 between BSF and LSF in the main effect and in the interaction. Moreover, the analysis showed a difference in T2 accuracy between BSF and HSF at Lag 7 ($t(390) = 2.39, p = .04, d = 0.30$) for the ASD group, suggesting greater AB after HSF distractors compared to BSF distractors at the longest lag.

Finally, we tested our main hypothesis: HSF distractors would produce a greater AB than LSF distractors for the ASD group as compared to the control group. We performed between-group paired t-tests with Tukey adjustment for each distractor type and within each Lag. The expected between-group difference on T2 accuracy after HSF distractors was only found at Lag 7 ($t(161) = -2.21, p = .03, d = -0.46$). Differences between groups on T2 accuracy were also found after LSF distractors at Lag 5 ($t(161) = -2.31, p = .02, d = -0.55$) and at Lag 7 ($t(161) = -3.00, p = .003, d = -0.73$). These unexpected findings indicate that LSF distractors also produce a greater AB for the ASD group as compared to the TD group at longer lags (5 and 7). No between-group differences in T2 accuracy were found after BSF distractors. These results are represented on *Figure 3*.

Analysis on T1

We calculated a correct response rate for T1 for each participant. The latter is abbreviated by “T1 accuracy” in the text. As variances were unequal, we performed a Mann-Whitney-Wilcoxon test. The test was not significant, indicating that T1 accuracy of autistic participants ($M = 52.7$, $SE = 1.4$) does not significantly differ from T1 accuracy of TD participants ($M = 58.0$, $SE = 0.8$).

Correlation analysis

Correlations plots between AQ, Age, as well as the estimations of FSIQ, VIQ, and PIQ with the T2 accuracy and the T1 accuracy are represented on *Figure 4 A* and *Figure 4 B* respectively. We did not find any significant correlation between T2 accuracy and AQ, FSIQ, nor VIQ. A significant negative correlation between age and T2 accuracy was found for the TD group only ($r = -.43$, $p < .01$), indicating that the older the TD participants, the stronger the AB. We also found a significant negative correlation between age and T1 accuracy in the TD group ($r = -.35$, $p < .05$), revealing that the older TD participants are, the lower is their T1 accuracy. Finally, we found a significant positive correlation between T1 accuracy and FSIQ in the TD group ($r = .41$, $p < .05$) and in the ASD group ($r = .39$, $p < .05$), indicating that the higher FSIQ is, the better is the T1 accuracy. We also found significant positive correlations between T1 accuracy and PIQ in the TD group ($r = .46$, $p < .01$) and in the ASD group ($r = .40$, $p < .05$), revealing that the higher the PIQ is, the better is the T1 accuracy.

Figure 4. A. Correlation plots between T2 accuracy (given correct answer on T1) and Autism-Spectrum Quotient (AQ), age, as well as estimations of Full-Scale Intelligence Quotient (FSIQ), Verbal Intelligence Quotient (VIQ), and Performance Intelligence Quotient (PIQ). B. Correlation plots between T1 accuracy and AQ, age, as well as estimations of FSIQ, VIQ and PIQ.

Discussion

The current study used an AB paradigm with spatial-frequency filtered distractors to investigate which spatial frequencies play a critical role in visual consciousness in autistic adults compared to TD control participants.

Replicating previous results on AB in TD people (Olivers and Meeter, 2008; Shapiro et al., 1997) and in ASD (Amirault et al., 2009; Gaigg and Bowler, 2009; Rinehart et al., 2010; Yerys et al., 2013), our results elicited a strong AB, as T2 accuracy was reduced for shorter lags and increased with longer lags. This finding is consistent with our first hypothesis. Although the timings of Lag 5 (665 ms) and 7 (931 ms) would usually be considered outside of the AB timeframe, we suggest that the AB is observed in longer lags here due to the task difficulty. Indeed, the AB magnitude can be modulated by factors such as task demands (Elliott and Giesbrecht, 2010; Shore et al., 2001).

We also found a stronger AB after HSF distractors and after BSF distractors as compared to LSF distractors, at Lag 5 and at Lag 7 in both groups taken together, which is

consistent with our second hypothesis. This result provides new evidence that HSF could play a primary role in visual consciousness, particularly of emotional faces, as previously suggested (De Gardelle and Kouider, 2010; Schyns and Oliva, 1994). As HSF are mainly conveyed by the ventral stream, our findings could support the idea that visual consciousness emerged, at least in part, from the temporal pathway processing (Navajas et al., 2013; Quiroga et al., 2008; Sergent et al., 2005). It should be noted that the difference between BSF and LSF at Lag 7 was only marginally significant. This could be explained by differences between groups on LSF distractors, which will be further discussed. No difference between distractors at Lag 3 can be explained by the strength of the AB at that lag.

Based on previous findings of perceptual bias favoring HSF information in autism, in general and particularly for emotional face recognition (Caplette et al., 2016; Deruelle et al., 2008, 2004; Jemel et al., 2006; Mottron et al., 2006), we predicted that autistic participants would show significantly reduced T2 accuracy in response to the HSF content of inter-target distractors compared to TD control participants. While there was no difference between groups on T2 accuracy according to distractor types at Lag 3, probably due to the strong AB effect at Lag 3 for both groups, group differences emerged at Lags 5 and 7. Of particular importance is lower T2 accuracy for autistic participants, compared to TD, after HSF distractors at Lag 7, which partially support our hypothesis. Interestingly, at Lags 5 and 7, our analysis also revealed that, in the ASD group, T2 accuracy after BSF were not lower than T2 accuracy after LSF, contrary to the control group and T2 accuracy for the ASD group after LSF distractors was unexpectedly lower as compared to the TD group. Additionally, we did not observe differences between groups on BSF. The latter finding indicates that the main effect of group observed on T2 accuracy in our experiment could be more related to the filtered nature of the distractors than to the emotional content, which could have reduced the AB in TD participants compared to ASD as it has been observed by Gaigg & Bowler (2009). Taken together, these results suggest that low level visual characteristics of both HSF and LSF could be critical for visual consciousness of emotional faces in autism, which may be different from how TD engage in visual processing. In other words, contrary to TD, autistic individuals might require a full spectrum of low-level visual information (i.e., more information than TD) for visual consciousness of emotional faces. Our results could be in line with the Enhanced Perceptual Functioning theory (Mottron et al., 2006) as they revealed a heightened sensitivity to low level characteristics. At a neural level, heightened low-level visual perception in autism could be related to superior functioning of the most posterior

region of the visual brain (Mottron et al., 2006). Our findings are also in line with the different pattern of activation between autistic individuals and control during the processing of emotional faces, the former exhibiting an increased sensitivity to LSF in the ventral occipital cortex (Corradi-Dell'Acqua et al., 2014). This atypical spatial frequencies processing at later stages of visual perception, particularly in temporal areas which are more involved in conscious perception (Sergent et al., 2005), might impair visual consciousness of emotional faces. In sum, atypical processing of low-level information in autism may result in enhanced low-level information sensitivity but in less efficient visuo-integrative processes, leading to atypical visual consciousness which may partly explain the difficulties for autistic individuals in face perception and emotion recognition. However, some alternative hypotheses could also explain the results. Indeed, impairments could also come from other cognitive and affective processes such as those describe hereafter.

Particularly, alexithymia, which can be describe as the inability to identify and describe its own emotions, is associated with autism in around 50% of the individuals (for a review and meta-analysis see Kinnaird et al., 2019). In addition to self-reported measure, alexithymia in autism (and in TD) is also associated with psychological markers such as reduced skin conductance responses (Gaigg et al., 2016). Alexithymia might be the main contributor to emotion recognition impairments in autism (Cook et al., 2013; Oakley et al., 2016; Ola and Gullon-Scott, 2020). This hypothesis could also explain why enhanced perceptual functioning lead to specific impairments in emotional face recognition in autism. Additionally, it would explain the heterogeneity in emotion recognition in autistic individuals (Cook et al., 2013). Thus, it would be of particular interest to include alexithymia scales in research like ours in the future. However, this hypothesis would not explain similar performances in autism and TD after BSF distractors in our experiment.

Alternatively, the sensitivity of autistic participants to filtered distractors could also provide evidence to support predictive coding theories of autism (Brock, 2012; Sinha et al., 2014; Van de Cruys et al., 2014). The general predictive brain framework posits that the brain is constantly generating top-down predictions about the sensory input (bottom-up), relying on an internal model constructed from past experiences (Friston, 2010). Prediction error is the difference between prediction and sensory input. The precision of prediction error can determine the relative weight of top-down versus bottom up information (Friston, 2010) and should be adjusted according to the context (relevance or not of predictive cues). This adjustment might be difficult in autistic individuals and each prediction error might be seen as

important (Van de Cruys et al., 2013). This hypothesis is supported by electrophysiological studies on Mismatch Negativity in autistic adults. The Mismatch Negativity paradigm is used to study brain reactions to an unexpected event occurring among regular events and can be seen as an electrophysiological signal of perceptual prediction errors (Stefanics et al., 2014). Autistic people often elicit atypical reactions to deviant stimuli in Mismatch paradigm (Gomot and Wicker, 2012). In our experiment, the second target appeared after a stream of distractors containing the same low-level characteristics (i.e., the same type of filtering was used for each distractor). It is reasonable to assume that participants became used to low-level characteristics of the distractors (at Lag 5 and 7) and made strong predictions for the next image, based on regularity. When distractors were low-pass or high-pass filtered, the appearance of the unfiltered second target T2 could violate the expectation generated by the statistical regularity of the stream (based on low level information) leading to prediction errors. The disruption of the statistical regularity of the stream may impact autistic participants more, which leads to impaired T2 accuracy. In other words, individuals with autism would struggle to disengage from their prior as they expect to see the same low-level information. The more effortful adaptation to the change in low-level features in T2 would prevent them to memorize the face, subsequently impairing their accuracy. By contrast, TD can more flexibly adapt the disruption of the statistical regularity and could stay concentrated on the task, without being disturbed by low-level changes. In the case of BSF distractors, targets and distractors had the same low-level content, generating no prediction error related to low-level characteristics of the stimuli (i.e., spatial frequencies filtering), which may explain the absence of between-group differences for BSF distractors. This Mismatch perspective on the task is supported by research showing MMN elicited by emotional faces among neutral faces of different actors (Astikainen et al., 2013), meaning that regularity can be extracted despite some variations in the standard stimuli. It is also supported by research showing MMN elicited by spatial frequency changes (Heslenfeld, 2003; Sulykos and Czigler, 2011). However, further research would be needed to investigate this idea.

Less importantly, T2 accuracy appear reduced in our experiment (i.e., $M = 33.5\%$) as compared to other experiments (where T2 accuracy range from approximately 60 % to 90 %), even if they implied autistic participants (Gaigg and Bowler, 2009; Yerys et al., 2013). It could be surprising as an attenuation of the AB (i.e., better T2 accuracy) is usually observed when targets are emotional faces (De Jong et al., 2009; Maratos et al., 2008). However, the similarity between targets and distractors, which were all emotional faces in our task, can

reduce salience of targets among distractors thus increasing the AB (Müsch et al., 2012; Raymond et al., 1995; Yerys et al., 2013). In addition, the answer choice in our task was presumably harder as compared to other similar tasks and may affect performances. Indeed, our participants have to identify the T1 face between three happy faces (and the same for T2). Finding a target face among three faces, without answering by chance, is more difficult than a dichotomous yes/no answer on a question such as “*Did you see a face?*”. Additionally, we gave the instruction not to answer by chance, giving the possibility to choose “*I don’t know*”. The general repartition of answers on T2 was the following: 38.6% “*I don’t know*”, 0.5 % No answer, 33.5% correct answers and 27.4% incorrect answers. Thus, considering only the trials when participants answer (i.e., the participant has a slight to strong degree of certainty regarding his answer), participants chose the correct answer in more than 50% (chance level at 33%). To better account for the confidence of participants, it could be interesting to employ a method used in Eiserbeck and Abdel Rahman (2020) in future research instead of offering the possibility to answer “*I don’t know*”. They used an AB paradigm with faces using objective as well as subjective criterion (i.e., degree of certainty of the participant regarding T2) as an index of T2 detection (Eiserbeck and Abdel Rahman, 2020). Whereas correct T2 report with a “slight impression” was between 70 % and 74 % (which is in accordance to usual T2 accuracy in AB task), correct T2 report with a “strong impression” was between 33 % and 36 % (which is similar to T2 accuracy in our task).

The task difficulty probably impaired T1 recognition as well. Indeed, we observed apparent poorer T1 accuracy in our experiment with greater variability as compared to T1 accuracy usually observed in other experiments. T1 accuracy was similar in both group, in accordance with intact happy faces identification in autism (Uljarevic and Hamilton, 2013). A correlation exists between T1 accuracy and FSIQ, as well as between T1 and PIQ for both groups, which could be in line with previous studies showing that higher IQ can enhance emotion recognition in both TD and ASD participants (Jones et al., 2011; Wright et al., 2008). Nevertheless, when we removed the few outliers in term of IQ performances (2 ASD and 2 TD participants), the correlations between T1 accuracy and FSIQ and PIQ were not significant anymore, although T1 accuracy still not significantly differed between groups. Correlation between FSIQ and T2 accuracy was not significant neither, which is congruent with previous research (Colzato et al., 2007) and contrary to Gaigg & Bowler (2009), we did not find any correlation between VIQ and T2 accuracy in ASD (nor in TD), which can probably be explained by the non-verbal nature of our task. Taken together, these findings

support the fact that IQ variations among our subjects have not impaired our results. Finally, we found a significant negative correlation between accuracy (for T1 and for T2) and age in TD, performances becoming weaker with age, but this is not found in ASD. AB performances tend to improve between 18 and 39 years old, and then to decline (Georgiou-Karistianis et al., 2007). Hence, the negative correlation could be at odds with the fact that only 9 TD participants are aged 39 and above. However, a fast decrease of performances after 39 might explain this result. Surprisingly, this decline is not observed in ASD participants despite they are a bit older than TD participants in our study (ASD age rank = 19 – 47, median = 33.5; TD age rank = 19 – 44, median = 31.0). Two hypotheses can be brought up. First, it may be related to high IQ of ASD participants as compared to TD in our study. Indeed, higher IQ is usually associated with less cognitive decline (Steffener and Stern, 2012). Second, ASD might also partially protect against a cognitive decline related to age (Lever and Geurts, 2015), which is yet to be determined.

Limitations

Our study has some limitations pertaining to participants. Firstly, autistic participants were adults, mainly late diagnosed and had very high intellectual abilities, thus representing a small subset of autistic adults. Hence, our results cannot be generalized to the whole spectrum. Secondly, there is a high variability in performances of autistic participants, probably reflecting the highly heterogeneous autism spectrum or some other aspects such as, the degree of alexithymia. Data driven analysis might be conducted to distinguish autistic subgroups (see Latinus et al., 2019), but would require larger sample size. Thirdly, the correlation found with age could potentially have a slight impact on the result and should conduct to lower the maximal age in further studies. Finally, we were not able to collect ADOS data from all participants (we collected ADOS scores of 19 participants) although it would have been interesting to study correlation between these scores and performances in addition to the AQ, as the later have sometimes weak correlation with ADOS (Ashwood et al., 2016).

There is another limitation pertaining to the experiment. Our experiment included happy targets only because it has been suggested that people, even with autism, can recognize happy emotion easily. This selection was intentional to focus on low level visual processing, which is the main research hypothesis. Further studies need to determine if the effect of spatial

frequencies reported here is specific to happy faces, or could be observed with other emotional facial expression, with non-social stimuli (e.g. International Affective Picture System) and non-emotional stimuli (e.g. gender, objects, natural scenes).

Conclusion

The present study shed light on the influence of spatial frequencies on visual consciousness in both autistic and TD individuals. The results of the study extend our understanding of the attentional blink phenomenon and of the role of spatial frequencies information for visual consciousness of emotional faces. Our findings suggest that bottom-up HSF information is probably more important for exogenous consciousness for TD participants, and even more in autism, compared to top-down LSF information provided by the orbitofrontal cortex. Additionally, our findings suggest that visual consciousness in autism rely also on LSF. It could indicate increased sensitivity to low-level visual characteristics in autism and be in accordance with the Enhanced Perceptual Functioning framework, an influential model of autism. Our results could be also explained by predictive coding frameworks, which are emerging models for explaining autism characteristics. However, further studies are required to tease apart low-level processing from predictive coding processing in autism. Results of the current research could have implications for our understanding of atypical visual processing in autism, which can partly contribute to social deficits.

List of abbreviations

ASD = Autism Spectrum Disorder

BSF = Broad Spatial Frequencies

cpd = cycle per degree

DSM = Diagnostic and Statistical of Mental Disorder

FSIQ = Full Scale Intelligence Quotient

620 HSF = High Spatial Frequencies
 621 IQ = Intelligence Quotient
 622 LSF = Low Spatial Frequencies
 623 ms = milliseconds
 624 PIQ = Performance Intelligence Quotient
 625 TD = Typically Developing
 626 VIQ = Verbal Intelligence Quotient
 627 WAIS = Wechsler Adult Intelligence Scale
 628 WISC = Wechsler Intelligence Scale for Children

629

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635 *Disclosure statement*

636 The authors declare that they have no competing interests.

637 *Data availability statement*

638 The datasets generated and/or analyzed during the current study are available in the Open
 639 Science Framework repository
 640 https://osf.io/maqyz/?view_only=3002780bdf8247ecb3669e9870b4c00d. E-prime experiment
 641 and stimuli are available in the following repository: <https://osf.io/n4svb/>. Any other materials
 642 are available from the corresponding author on reasonable request.

643 *Ethics approval and consent to participate*

644 Written informed consent was obtained from all individual participants included in the study.
 645 All procedures performed in this study involving human participants were in accordance with
 646 the Code of Ethics of the World Medical Association (Declaration of Helsinki) and approved

by the local ethics committee (CER-Grenoble Alps, COMUE University Grenoble Alpes, IRB00010290).

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Author's contribution

AL collected, analyzed, interpreted the data, and wrote the manuscript. MG and MM were major contributors to data interpretation and writing of the manuscript. MF largely contributed to data collection. MP and MM conceived the experiment. GP, CP, NV, MP and FD contributed in data interpretation and substantively revised the manuscript. All authors provided approval for publication of the content.

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