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ORIGINAL INVESTIGATION

Spatial frequency processing and its modulation by emotional content in severe alcohol use disorder

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Rationale Visuo-perceptive deficits in severe alcohol use disorder (SAUD) remain little understood, notably regarding the respective involvement of the two main human visual streams, i.e., magnocellular (MC) and parvocellular (PC) pathways, in these deficits. Besides, in healthy populations, low-level visual perception can adapt depending on the nature of visual cues, among which emotional features, but this MC and PC pathway adaptation to emotional content is unexplored in SAUD.
Objectives To assess MC and PC functioning as well as their emotional modulations in SAUD.
Methods We used sensitivity indices (d') and repeated-measures analyses of variance to compare orientation judgments of Gabor patches sampled at various MC- and PC-related spatial frequencies in 35 individuals with SAUD and 38 matched healthy controls. We then explored how emotional content modulated performances by introducing neutral or fearful face cues immediately before the Gabor patches and added the type of cue in the analyses.
Results SAUD patients showed a general reduction in sensitivity across all spatial frequencies, indicating impoverished processing of both coarse and fine-scale visual content. However, we observed selective impairments depending on facial cues: individuals with SAUD processed intermediate spatial frequencies less efficiently than healthy controls following neutral faces, whereas group differences emerged for the highest spatial frequencies following fearful faces. Altogether, SAUD was associated with mixed MC and PC deficits that may vary according to emotional content, in line with a flexible but suboptimal use of low-level visual content. Such subtle alterations could have implications for everyday life's complex visual judgments.

Keywords Alcohol use disorder · Vision · Visual pathways · Spatial frequency · Emotion · Faces · Magnocellular · Parvocellular

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Introduction

Severe alcohol use disorder (SAUD) refers to an excessive and chronic pattern of alcohol consumption characterized by the inability to control one's consumption and to resist the urge to seek and drink alcohol despite notable consequences on health, as well as on the family, leisure and/or professional spheres (DSM-5; American Psychiatric Association 2013). It corresponds to the extreme of a continuum ranging from mild to moderate, and finally severe, alcohol use disorder, depending on the number of diagnostic criteria fulfilled by the individual. SAUD is associated with neuropsychological deficits encompassing cognitive, socio-affective, but also sensory disturbances (Creupelandt et al. 2021a, b), among which visual alterations. Indeed, patients with SAUD present reduced perception of motion and speed (Chambers and Wilson 1968; Wegner et al. 2001), consistent with higher temporal frequency thresholds (Williams 1984; Pillunat et al. 1985), as well as color vision modifications (Mergler et al. 1988; Braun and Richer 1993; Kapitany et al. 1993; Martins et al. 2019), and changes in luminance contrast sensitivity and gain (Creupelandt et al. 2021c). These behavioral impairments are associated with alterations in the brain networks related to visual processing (e.g., Bagga et al. 2014; Fein et al. 2009; Mackey et al. 2019). Together, these deficits have significant implications for research purposes, as they qualify our interpretation of results from cognitive tasks based on visual stimuli, but also impact everyday life functioning, as individuals with SAUD may base their decisions on perceptually degraded information. Recent results also hint at a link with treatment outcomes by showing predictive associations between smaller gray matter volumes in vision-related regions and relapse (Rando et al. 2011; Wang et al. 2018). This finding highlights the potential importance of sensory processing for rehabilitation and the need to focus on the long-term effects of alcohol on vision, beyond the temporary visual changes related to acute alcohol intoxication, which have been much more explored, notably in relation to driving (Hartung et al. 2020; Martino et al. 2021).

However, little effort has been made to interpret such visual perceptual deficits in light of our current understanding of the human visual system. So far, studies have rarely considered the division of vision into two main anatomo-functional streams, namely, the magnocellular (MC) and parvocellular (PC) pathways. This division originates in retinal ganglion cells, or even photoreceptors, so that the MC and PC pathways carry different types of information (Wandell 1995). MC cells have low spatial but high temporal sensitivity. They show high contrast sensitivity to achromatic stimuli, respond transiently with short latencies, and project predominantly to dorsal cortical areas where they promote spatial vision, notably through motion and depth (Kravitz et al. 2011; Livingstone and Hubel 1988; Merigan and Maunsell 1993). Conversely, PC cells are highly spatially sensitive but show low temporal and contrast sensitivity. They convey a tonic chromatic signal at low conduction velocities to the temporal cortex, where they contribute to the recognition of shapes and visual identities (Livingstone and Hubel 1988; Merigan and Maunsell 1993; Kravitz et al. 2013). Considering their distinct characteristics, exploring MC- and PC-related properties may thus help to better delineate visual perceptual deficits in SAUD.

One way to assess MC and PC functioning while informing about low-level processing is to explore spatial frequencies (SF). SF constitute the building blocks of vision and code the variations in contrast that occur at various frequencies across space (De Valois and De Valois 1988; Goldstein 2010). The outcome forms the basis for higher-level operations such as categorization and recognition (Morrison and Schyns 2001). Low SF (LSF) correspond to large-scale variations in luminance that match the large receptive fields of MC cells. They provide coarse global information about an image, such as its general shape, orientation, and proportions (Loftus and Harley 2004; Bar 2004). By contrast, high SF (HSF) reflect the small-scale variations in luminance captured by the narrower receptive fields of PC cells. They inform about details such as edges and borders (Loftus and Harley 2004; Bar 2004). SF processing acts in a dynamic coarse-to-fine fashion under natural viewing conditions, where the rapid but coarse MC input informs the slower but more detailed PC analysis (Nirody 2014; Purushothaman et al. 2014). Considering this synergy, it is important to clarify whether the visual deficits associated with SAUD initially arise from MC and/or PC alterations, as the origin of perceptual errors is not detectable based on the final behavioral output mixing PC and MC contributions.

Current results regarding SF processing in SAUD are mixed. Measuring the contrast sensitivity function, i.e., the inverse U-shaped function that describes how contrast sensitivity varies with SF (Campbell and Robson, 1968), some found impaired contrast sensitivity at all SF (Roquelaure et al. 1995; Cruz et al. 2016), whereas other did not spot any difference at any SF compared to healthy controls (de Oliveira Castro et al. 2009). According to Roquelaure et al. (1995), individuals with SAUD show stronger reductions in contrast sensitivity for LSF and HSF than intermediate SF, with a switch in optimal sensitivity toward lower SF ranges compared to healthy controls. However, Martins et al. (2019) observed reduced contrast sensitivity at very LSF only (0.3 and 0.5 cycles per degree, cpd). Additional empirical data is thus needed.

Recent research also stresses that vision is a flexible mechanism, influenced in a top-down fashion by endogenous factors, such as attention, memory, and emotion (Panichello et al. 2013; Newen and Vetter 2017). Indeed, healthy individuals use SF flexibly depending on the needs of the tasks and categories of visual stimuli to be processed (Morrison and Schyns 2001). In this framework, affective content can influence vision by sharpening or conversely blunting perceptual processes depending on their contextual relevance. This assumption is supported by empirical data, notably by Bocanegra and Zeelenberg (2009) who showed that the presentation of a fearful face biases the perception of directly following Gabor patches. They documented improved visibility of LSF over HSF, implying that fearful cues favored fast temporal vision at the expense of fine-grained spatial vision. They concluded that emotions facilitate rapid and coarse MC processing and tune the visual system toward the perceptual features most important for threat detection (see also Phelps et al. 2006). Exploring such interactions in patients with SAUD could help to understand their emotion decoding difficulties, notably for facial emotional expressions (Bora and Zorlu 2017; Hoffman et al. 2019). Indeed, the underlying rationale is to examine how the visual system is tuned after viewing an emotional stimulus, as if we could capture an image of the visual system state when processing it, indexed by participants' sensibility to the following visual stimulation. In this context, a lack of flexible use of SF may contribute to explaining the inability of individuals with SAUD to process the most relevant facial cues, contributing to lowering their decoding performances. More generally, reduced visual flexibility may also increase the cognitive cost of many visually-based processes, opening new clinical and research avenues.

Accordingly, our objective was two-fold: measuring MC and PC functioning through SF processing, and exploring its flexible use following the presentation of an emotional face in a group of individuals with SAUD and matched healthy controls. To do so, we replicated the experimental paradigm of Bocanegra and Zeelenberg (2009), which was specifically calibrated to distinguish MC and PC functioning, and asked participants to report the orientation of briefly presented Gabor patches containing different SF. Participants first performed a purely perceptual (no-cue) version of the task, and then a second version including facial (neutral/fearful) cues. Based on existing evidence, we hypothesized that the processing of LSF could be maximally affected by SAUD. We also expected individuals with SAUD to show a reduction in the emotional modulation of SF processing compared to healthy controls due to their combined visual and emotional difficulties.

Method

Participants

Thirty-five detoxified inpatients with SAUD recruited from two Belgian treatment facilities (Le Beau Vallon, Saint-Servais; Saint-Luc University Hospital, Brussels) and 38 healthy controls (HC) took part in the study (Table 1), making this sample larger than those used in previous comparable studies while ensuring sufficient statistical power (e.g., $N = 16$ in Bocanegra and Zeelenberg 2009; $N = 17$ in Martins et al. 2019). Inpatients had to fulfill DSM-5 criteria for SAUD (American Psychiatric Association 2013), score a minimum of 20 at the Alcohol Use Disorders Identification Test (AUDIT; Babor et al. 2001), and be free of comorbid psychiatric diagnoses, except tobacco use disorder. The mean abstinence duration was 20 days at testing time (range: 9–40 days). To avoid any influence of alcohol-withdrawal or pharmacological short-term effects, we tested inpatients at the end of their detoxification program, when benzodiazepine

Table 1 Group characteristics for individuals with severe alcohol use disorder (SAUD) and healthy controls (HC): mean (SD)

	SAUD ($N = 35$)	HC ($N = 38$)
Demographic measures		
Gender ratio (M/F)^{NS}	20/15	18/20
Age (in years)^{NS}	46.97 (9.34)	49.47 (10.95)
Education (in years)^{NS}	13.34 (2.73)	13.87 (3.33)
Alcohol and tobacco consumption		
DSM-5 criteria	8.60 (1.68)	NA
AUDIT score***	29.31 (5.58)[a]	2.63 (2.38)
Alcohol units per day***	19.92 (9.12)	0.38 (0.45)
Duration of SAUD (in years)	11.73 (11.20)	NA
Duration of abstinence (in days)	20.03 (5.54)	NA
No. of previous detoxifications	1.74 (2.37)	NA
No. of cigarettes per day***	13.34 (13.09)	1.95 (6.35)
Psychopathological measures		
BDI-II***	17.61 (12.60)[a]	6.95 (7.48)
STAI-A (state)***	34.79 (9.92)[a]	27.97 (7.85)
STAI-B (trait)***	52.71 (8.22)[b]	39.00 (11.01)
LSAS***	46.70 (25.72)[b]	30.56 (22.47)[b]
FrACT examination		
Visual acuity (logMAR)$^{NS\,c}$	−0.11 (0.11)	−0.11 (0.11)

NA not applicable, *NS* non-significant

[a]One missing datum

[b]Two missing data

[c]Results, in logMAR units, express the logarithm of the minimum angle of resolution in minutes of arc. A score of 0.0 logMAR reflects "normal vision", and the better the acuity, the lower the logMAR value.

$^{***}p < 0.001$

medication was stopped or strongly minimized. Only five patients still took benzodiazepines at testing time, with a limited average daily dosage of 8.0 mg (SD = 4.47) of diazepam. We recruited HC through advertisement at the University (UCLouvain, Louvain-la-Neuve), in hospitals, and on social networks. HC had to be free of any history of psychiatric diagnosis (except tobacco use disorder) and drink a maximum of 10 standard alcohol units (1 unit = 10 g of pure ethanol) weekly, with an upper limit of 3 per day. They also had to score lower than 8 at the AUDIT and avoid drinking alcohol 72 h before testing. Common exclusion criteria included uncorrected ophthalmological problems, neurological diseases, and severe head trauma. Participants reported normal or corrected-to-normal vision and audition. Normal visual acuity was confirmed using the Landolt C visual acuity task from the Freiburg Visual Acuity Test (FrACT version 3.9.9a; Bach 1996, 2007). We gathered self-reported measures of depression, state and trait anxiety, and social anxiety via Beck's Depression Inventory (BDI-II; Beck et al. 1996), the State and Trait Inventory forms A and B (Spielberger et al. 1983), and Liebowitz's social anxiety scale (LSAS; Liebowitz 1987), respectively.

The biomedical ethics committee of UCLouvain approved the study protocol, which we carried out following the standards of the Declaration of Helsinki. Participants gave their written informed consent before inclusion in the study, and HC were financially compensated (20€).

Apparatus and stimuli

We ran the tasks on Matlab (Mathworks Inc., version R2017a) using the Psychtoolbox-3 extension (Kleiner et al. 2007). Stimuli were displayed on a 24.5-inch AORUS KD25F screen (240 Hz refresh rate; 1920 × 1080 pixels resolution) calibrated with a Minolta LS-100 photometer and controlled by an ASUS ROG ZEPHYRUS-S-GX535GV-ES021T laptop with an NVidia GeForce RTX 2060 graphic card. A light-grey (25 cd/m^2) fixation point (0.2° × 0.2°) was displayed at the center of the screen on a uniform grey background (15 cd/m^2). Gabor patches were composed of 2° Gaussian enveloped sine wave gratings sampled at 1.5, 2.1, 3.0, 4.2, or 6.0 cpd, and displayed at 30% Michelson luminance contrast. Facial cues (5.2° × 8.2°) were selected from the Radboud Face database (Langner et al. 2010) and depicted prototypical neutral and fearful expressions according to the Facial Action Coding System (FACS, Ekman et al. 2002). We chose the four identities (2 males, 2 females, Online Resource 1) with the highest emotional inter-rater consensus and cropped the eight original pictures (4 identities × 2 facial expressions) to remove non-facial attributes. Faces were then turned to black and white and equalized on luminance and contrast using Matlab's ShineToolbox (Willenbockel et al. 2010).

Procedure

Participants seated 57 cm away from the screen in a dark room, ensuring constant ambient luminance, and performed the perceptual task (~ 7 min) before its emotional counterpart (~ 15 min). In Bocanegra and Zeelenberg (2009), there was no "perceptual task" and participants performed the emotional task preceded by 100 emotional training trials. In our study, they systematically performed the perceptual task first and then the emotional one, each preceded by 20 training trials. We only included 20 training trials per task instead of 100 to avoid making the testing too long and considered that the perceptual task could also contribute to training participants for the emotional task. We recorded responses via keyboard presses ("w" and "m," counterbalanced across participants), and provided brief visual feedback (a plus or minus sign) after each response. This study was part of a more global experiment exploring visual processes in SAUD (Creupelandt et al. 2022).

In the perceptual task (Fig. 1a), participants saw the fixation dot for 500 ms, directly followed by a target Gabor patch for 40 ms, whose content varied according to five SF levels: 1.5, 2.1., 3.0, 4.2, and 6.0 cpd. Those levels were selected

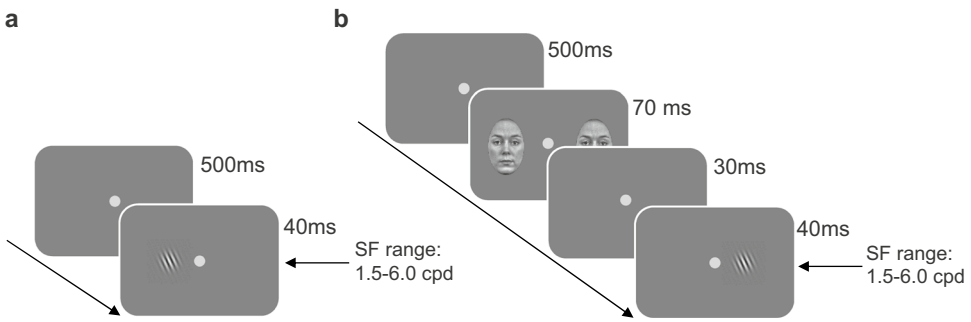

Fig. 1 Illustration of our experimental tasks based on Bocanegra and Zeelenberg (2009). **a** Perceptual task: Target Gabor patches whose spatial frequency content varied from trial to trial appeared randomly on the right or left of the fixation point. Participants had to indicate whether they were slightly tilted or strictly vertical. **b** Emotional task: Facial cues consisting of black and white cropped neutral and fearful faces (male/female) appeared briefly before the target Gabor patches. Instructions remained unchanged. *cpd* cycles per degree, *SF* spatial frequency

to target MC- (< 2 cpd) and PC-related (> 4 cpd) channels (De Valois et al. 2000; Vuilleumier et al. 2003; Leonova et al. 2003; Winston et al. 2003) and to include middle-range SF as well. Gabor patches appeared randomly on the right or left side of the fixation point, at 4° of eccentricity, and were either slightly titled (5.0°) or vertically oriented. Participants had to indicate whether Gabor patches were straight or slightly tilted (to the left or right). Whereas Bocanegra and Zeelenberg (2009) originally calibrated the degree of tilt individually (from 1 to 4°) to obtain approximately 80% of correct responses across SF, we did not perform individual calibrations to generate direct group differences. We also selected a slightly enhanced degree of tilt based on pilot sessions showing that the task was too difficult to perform when the tilt was less pronounced. There were 160 fully randomized trials: 2 (tilted/straight Gabors) × 5 (SF) × 2 (tilted to the left/right) × 2 (left/right position) × 4 (repetitions).

In the emotional task (Fig. 1b), facial cues were briefly (70 ms) displayed before the target Gabor patch. Two identical neutral or fearful faces appeared simultaneously on the screen, one in each visual hemifield, at 10° eccentricity from the fixation point. Facial cues and Gabors were separated by a 30-ms interval with only the fixation point visible. All other parameters remained unchanged, including participants' instructions. There was twice the number of trials ($N = 360$) considering the extra 2-level facial cue (neutral/fearful) factor.

Analytic plan

We conducted the analyses in IBM SPSS Statistics v25.0 (IBM Corp., Armonk, NY) with an alpha set to 0.05. All tests were two-tailed. We compared group characteristics using Mann–Whitney or independent-sample *t*-tests for quantitative variables, and Pearson chi-square tests for qualitative variables. Following the analytic plan proposed by Bocanegra and Zeelenberg (2009), we computed sensitivity indices (d'), calculated as z(hits)–z(false alarms), to get an unbiased measure of accuracy (Macmillan et al. 2004).[1] We applied a repeated-measures analysis of variance (ANOVA) to d' from the perceptual task with Group as a between-subject factor and SF as a within-subject factor and performed a second ANOVA with facial cue as an additional within-subject factor for the emotional task. Consistent with the inverted U-shape of the contrast sensitivity function (Campbell and Robson 1968), we expected d' not to share a strictly linear relationship with SF but rather to follow a negative quadratic function. We thus focused our analysis on linear and quadratic contrasts. Besides, Bocanegra and Zeelenberg (2009) showed that the relationship between d' and SF differs according to facial cues. We tested this hypothesis by decomposing significant interactions involving facial cues into additional ANOVAs followed by complementary Bonferroni-corrected *t*-tests when relevant. As in Bocanegra and Zeelenberg's (2009) paper, we also fitted quadratic functions to predict performance as a function of SF separately for each observer in each task. Based on the obtained fitted parameters, we then calculated the abscissa and ordinate of the estimated points of maximum SF sensitivity. We compared these x and y coordinates across and within groups using Mann–Whitney and Wilcoxon signed ranked tests, respectively. Finally, we measured the association between mean d' from each task and descriptive variables associated with a group difference using Pearson's or Spearman's correlations separately in each group. We also examined correlations between individuals with SAUD's d' and alcohol-related measures as well as medication.

Results

General sample characteristics

Group comparisons (Table 1) showed no difference in age ($U = 550$, $p = 0.204$), gender ratio [$\chi^2(1) = 0.697$, $p = 0.404$], education level ($U = 616$, $p = 0.581$), and visual acuity [$t(71) = -0.504$, $p. = 616$]. Patients with SAUD reported higher AUDIT scores ($U = 0$, $p < 0.001$) and daily alcohol consumption ($U = 0$, $p < 0.001$) than HC. They also smoked more cigarettes per day ($U = 293$, $p < 0.001$) and reported higher scores of depression ($U = 258$, $p < 0.001$), state anxiety ($U = 368.5$, $p = 0.002$), trait anxiety [$t(69) = 5.869$, $p < 0.001$] and social anxiety ($U = 348$, $p = 0.003$).

Perceptual task

Results revealed a significant Group main effect [$F(1,71) = 4.517$, $p = 0.037$, $\eta^2 = 0.060$], with lower d' in individuals with SAUD than HC. As expected, we also found a significant quadratic contrast for SF [$F(1,71) = 9.738$, $p = 0.003$, $\eta^2 = 0.121$].[2] There was, however, no significant Group X SF linear [$F(1,71) = 0.059$, $p = 0.809$, $\eta^2 = 0.001$] nor quadratic [$F(1,71) = 0.601$, $p = 0.441$, $\eta^2 = 0.008$] contrast, indicating that the group difference did not vary according to SF. Figure 2 illustrates raw d' and quadratic fittings on group means. The ordinate of the estimated point of maximum SF sensitivity[3] calculated on individual fittings was lower in individuals with SAUD [SAUD: M = 1.069,

[1] Raw proportions of hits and false alarms are available in Online Resource 2.

[2] The linear contrast for SF was also significant: $F(1,71) = 109.133$, $p < .001$, $\eta^2 = .606$.

[3] We removed the coordinates of one individual with SAUD whose x and y values exceeded the SAUD group mean from more than 4 and 5 standard deviations, respectively. We re-ran the ANOVA without this participant to ensure that it did not significantly bias our findings. Conclusions remained unchanged.

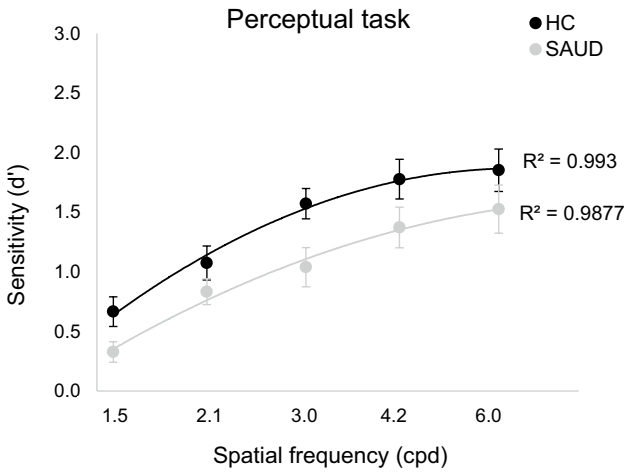

Fig. 2 Raw *d′* and quadratic fittings based on group means for the perceptual task. Error bars represent the standard error of the mean

SD = 1.552; HC: M = 1.559, SD = 1.380; $U = 498$, $p = 0.047$], consistent with the overall group difference. Its location on the abscissa did not differ between groups [SAUD: M = 3.628, SD = 6.608; HC: M = 3.890, SD = 4.197; $U = 601$, $p = 0.612$], suggesting the absence of a shift in sensitivity toward either LSF or HSF in individuals with SAUD compared to HC. In both groups, maximal SF sensitivity peaked around 3.6–3.9 cpd.

Emotional task

Results also yielded a significant Group main effect [$F(1,71) = 49.597$, $p = 0.003$, $\eta^2 = 0.119$], with lower *d′* in individuals with SAUD. The quadratic contrast for SF again reached significance [$F(1,71) = 7.486$, $p = 0.008$, $\eta^2 = 0.095$].[4] The main effect of Facial cue [$F(1,71) = 0.378$, $p = 0.541$, $\eta^2 = 0.005$] and the Group × facial cue interaction [$F(1,71) = 0.313$, $p = 0.577$, $\eta^2 = 0.004$] were non-significant. Likewise, there was no significant linear or quadratic contrasts for Group × SF [linear: $F(1,71) = 3.831$, $p = 0.054$, $\eta^2 = 0.051$; quadratic: $F(1,71) = 2.712$, $p = 0.104$, $\eta^2 = 0.037$] and SF × Facial cue [linear: $F(1,71) = 0.668$, $p = 0.416$, $\eta^2 = 0.009$; quadratic: $F(1,71) = 0.728$, $p = 0.397$, $\eta^2 = 0.010$]. Of most interest, we found a Ggroup × SF × Facial cue significant quadratic contrast [$F(1,71) = 5.086$, $p = 0.027$, $\eta^2 = 0.067$] consistent with our hypothesis that facial cues influence the quadratic relationship between *d′* and SF, and that this perceptual modulation may differ between groups.

We first analyzed this interaction by testing for the presence of a facial cue modulation of SF sensitivity for each group separately. Facial cue main effects were non-significant in both groups [SAUD: $F(1,34) = 0.002$, $p = 0.967$, $\eta^2 = 0.000$; HC: $F(1,34) = 0.625$, $p = 0.434$, $\eta^2 = 0.017$]. There was a barely significant SF × Facial cue quadratic contrast in the SAUD group, but not among HC [SAUD: $F(1,34) = 4.142$, $p = 0.050$, $\eta^2 = 0.109$; HC: $F(1,37) = 1.153$, $p = 0.290$, $\eta^2 = 0.030$]. Paired-samples *t*-tests showed that individuals with SAUD performed better after neutral than fearful faces for Gabors at 6.0 cpd, but this difference did not hold after Bonferroni correction [$t(34) = 2.070$, $p = 0.230$]. Contrary to our expectations, we thus found no direct SF modulation following Facial cueing ($ps > 0.555$ for all other *t*-tests). Consistently, estimated points of maximum SF sensitivity (reported in Table 2) did not differ across facial cue conditions in either group on either the *x* (SAUD: $Z = -0.082$, $p = 0.935$; HC: $Z = -0.718$, $p = 0.473$) or *y* (HC: $Z = -0.688$, $p = 0.492$; HC: $Z = -0.660$, $p = 0.509$) axis.

Table 2 Coordinates [Mean(SD)] of the estimated points of maximum SF sensitivity in the SAUD and HC groups according to neutral and fearful facial cues

	SAUD		HC	
Coordinate	Neutral	Fearful	Neutral	Fearful
x	4.397 (3.010)	4.340 (2.682)	3.393 (8.902)	4.424 (3.846)
y	1.503 (1.436)	1.664 (1.155)	2.144 (1.766)	2.425 (1.340)

We then tested whether group differences in SF sensitivity varied according to facial cues. When examining the neutral face cues, the Group main effect [SAUD < HC; $F(1,71) = 9.537$, $p = 0.003$, $\eta^2 = 0.118$] and Group × SF quadratic contrast [$F(1,71) = 6.696$, $p = 0.012$, $\eta^2 = 0.086$] were significant. Figure 3 shows a more negative quadratic SF sensitivity function in HC individuals compared to individuals with SAUD. The quadratic contrast indicated more pronounced SF sensitivity loss for the intermediate compared with the lowest and highest SF tested. Bonferroni-corrected independent-samples *t*-tests confirmed impaired sensitivity in individuals with SAUD for Gabors containing 2.1 [$t(71) = 3.355$, $p = 0.003$], 3.0 [$t(71) = 2.781$, $p = 0.017$], and 4.2 [$t(71) = 2.790$, $p = 0.017$], but not 1.5 [$t(71) = 1.218$, $p = 0.568$] and 6.0 [$t(71) = 1.718$, $p = 0.237$] cpd SF. Groups' estimated point of maximum SF sensitivity differed on the *y* ($U = 464$, $p = 0.026$) but not *x* ($U = 591$, $p = 0.414$) axis, indicating that the change in the shape of the sensitivity function in individuals with SAUD was not accompanied by a measurable deviation to the left or right.

When examining the fearful face cues, we observed a significant Group main effect [$F(1,71) = 8.339$, $p = 0.005$,

[4] The linear contrast for SF was also significant: $F(1,71) = 238.255$, $p < .001$, $\eta^2 = .770$.

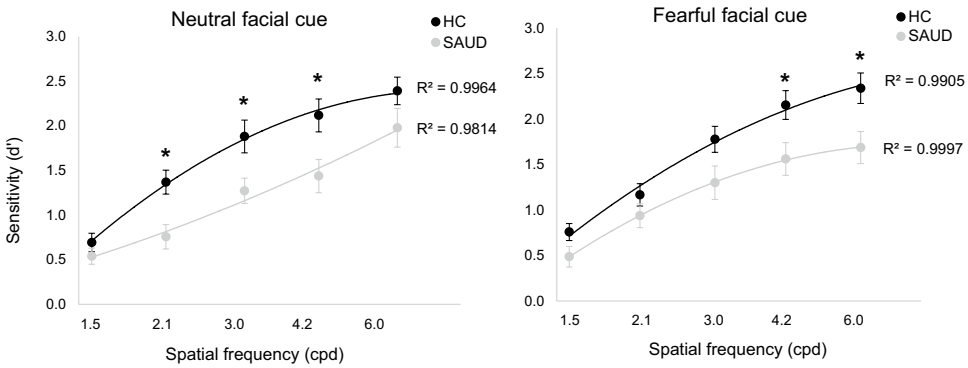

Fig. 3 Raw d' and quadratic fittings based on group means for the emotional task. Error bars represent the standard error of the mean

$\eta^2 = 0.105$] and group × SF linear [$F(1,71) = 5.753$, $p = 0.019$, $\eta^2 = 0.075$], but not quadratic [$F(1,71) = 0.020$, $p = 0.888$, $\eta^2 = 0.000$], contrast. As illustrated in Fig. 3, individuals with SAUD displayed a profile of SF sensitivity overall closer to that of HC but showed a reduced increase in d' with higher SF, potentiating group differences in the highest range. Bonferroni-corrected independent-samples t-tests confirmed significantly lower d' in individuals with SAUD than HC at the two highest SF considered [4.2 cpd: $t(71) = 2.740$, $p = 0.020$; 6.0 cpd: $t(71) = 2.960$, $p = 0.010$]. No group difference emerged for the lowest three, though there was a trend for 3.0 cpd [1.5 cpd: $t(71) = 1.960$, $p = 0.135$; 2.1 cpd: $t(71) = 1.292$, $p = 0.500$; 3.0 cpd: $t(71) = 2.266$, $p = 0.067$]. Coordinates of groups' estimated points of maximum SF sensitivity differed again on the y ($U = 457$, $p = 0.022$) but not x ($U = 629$, $p = 0.691$) axis.

Correlations

There was no significant correlation between individuals' mean d' from each task (aggregated across facial cues for the emotional task considering the absence of within-group modulation) and the number of cigarettes smoked per day, depression, state/trait anxiety, and social anxiety scores in either group (all $ps \geq 0.055$). This lack of association argued against the inclusion of these variables as covariates in the models, as including variables that correlate with SAUD group membership but not the experimental dependent variables may compromise the construct validity of SAUD and limit inferences about this population (Miller and Chapman, 2001). We found no association between individuals with SAUD's d' and alcohol-related indices (all $ps \geq 0.285$) nor medication (no cue task: $r_s = -0.263$, $p = 0.127$; facial cue task: $r_s = -0.214$, $p = 0.218$).

Discussion

Our main aim was to improve our understanding of SF deficits in SAUD and test the hypothesis of impaired MC-related LSF processing using Gabor patches. In addition, we assessed whether individuals with SAUD show modified interactions between vision and emotion based on a paradigm manipulating the affective content of faces presented directly before Gabor patches. Considering the dynamic nature of vision, the overall objective was thus to explore the flexibility of SF processing depending on visual content.

Results from the perceptual task without cues did not corroborate our first hypothesis and rather supported a generalized deficit for SF, as individuals with SAUD showed less sensitivity to the orientation of the Gabor patches than HC at all the SF considered (1.5–6.0 cpd). This result matches the findings of Cruz et al. (2016) who observed a global reduction in contrast sensitivity for sinusoidal gratings sampled at 0.6, 2.5, 5, and 20 cpd, thus partially overlapping with the SF range used here. It is also consistent with Roquelaure et al. (1995)'s report of reduced contrast sensitivity between 0.1 and 9.0 cpd, though we did not identify more intense deficits for the most extreme SF. We did not find any difference in sensitivity between more extreme and middle-range SF either. Roquelaure et al. (1995) however selected a larger range of SF, impeding more precise direct comparisons with our study. Discrepancies with other previous results, especially those of de Oliveira Castro et al. (2009) who found no deficit at any SF from 0.2 to 30 cpd, and Martins et al. (2019) who measured deficits for LSF at 0.5 and 0.8 cpd only, could be explained by other methodological differences. For instance, these authors used psychophysical adjustment techniques that are more sensitive to the response criterion of participants compared to forced-choice responses (Cruz et al. 2016). Besides, the contrast was maintained to

a fixed level of 30% in the present study, so that SF deficits were measured for supra-thresholds Gabors under rapid viewing conditions and were thus less limited by contrast. Of most interest, the global SF alterations reported by Cruz et al. (2016) were measured in individuals with long-term abstinence (M = 12.65 years, SD = 8.76), suggesting that the impairments observed in our sample could persist despite abstinence. They indicated changes in broad sensory mechanisms or selective visual channels (Cruz et al. 2016), and probably involved optic nerve dysfunction (Roquelaure et al. 1995). The absence of a shift in the estimated point of maximum SF sensitivity of individuals with SAUD argued against a specific change in SF processing strategy that would favor LSF or HSF and rather implied a global efficiency reduction. Altogether, this first line of observations did not support a specific MC-related LSF deficit in SAUD but indicated that individuals with SAUD may miss important low-level visual information not only at a coarse but also fine spatial scale, at least under brief presentation timings, with implications for the following higher-level cognitive steps.

It is important to stress that while we postulated that d' for SF would share a curvilinear relationship and did find a quadratic pattern in the data — consistent with the inverted U-shape observed for contrast sensitivity functions (De Valois and De Valois 1988) — we were only capable of capturing the initial ascending portion of this function. While this could be partly due to the limited range of SF included, this is also in contradiction with the original pattern of results obtained by Bocanegra and Zeelenberg (2009). Indeed, the authors did not measure a systematic increase in d' with higher SF and rather found an attenuated, yet recognizable, inverted U-shape. This difference questions the extent of MC pathway contribution to task performance as it appears that all participants predominantly recruited the PC pathway in our study. Consistent with this interpretation, performances were much lower than expected at the lowest SF considered (1.5 cpd), which should not saturate participants' visual system the way it did. The small size of the Gabors (2°) probably prevented efficient processing at the lowest SF. In this configuration, only a very limited number of SF cycles were visible in the Gabors sampled at 1.5 cpd, especially since contours were blurred. Previous studies measuring SF generally used larger (e.g., twice as big) stimuli, and sometimes even increased their size for the lowest SF in order precisely for the outlines not to interfere with the SF pattern (e.g., Leonova et al. 2003). Besides, the small absolute size of Gabors may have promoted PC-related HSF tuning.

This may also partly contribute to explaining our inability to observe Bocanegra and Zeelenberg's (2009) emotional modulations of SF sensitivity. Indeed, we did not find any difference in SF sensitivity, and hence, no improved LSF processing, following the presentation of a fearful versus neutral facial cue in either group. Considering that this modulation is supposed to be driven by an MC enhancement (Bocanegra and Zeelenberg, 2009, 2011), inducing a counter-balancing PC decay, the potentially reduced influence of the MC pathway in the task may have strongly impaired this dynamic. Methodological dissimilarities and variations in group characteristics compared to the original study may also have influenced the results. For instance, we used facial cues from a different battery and homogenized the contrast and luminance of faces, which may have slightly modified their natural saliency. Our participants also did not perform 100 training trials with facial cues before the emotional task, nor benefitted from any individual calibration of the degree of tilt, potentially increasing intra- and inter-individual variations in performances. Moreover, Bocanegra and Zeelenberg (2009) did not collect any socio-demographic and psychopathological information from their sample, so that we may have tested potentially older individuals with a different psychological profile. However, this null effect is not unprecedented as another study by Ferneyhough et al. (2010) also failed to replicate a different effect of fearful and neutral facial cues (equated on luminance and contrast) on the orientation discrimination of Gabor patches in a young adult sample (M = 27.15 years old). The authors however used a fixed mid-level 4 cpd SF Gabor and reasoned that this was probably not the best SF to measure the benefits of emotions on SF processing. Nevertheless, Bocanegra and Zeelenberg (2009) not only measured beneficial effects for LSF but also documented detrimental effects for HSF, notably for 4 cpd SF Gabors, which were not found either.

That being said, we did find different results for between-group comparisons depending on facial cues. In the neutral facial cue condition, individuals with SAUD showed reduced SF sensitivity for the intermediate but not lowest and highest SF included in the study. This might be particularly detrimental as middle-range SF (2–4 cpd) are useful for most visual tasks and correlate with the quick and accurate identification of all categories of objects, including faces (Collin et al. 2006; Caplette et al. 2014). We could not measure any group difference at the lowest SF, but this might be due to the very low performances in both groups and the aforementioned potential limited use of the MC pathway. By contrast, individuals with SAUD reached lower d' than HC at the highest two SF (4.2 and 6.0 cpd) following the presentation of fearful faces, indicating a reduced ability to process the directly following fine visual details. If we assume that this aftereffect reflects their SF tuning for emotional faces, this suggests that they might be less able to discriminate very informative fine facial details such as the contour of the eyes or mouth, or wrinkles of expressions, compared to HC. This distinctive result reflected a different SF tuning in individuals with SAUD as if fearful

faces contributed to normalizing the overall shape of the SF sensitivity function and improved the processing of low to middle-range SF (especially 2.1 cpd), but at the expense of higher SF. Actually, this pattern would partly agree with Bocanegra and Zeelenberg (2009) proposal of improved LSF and reduced HSF processing following fearful faces. Even though these results must be interpreted with caution in the absence of within-group modulations or shifts in the estimated points of maximum SF sensitivity, these distinct patterns of group differences open up the possibility that the SF processing deficits of individuals with SAUD might unveil differently depending on the content of faces, consistent with the proposal of flexible usage of SF. Intriguingly, and while they cannot be directly compared with the short-term acute effects of alcohol consumption, these results also tend to match reports of greater damage in medium SF and HSF, especially in the range of 3.0 and 6.0 cpd, following low to high doses of alcohol consumption (Andre 1996; Cavalcanti-Galdino et al. 2014; Casares-López et al. 2020).

Future studies should extend the present findings using larger stimuli and a wider range of SF, notably to ensure proper MC activity and explore a larger portion of the SF sensitivity function. In the present work, the fixed order between the perceptual and emotional tasks also prevented interpreting the higher d' obtained for neutral faces in the emotional task (compared to d' in the perceptual tasks) as the result of a face-induced perceptual enhancement effect. Indeed, the increase may also reflect a training effect. Since the perceptual task was systematically performed first, it may have induced a form of perceptual learning. Additional work comparing visual tuning across different types of stimuli, among which different types of faces (including neutral ones) but also alcohol-related stimuli, will thus also be of primary interest in SAUD. As a direct extension of the present study, we suggest, for instance, assessing emotional decoding for emotional faces filtered to retain low, middle-range, or high SF. This would help to understand whether some (and which) interpretative errors and patterns of confusion in patients could be partly explained by low-level differences in spatial frequency processing.

In sum, our results did not support a strong dissociation between MC and PC functioning in SAUD as we could not identify a clear-cut pattern favoring either LSF or HSF impairments. We rather demonstrated mixed deficits for low-level non-meaningful Gabor patches that may vary subtly depending on the nature, and especially the affective value, of the visual content presented immediately before. From a theoretical perspective, our findings thus stress the need to include sensory disturbances in the current dominant addiction models. This is notably true for dual-process models that oppose an overactivated affective/impulsive system and an underactivated executive/controlled system. Indeed, these models generally fail to address changes in perception, neglecting how the very first low-level processes are conducted and how they influence the two presupposed systems. Several cardinal features of SAUD, such as attentional biases and emotional decoding deficits, share a central visual component and yet are generally interpreted as reflecting rather high-level cognitive and affective impairments solely. They may however be better appraised in terms of vision-emotion interactions, implying that visual impairment could have an indirect link with relapse (see Rando et al. 2011 and Wang et al. 2018, for associations between visual cerebral activity and relapse). From a clinical perspective, perceptual learning, including training in spatial frequency processing, has long been documented in HC, suggesting that it is possible to train low-level visual skills (for a review see Dosher and Lu 2017). While visual training has not been implemented in neuropsychological rehabilitation programs for SAUD yet, encouraging results from other clinical populations, especially schizophrenia, demonstrate the effectiveness of visual remediation interventions and suggest that improvements in visuo-perceptive processes could generalize to other visual perceptual and cognitive functions (Demmin et al. 2019). Reviews on cognitive training for impaired neural systems in neuropsychiatric disorders insist on the need for cognitive training programs to address limitations in perceptual and pre-attentive processing as any remediation approach that does not consider early perception will probably hit a plateau performance at some point (Vinogradov et al. 2012). As such, omitting visuo-perception may hamper the possibility to maximize the efficiency of current cognitive programs in SAUD.

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Declarations

Conflict of interest The authors declare no competing interests.

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