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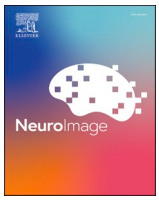

Autistic traits modulate neural responses to social signals during natural vision

Qingying Ye [a,b,*], Jinglu Chen [a,b], Severi Santavirta [a,b], Vesa Putkinen [a,b], Juha Salmi [c,d], Lauri Nummenmaa [a,b,e]

[a] Turku PET Centre, University of Turku, Turku, Finland
[b] Turku PET Centre, Turku University Hospital, Turku, Finland
[c] Unit of Psychology, University of Oulu, Oulu, Finland
[d] Department of Neuroscience and Biomedical Engineering, Aalto University, Espoo, Finland
[e] Department of Psychology, University of Turku, Turku, Finland

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ABSTRACT

Differences in social perception, a hallmark of autism spectrum disorder (ASD), are also evident at subclinical levels in the general population. However, it remains unclear how such variation in autistic traits relate to neural processing of different types of social information. Here, we investigated whether autistic traits in neurotypical individuals are associated with neural responses to a broad array of social perceptual features during watching naturalistic stimuli using functional magnetic resonance imaging (fMRI). We also tested the generalizability of these effects across two experiments. Ninety-seven participants completed the Autism Spectrum Quotient (AQ) and watched a set of 96 movie clips and a full movie during an fMRI scan. Intensity of 126 social features in the movie stimuli was continuously annotated by independent observers, and 44 most reliably rated features were used to model neural responses. We examined how consistently the responses to each social feature were dependent on the participants' AQ scores. Replicable AQ-dependent neural responses to social features were found in both datasets. The temporal cortex and especially the superior temporal gyrus (STG), served as a central "hub" where autistic traits were consistently associated with neural responses to social features across datasets. Different AQ subscales also revealed distinct association patterns in other brain regions. These findings indicate how autism-related traits broadly relate to neural processing of naturalistic social signals, providing neurobiological evidence for the heterogeneous nature of autism-related traits.

1. Introduction

Autism spectrum disorder (ASD) is a heterogeneous neurodevelopmental condition characterized by differences in social interaction and communication, along with repetitive behaviors and restricted interests (American Psychiatric Association, 2013). Subclinical variation in similar behavioral characteristics is observed in the general population, and such autism-related traits are conceptualized as phenotype markers (Constantino et al., 2003). Individuals with higher versus lower levels of autistic traits show distinctive performance on social cognition tasks such as decreased expressiveness (Alkhaldi et al., 2024), reduced accuracy in emotional recognition (Corluka and Laycock, 2024), and lower cognitive empathy (Le et al., 2024), resembling the patterns observed in ASD (Che and Zhou, 2025; Fatima and Babu, 2024; Grossman and Tager-Flusberg, 2012). Therefore, studying these autism-like traits with neuroimaging methods in the general population could elucidate the brain basis underlying autistic characteristics, without the confounding effects of the course of development, rehabilitation, treatment, and co-morbid conditions often present in clinical studies.

Atypical social cognition, especially in social perception, is one of the key factors behind social challenges in ASD. Social perception refers to the early stage of sensory information processing in which individuals detect and interpret cues critical for understanding others' intentions and dispositions (Allison et al., 2000). Various aspects of social perception in ASD have been investigated at behavioral (Chita-Tegmark, 2016; Riddiford et al., 2022) and neural (Deen et al., 2015; Floris et al., 2025; Limanowski and Blankenburg, 2016; Ropar et al., 2018) levels.

* Corresponding author at: Turku PET Centre, University of Turku, 4-8 Kiinamyllynkatu, 20520, Turku, Finland.
E-mail address: qingye@utu.fi (Q. Ye).

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For example, eye-tracking meta-analyses show that individuals with ASD exhibit reduced eye gaze toward social stimuli, particularly the eye region of the human face, compared to neurotypical controls (Chita-Tegmark, 2016; Riddiford et al., 2022). Neuroimaging studies have revealed structural and functional alterations in ASD across brain regions involved in perception of eye contact (superior temporal sulcus, STS; Pelphrey et al., 2005), faces (fusiform gyrus; Floris et al., 2025), bodies (temporo-parietal junction, TPJ; Limanowski and Blankenburg, 2016; Ropar et al., 2018), and other higher-order social-cognitive processes (e.g., superior temporal gyrus, STG; medial prefrontal cortex, mPFC; Amodio and Frith, 2006; Redcay, 2008).

The above evidence suggests that ASD is associated with neural alterations across a broad range of social perceptual domains. Similar neural alterations are also observed in the general populations with autistic traits during perceiving eye gaze (Nummenmaa et al., 2012a), social voice (Skjegstad et al., 2022), and social touch (Voos et al., 2013). However, research on social perception has typically used simplified study designs (e.g., static images) and studied isolated social features one at a time, although it is unlikely that social features are processed independently of other social information by distinct neural regions or systems (Huth et al., 2012; van den Heuvel and Sporns, 2011). Therefore, evidence from studies using simplified stimuli may not generalize to real-world social perception.

Movie-watching combined with functional magnetic resonance imaging (fMRI) enhances ecological validity, yielding results that are more generalizable to real-world settings and demonstrating significant advantages in research on social perception. Movie stimuli provide continuous, naturalistic input with rich social and emotional contents, eliciting cognitive and affective processes that closely approximate real-world experience (Hasson et al., 2004; Nummenmaa et al., 2012b; Salmi et al., 2013). fMRI studies using movie-watching paradigms have revealed a distributed but functionally organized neural network for social perception among the general population, highlighting the STS as a general hub for social perception (Lahnakoski et al., 2012). Furthermore, this network follows a posterior-to-anterior gradient: temporal, occipital and parietal regions are broadly engaged in the perception of diverse social features, whereas frontal and subcortical regions are recruited more selectively (Santavirta et al., 2023). Additionally, the neural basis of separate social features (e.g., laughing, crying, and biological motion) in natural scenes has also been investigated in the general population (Hudson et al., 2023; Nummenmaa et al., 2023).

Previous movie-watching fMRI studies have yielded inconsistent findings on the effects of autism-like traits on brain responses to social signals. One study found that global autistic traits, as indexed by the total score of the Autism Spectrum Quotient (AQ), significantly predicted intersubject synchronization in brain regions involved in social perception (Salmi et al., 2013). Another study demonstrated that beyond global AQ scores, the social skills subdomain was associated with decreased neural activity in middle cingulate gyrus and precuneus during the perception of naturalistic biological motion (Hudson et al., 2023), suggesting the domain-specific effects of autistic traits on naturalistic social perception. However, other studies have found no consistent relationships between autistic traits and neural activation in social brain networks during movie watching (Pantelis et al., 2015; Turner et al., 2025). Therefore, the effects of autistic traits on brain activity during naturalistic social perception and whether such effects differ across distinct domains of autistic traits remain elusive.

1.1. The current study

Despite the growing literature on the neural basis of social perception in general population, limited research has focused on studying how autistic traits relate to neural responses for social perception under naturalistic conditions. Since most previous studies have mapped how autistic traits relate to the perception of isolated social features although, in reality, multiple social features are perceived simultaneously, a more comprehensive understanding of how these traits affect neural responses to diverse aspects of social perception is needed. Here, we tested whether autistic traits in neurotypical populations are associated with neural responses when watching naturalistic movies in two experiments with independent stimulus sets. Participants (N = 97) completed the AQ, and their haemodynamic brain activity was measured with fMRI when watching a set of 96 movie clips (**movie clips** dataset) and a full movie (**full movie** dataset, see Fig. 1). The presence of 126 social features was dynamically rated in a separate experiment by independent observers to get a comprehensive description of the social contents. The 44 most consistently evaluated social features were then selected for analyses, to enable reliable modelling of the neural responses in the independent fMRI sample. We then tested how consistently the responses to each social feature were dependent on the participants' AQ scores, both the total score and subscale scores. The present results indicated both general and dimension-specific relationships between AQ scores and neural responses to social features in two datasets, suggesting that autism-like traits are consistently associated with the neural processing of naturalistic audiovisual social information in the general population.

2. Methods

2.1. Participants

A total of 104 Finnish participants were recruited for the fMRI study. The exclusion criteria included a self-reported history of neurological or psychiatric disorders, alcohol or substance abuse, BMI under 20 or over 30, current use of psychoactive medications and the contraindications for MRI (e.g., metallic implants, pregnancy, and claustrophobia). Dataset-specific quality control procedures led to the exclusion of different participants in each dataset. For the **movie clips** dataset, seven participants were excluded (two due to gradient coil malfunction, two due to structural abnormalities, and three due to visible motion artefacts in the preprocessed fMRI data), resulting in a final sample of 97 participants (50 females; mean age = 31 years; range = 20–57). For the **full movie** dataset, eight participants were excluded (two due to gradient coil malfunction, two due to structural abnormalities, and four due to excessive motion), yielding a final sample of 96 participants (47 females; mean age = 31.5 years; range = 20–57). All subjects provided written informed consent and were compensated for their participation. The study was conducted in accordance with the Helsinki Declaration and was approved by the ethics board of the hospital district of Southwest Finland (protocol number: ETMK: 46 /1801/2017; Date: May 16th, 2017).

2.2. Autistic traits of study sample

Autistic traits were measured using AQ questionnaire (Baron-Cohen et al., 2001). The AQ is a 50-item self-report scale designed to assess the degree of autistic traits across five domains: Imagination, Communication, Attention switching, Social skills, and Attention to detail. Participants responded on a 4-point Likert scale ranging from "definitely agree" to "definitely disagree". Responses were converted into binary scores (0 or 1), with 26 items reverse-scored. For positively keyed items, "definitely agree" and "slightly agree" responses were coded as 1, whereas "definitely disagree" and "slightly disagree" responses were coded as 0. Item scores were summed to yield total and subscale scores, with higher scores reflecting higher levels of autistic traits. As the study sample did not contain participants with neuropsychiatric disorders, the AQ questionnaire was used to measure the variation of autistic traits within the normal range. The Finnish version of AQ was used in the present study, which has shown good reliability (Loukusa et al., 2021), and has been successfully applied in previous Finnish studies (Hudson et al., 2023; Roine et al., 2013). The Cronbach's α coefficients for subscales and the total score ranged from 0.49 to 0.71 (Imagination: 0.48;

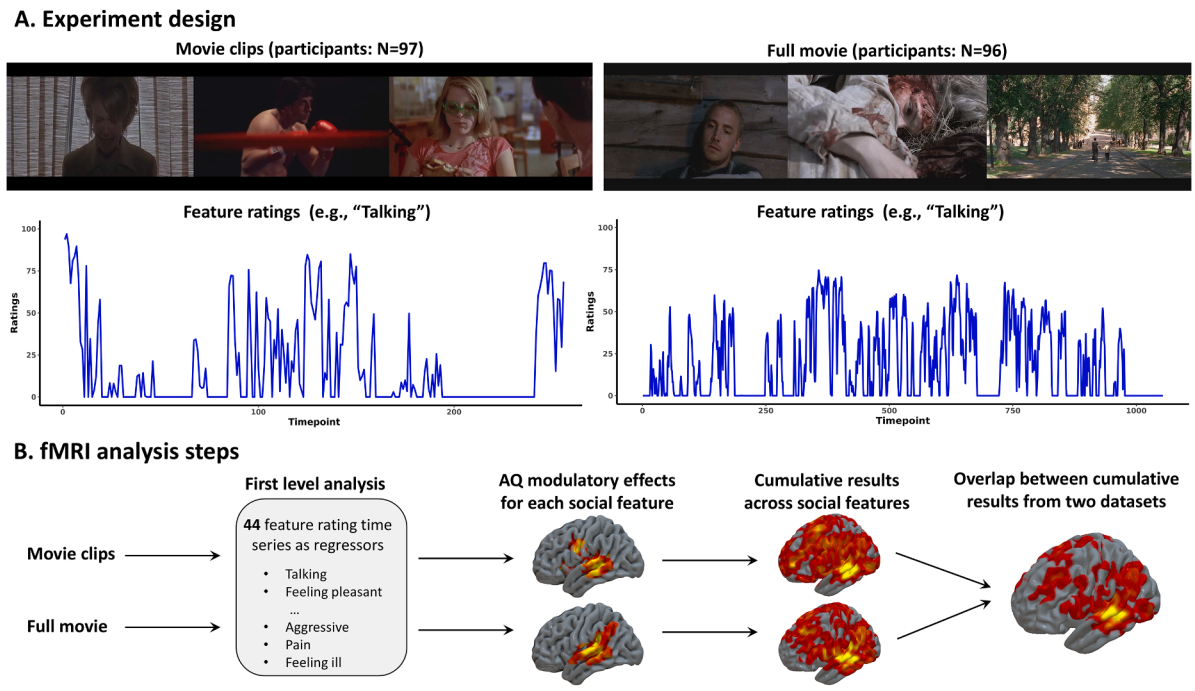

Fig. 1. Experimental design and analytical pipeline of the study. (A) Participants (N = 97) watched 96 unrelated video clips of social scenes and a full movie in two separate fMRI sessions. (B) Social contents of the stimuli were dynamically annotated and 44 most consistently annotated social feature ratings were used to model the heamodynamic responses of neurotypical participants. Next, their AQ scores were used to model the interindividual differences in the response patterns for each social feature. To summarize the findings, cumulative maps were generated over all social features to highlight areas where AQ scores significantly modulated neural responses to multiple social features. Finally, the generalizability across fMRI datasets was assessed.

Communication: 0.56; Attention switching: 0.47; Social skills: 0.58; Attention to detail: 0.56; total score: 0.71; see **Table S1**).

2.3. The movie stimulus

Two sets of validated movie stimuli were utilized in the study, both with variable social and emotional contents (Karjalainen et al., 2017; Lahnakoski et al., 2012; Nummenmaa et al., 2023; Santavirta et al., 2023). For the **movie clips** dataset, participants watched a series of 96 English movie clips (19 min 44 s) extracted from Hollywood movies in a fixed order without breaks, while a slightly shorten version of Finnish feature-film "Käsky" (70 min 11 s) was used in the **full movie** dataset (Louhimies, 2008; Santavirta et al., 2024). Participants were instructed to watch movie stimuli as if they were viewing a movie at cinema or at home. Comparisons across the datasets allow testing how well the findings generalize across different naturalistic stimuli (i.e., from short unrelated movie clips to a full movie with continuous narrative).

2.4. Annotated social features

The movie stimuli were dynamically annotated for 126 social features with four second temporal resolution to allow parametric modelling of fMRI data. These feature annotations were obtained from an independent set of subjects (**movie clips** dataset: n = 5; **full movie** dataset: n = 5) who did not participate the fMRI experiment. Participants were instructed to indicate the extent to which each feature was perceived, on a scale from "absent" to "extremely much" that represented continuous values from 0 to 100. To allow reliable modelling of the independent fMRI samples with the average social feature ratings, it was necessary to identify which features are perceived consistently across individuals and are also present in the stimuli. Only features with an intra-class correlation coefficient (ICC) greater than 0.5 were considered to be rated consistently across participants. The ICC2 model was selected since both subjects and movie clips were assumed to represent random samples from their respective populations and videos. A feature was considered to be present often enough for modelling if the averaged rating minus the standard error was over five in at least five rating time points (5% of the total rating range). Based on these criteria, 44 social features were identified as reliable predictors for fMRI modelling. Detailed descriptions of the experimental design and stimuli can be found in previous studies using same movie-watching paradigms (Santavirta et al., 2023, 2024). The raw average ratings of 44 features in each dataset are presented in Supplementary **Figs. S1** and **S2**.

2.5. MRI data acquisition and preprocessing

The MRI data were collected using a Phillips Ingenuity TF PET/MR 3T scanner at Turku PET Centre. Functional volumes were acquired with a T2* - weighted echo - planar imaging (EPI) sequence (TR 2600 ms, TE 30 ms, flip angle 75°, FOV 240 mm, 80 × 80 reconstruction matrix, 62.5 kHz bandwidth, 3.0 mm slice thickness, 45 interleaved axial slices acquired in ascending order without gaps). Structural images were obtained with a Philips 3D T1-weighted turbo field echo (TFE) sequence with SENSE acceleration (1 mm^3 resolution, TR 9.8 ms, TE 4.6 ms, flip angle 7°, FOV 256 mm, 256 × 256 reconstruction matrix).

The structural and functional imaging data were preprocessed with fMRIPrep (Esteban et al., 2019) (v 1.3.0). First and last two functional volumes were discarded to exclude the time points before and after the stimulus. T1w reference images were corrected for intensity non-uniformity using N4BiasFieldCorrection (Tustison et al., 2010) (v2.1.0) and skull-stripped using antsBrainExtraction.sh (v2.1.0) and OASIS as template. Brain surfaces were reconstructed with recon-all (FreeSurfer v6.0.1) (Dale et al., 1999), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical grey matter of Mindboggle (Klein et al., 2017). Spatial normalization to the ICBM 152 Nonlinear Asymmetrical template version 2009c (Fonov et al., 2009) was performed through nonlinear registration with the antsRegistration (ANTs v2.1.0) (Avants et al.,

2008), using brain-extracted versions of both T1w volume and template. Brain tissue segmentation of cerebrospinal fluid, white-matter and grey-matter was performed on the brain-extracted T1w image using FAST (Zhang et al., 2001) (FSL v5.0.9).

Functional data were preprocessed as follows: slice-timing correction was done using 3dTshift and motion-corrected using MCFLIRT. The preprocessed BOLD was then co-registered to the T1w image using bbregister for boundary-based registration with six degrees of freedom. All transformations (i.e., motion-correction, coregistration, and spatial normalization) were concatenated and applied in a single step using antsApplyTransforms (ANTs) and Lanczos interpolation. Spatial smoothing was applied with an isotropic 6-mm Gaussian kernel. ICA-AROMA was performed in MNI space using the standard FSL implementation in a non-aggressive manner to remove motion-related components.

2.6. Modelling of the fMRI data

The fMRI data were analyzed in SPM12 (Wellcome Trust Center for Imaging, London, UK, https://www.fil.ion.ucl.ac.uk/spm/). To investigate how autistic traits relate to the neural responses to social perception in the general population, we first modelled the neural responses to the 44 dynamically annotated social features in separate first-level models and then added the participant-specific AQ scores as predictors in the second-level models. The statistical assumptions tested for GLMs were shown in **Fig. S3**.

Before first-level modelling, standardized rating time series of the social features were convolved with the canonical HRF. Neural responses to each social feature were estimated with separate independent regression models for each feature. Participant-specific first-level contrasts for social features were then subjected to group-level regression analyses. Separate second-level models were constructed for each AQ-related score (i.e., AQ total score and five subscale scores) to identify how different autistic traits modulate the neural responses to social features. Statistically significant clusters were identified using one sample *t*-tests (voxel-level threshold $p < 0.05$ with cluster-level family-wise error rate (FWE) correction, $p < 0.05$). To summarize the results on the regional level, mean beta weights for 56 bilateral anatomical regions of interest (ROI) defined by the AAL2 atlas (Rolls et al., 2015) were extracted for each participant. Then, second-level modelling of the regional data was conducted similarly to the full-volume analysis to estimate the modulatory effect of AQ score on the regional level. We further conducted a supplementary similarity analysis within the STG to assess whether AQ-related modulation was shared or feature-specific across social features. A more detailed description is provided in the Supplementary Materials.

2.7. Cumulative maps for AQ score effects

To identify the regions where brain responses to different social features were most consistently associated with autistic traits, we calculated cumulative maps for the AQ modulatory effects. This was achieved by first binarizing (1 = significant effect, 0 = no effect) the statistically thresholded beta coefficient maps for each feature, and then calculating the sum of these binarized maps. These cumulative maps were calculated first separately for the two datasets, highlighting the regions where multiple AQ effects were observed.

To investigate the cross-dataset consistency of cumulative maps, we calculated the minimum number of significant feature responses for each brain area across the datasets, which highlights regions where multiple AQ effects were consistently observed in both datasets. Furthermore, on a regional level, we identified the peak AQ effect in each anatomical region by averaging values above the 95th percentile of the accumulation across all voxels within the region and correlated the peak values across datasets to identify anatomical regions with consistent AQ effects. Peak values were used instead of raw regional averages to make anatomical regions of vastly different sizes more comparable with each other. To quantify the cross-dataset consistency, we computed the ICC (3,1), a two-way mixed-effects model assessing absolute agreement for single measurements (Koo and Li, 2016). This model was selected because the two datasets represent fixed experimental conditions, and each ROI yields a single mean value per dataset.

3. Results

3.1. Demographic characteristics

In all participants, AQ total score and Imagination subscale score were significantly higher in males than females (**Table S1**). There were no significant correlations between age and AQ scores, except for Attention to detail ($r = 0.24$, $p = 0.018$). Supplementary **Figs. S4 and S5** shows the correlations between AQ total score and subscale scores.

3.2. AQ-related modulation of neural responses to social features in the movie clips dataset

Next, we examined how consistently autistic traits were associated with responses to social features across the brain (Fig. 2). This analysis revealed both general and specific patterns of associations between social perception and AQ dimensions in the **movie clips** dataset, with most consistent effects being observed in the temporal cortex. AQ total score was positively associated with neural responses in the STG and precuneus, while negative association was observed in the fusiform gyrus, orbitofrontal cortex (OFC), insula, MTG, and anterior cingulate cortex (ACC). Regarding the AQ subscales, Attention to detail showed the strongest effects followed by Imagination. Specifically, Attention to detail subscale score showed positive association with neural responses in the frontal pole, ACC, and cuneus gyrus, and negative association was observed in the inferior temporal gyrus (ITG) and lateral occipital cortex (LOC). Imagination subscale score was positively associated with neural responses in the STG, MTG, fusiform gyrus, precuneus, LOC and supramarginal gyrus (SMG), and negative association was observed in the parahippocampal gyrus. Communication subscale score was also positively linked to neural responses in the STG, MTG, and SMG, and negative link was observed in the insula. Additionally, positive relationships between Attention switching score and neural responses were found in the STG, LOC, and posterior cingulate cortex (PCC), while negative relationships were found in the OFC and frontal pole. Unlike the other subscales, Social skills score showed selectively negative association with BOLD responses in subcortical regions (i.e., hippocampus and amygdala), frontal pole, and supplementary motor area (SMA), and positive association was observed in the STG and fusiform gyrus.

3.3. AQ-related modulation of neural responses to social features in the full movie dataset

To assess the generalizability of our findings to other movie stimuli, we examined the modulatory effects of AQ in the **full movie** dataset. AQ total score was positively associated with neural responses in the STG, while negative association was observed in the OFC, insula, inferior frontal gyrus (IFG) and ACC. Regarding the AQ subscales, Attention to detail subscale score showed primarily negative association with BOLD responses in the ITG, LOC and ACC, and positive association was observed in the frontal pole and cuneus gyrus. Conversely, Imagination subscale score showed strongly positive association with BOLD response in the fusiform gyrus, STG, MTG, precuneus, LOC and SMG, and negative association was observed in the parahippocampal gyrus. Communication subscale score was negatively associated with neural responses in the insula and Heschl gyrus, and positive association was observed in the STG, MTG and PCC. Attention switching score was negatively associated with neural response in the OFC, ACC and frontal pole, while positive association was observed in the PCC. Social skills score showed negative

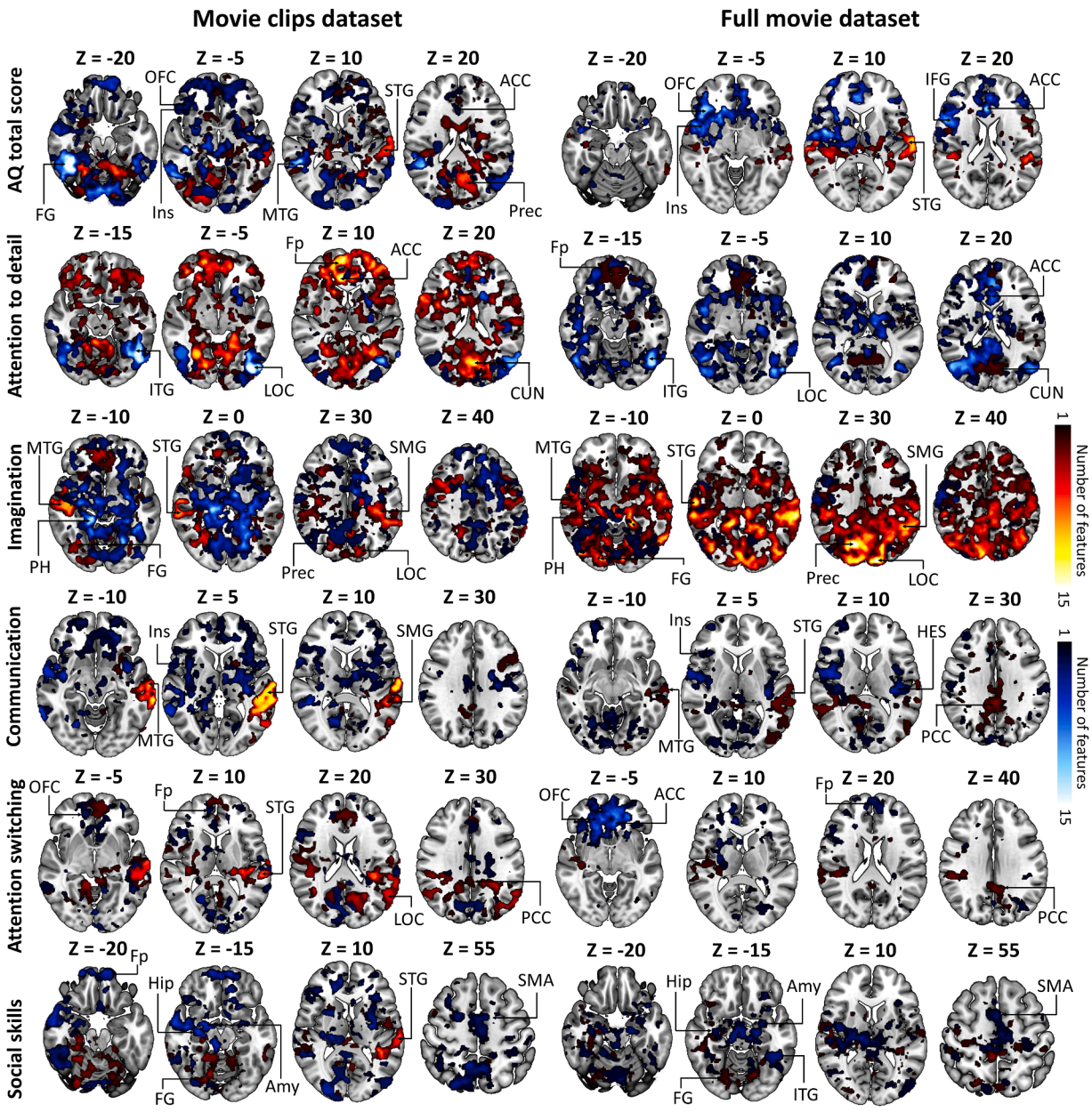

Fig. 2. Cumulative maps on AQ-dependent neural responses to multiple social features during movie viewing. Voxel intensities indicate the number of social features (out of 44) where AQ scores were positively (hot colors) or negatively (cold colors) associated with feature-dependent BOLD responses. ACC = anterior cingulate cortex, Amy = amygdala, CUN = cuneus, FG = fusiform gyrus, Fp= frontal pole, Hip = hippocampus, HES = Heschl gyrus, IFG = Inferior frontal gyrus, Ins = Insula, ITG = Inferior temporal gyrus, MTG = middle temporal gyrus, OFC = orbitofrontal cortex, PCC = posterior cingulate cortex, PH = parahippocampal gyrus, PoCG = Postcentral Gyrus, Prec = precuneus, SMA = supplementary motor area, SMG = supramarginal gyrus, STG = superior temporal gyrus.

association with BOLD responses in the hippocampus, amygdala, ITG and SMA, and positive association was observed in the fusiform gyrus.

3.4. Consistent AQ modulation across datasets

Fig. 3 shows a consistent pattern of associations between autistic traits and neural responses to social features across the two datasets. Generally, AQ total score was positively associated with neural responses in the STG, and negative association was observed in the OFC, ACC, and insula. Dimension-specific patterns were also evident: Attention to detail subscale score was negatively linked to neural responses in the LOC, ACC and ITG, and positive association was observed in the cuneus gyrus and frontal pole. Imagination subscale score showed positive association with neural responses in the SMG, STG, MTG, LOC, precuneus and fusiform gyrus, and negative association was observed in the parahippocampal gyrus. Additionally, Communication subscale score was negatively associated with neural responses in insula and positive association was found in the STG and MTG. Attention switching subscale score was negatively associated with neural responses in the OFC and frontal pole, and positive association was observed in the PCC. Social skills subscale score was negatively linked to BOLD responses in the hippocampus, amygdala, and SMA, and positive correlation was observed in the fusiform gyrus.

To assess the spatial similarity of the cumulative responses across two datasets, we conducted correlation analyses with the ROI analysis results. Results revealed differences in consistency across datasets in AQ-related modulation patterns, with Pearson's r values ranging from −0.28 to 0.63 (Fig. 4). Positive modulation was most consistent in Attention switching, followed by Communication and Imagination, with overlap in temporal, parietal and frontal cortices. In contrast, for the negative

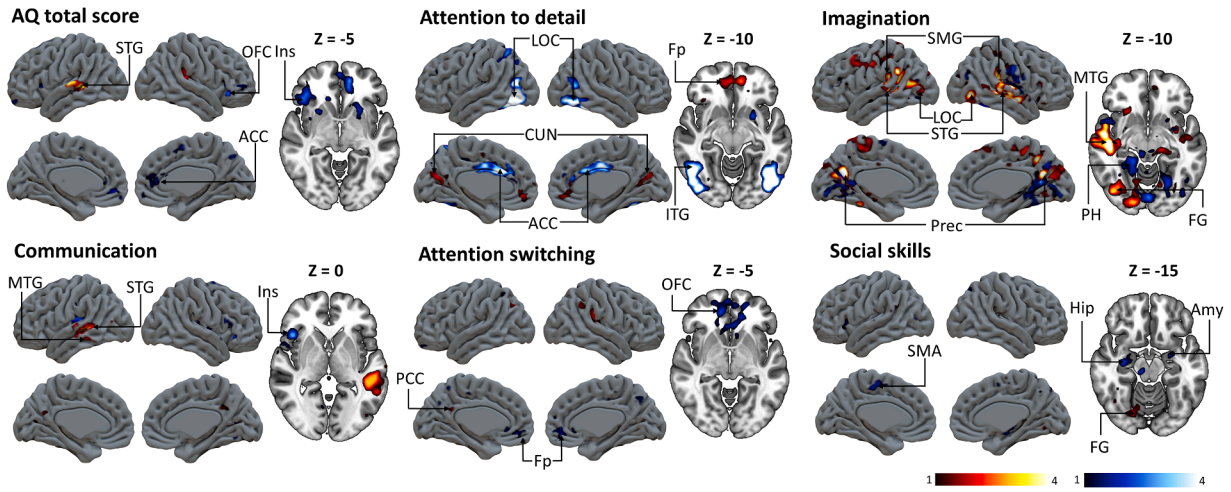

Fig. 3. Consistent AQ-related modulation effects across the two datasets. Color bar indicates the range of minimum cumulative value in each brain area where AQ scores showed consistent positive (hot colors) or negative (cold colors) associations with feature-dependent BOLD responses in both datasets. ACC = anterior cingulate cortex, Amy = amygdala, CUN = cuneus, FG = fusiform gyrus, Fp= frontal pole, Hip = hippocampus, Ins = Insula, ITG = Inferior temporal gyrus, MTG = middle temporal gyrus, OFC = orbitofrontal cortex, PH = parahippocampal gyrus, Prec = precuneus, SMA = supplementary motor area, SMG = supramarginal gyrus, STG = superior temporal gyrus.

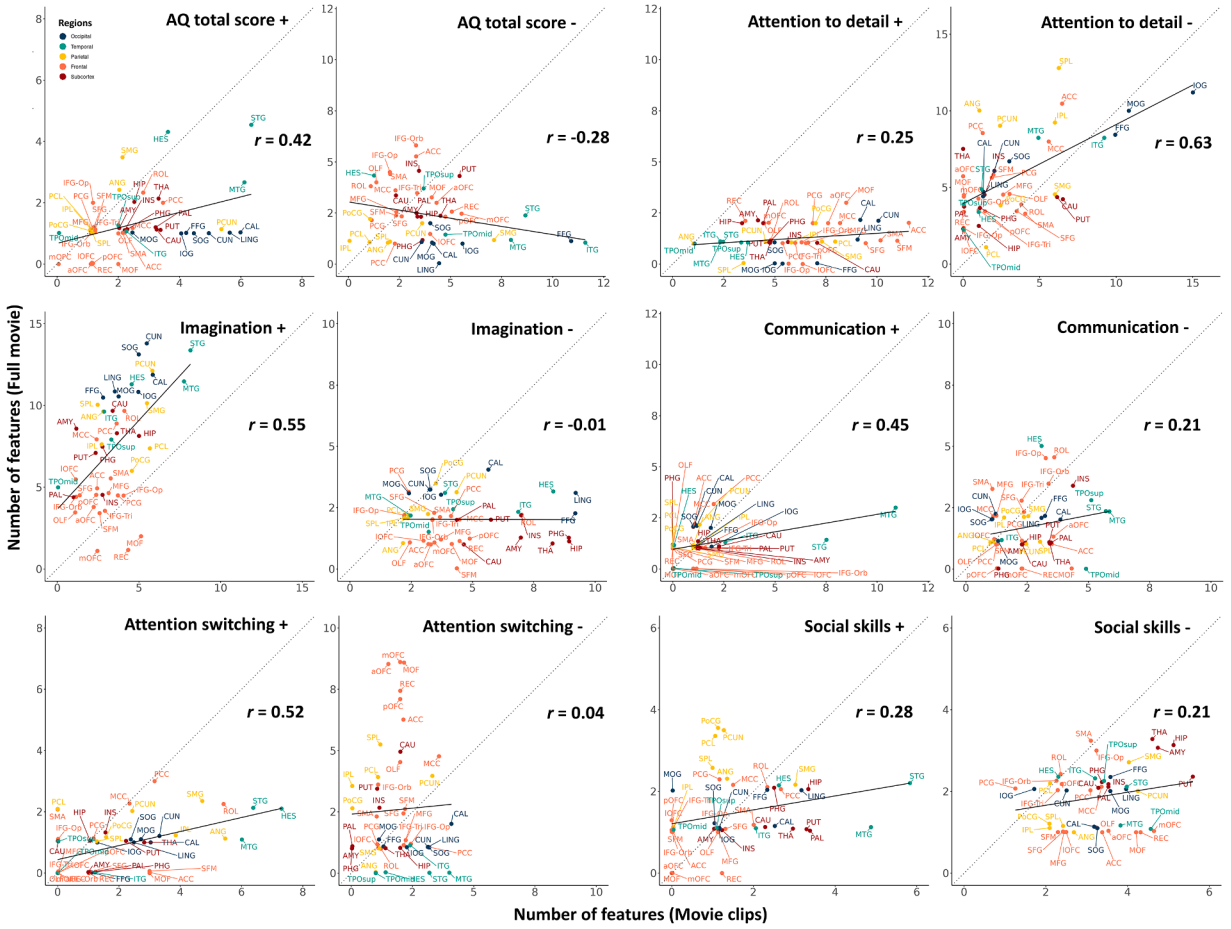

Fig. 4. Scatterplot showing the relationship between the Peak AQ effect across the datasets at regional level. The Y-axis (**full movie** dataset) and the X-axis (**movie clips** dataset) represent the number of social features (out of 44) with significant AQ-related modulations. Each point represents an anatomical ROI (see Table S2 for the full name of the regions). For each region, the peak AQ effect was computed as the mean value above the 95th percentile of the accumulation across all voxels within that region. The black regression line depicts the cross-dataset correlation. The gray dashed diagonal marks identical AQ effects across datasets, with the distance of each point from the diagonal reflecting their similarity. The position in relation to the diagonal indicates whether a ROI is more tuned to the movie clips (below diagonal) or full movie (above diagonal).

AQ-dependent modulation, cross-dataset consistency was highest for Attention to detail, particularly in occipital, temporal, and frontal cortices. The ICC analysis showed a similar pattern. Across all ROIs, positive AQ effects showed low-to-moderate consistency across datasets (ICC values ranging from 0.12 to 0.45), while negative AQ effects exhibited little cross-dataset consistency, with the exception of Attention to detail showing relatively strong consistency (ICC = 0.61) (**Table S3**). In addition, we assessed the similarity of the broader patterns of AQ dimension and ROI-feature responses across datasets, with the Pearson's *r* values ranging from 0.08 to 0.22. For the detailed distribution of feature-specific patterns, see Supplementary **Figs. S6 and S7**. Within the STG, supplementary similarity analysis revealed low-to-moderate similarity in neural response patterns associated with overall autistic traits across social features (movie clips: $r = 0.23$; full movie: $r = 0.17$; see **Fig. S8**).

4. Discussion

Our study has three main findings: (1) autistic traits showed replicable general and dimension-specific associations with the neural responses to a wide range of social perceptual features; (2) autistic traits were most consistently associated with neural responses to naturalistic social stimuli in the temporal cortex and particularly in the STG, while AQ subscales showed distinct patterns involving frontal, parietal, occipital, and subcortical regions; and (3) Attention to detail and Imagination subscales were most consistently linked with social perceptual responses, whereas Social skills showed selective pattern involving reduced subcortical activations. These findings indicate that autism-related traits broadly relate to neural processing of naturalistic social signals.

4.1. Brain regions modulated by general autistic traits in social perception

Consistency analysis revealed that the AQ total scores were positively associated with brain responses in the STG, paralleled with negative association in the OFC, ACC and insula (Fig. 3).

The STG is associated with speech perception and social processing (Bigler et al., 2007; Lee Masson et al., 2024a; Robins et al., 2009), and is anatomically and functionally connected to the STS (Petrides, 2013, 2023), which plays a central role in processing audiovisual social information during movie-watching (Lahnakoski et al., 2012; Lee Masson et al., 2024b; Nummenmaa et al., 2012a; Santavirta et al., 2023). The positive relationship between AQ total scores and the brain responses in the STG aligns with previous findings (Chen et al., 2023; Nummenmaa et al., 2012a; Puglia and Morris, 2017), suggesting individual differences in autistic traits are linked to neural responses in social perception regions. Importantly, our data extends these findings to naturalistic conditions.

The OFC is involved in integrating sensory, emotional, and reward-related information, and in guiding social behavior according to the anticipated value of social cues (Rempel-Clower, 2007; Rushworth et al., 2011). Hypoactivation in OFC is consistently observed in ASD (Patriquin et al., 2016), which may reflect the diminished ability to detect social salience and reduced social motivation.

The ACC is associated with emotion regulation (Etkin et al., 2006) and empathy (Arioli et al., 2021), and dysfunctions in ACC are significantly associated with social cognition impairments in ASD (Di Martino et al., 2009). The insula is associated with emotion recognition and interoception (Terasawa et al., 2021) and its hypoactivation may lead to deficits in emotional processing in ASD (Di Martino et al., 2009). Therefore, AQ-dependent responses to social signals in the STG, OFC, ACC and insula support the notion that the neural mechanisms underlying social perception in ASD extend across a broader spectrum that includes typically developing individuals.

4.2. Brain regions modulated by specific autistic traits in social perception

Several AQ dimension-specific modulations on the neural responses to social perceptual features were replicable across datasets. Scores on the Attention to detail subscale were negatively associated with neural responses in the ACC, ITG and LOC, and positive association was found in the frontal pole and cuneus gyrus (Fig. 3). The cuneus gyrus plays a role in basic visual processing, such as encoding position, local orientation, edges and colors (Cohen, 2011; Palejwala et al., 2021), whereas the ITG and LOC are part of the ventral visual stream (Kravitz et al., 2013), responsible for higher-level visual processing, including holistic or global shape, face, and object representations (Cichy et al., 2011; Miyahara et al., 2013), indicating an enhanced sensitivity to local features alongside diminished engagement in global visual integration. On the other hand, the frontal pole is involved in goal-directed persistence (Burgess et al., 2007), and the ACC is well known for its role in conflict monitoring and cognitive control (Agam et al., 2010; Etkin et al., 2006), suggesting that additional neural resources may be recruited to sustain a detail-oriented cognitive style, and reduced flexibility in shifting between different attention strategies.

Imagination subscale score showed the strongest positive association with neural responses in regions located in the parietal and adjacent multimodal association cortices (i.e., STG, MTG, SMG, and precuneus), as well as occipitotemporal regions (i.e., LOC and fusiform gyrus). These regions have been implicated in visual mental imagery (Pearson, 2019; Spagna et al., 2024; Suchan et al., 2002) and visual perception. In contrast, negative association was observed in the parahippocampal gyrus that is related to autobiographical memory retrieval and scene construction (Aminoff et al., 2013; Mouga et al., 2022). This pattern aligns with a recent fMRI meta-analysis of visual mental imagery, which emphasizes that imagination engages a distributed frontal-temporal-occipital network: prefrontal regions initiate retrieval of semantic and perceptual information from the temporal lobe and occipitotemporal areas, while attention and working memory systems sustain and manipulate the reconstructed mental images (Spagna et al., 2021). Within this framework, difficulties with imagination in individuals with autistic traits may result from an imbalance between over-recruitment of semantic and perceptual networks and under-recruitment of memory-based scene construction mechanisms.

Lower communicative ability was linked to decreased activation in the insula and increased activation in the STG and MTG. Decreased activation in the insula may reflect impaired integration of visual and auditory signals (Bamiou et al., 2003), social motivation (Clements et al., 2018) and emotion processing (Thom et al., 2014), while increased activation in the STG and MTG may be a compensatory response as an attempt to understand conversations and manage social interactions (Landsiedel and Koldewyn, 2023; Leonard and Chang, 2014). Deficits in attention switching were negatively associated with neural responses in the frontal pole and OFC, both of which are key frontal regions for cognitive flexibility, such as attentional shifting (Hampshire and Owen, 2006). Meanwhile, increased activation associated with attentional inflexibility was observed in the PCC, a core region of the default mode network that is implicated in internally directed attention (Leech et al., 2011). The AQ-dependent modulation in the present study may reflect an impaired capacity to intentionally shift between external perceptual features and internal cognitive control, and to adapt behavior in response to changing environmental demands (Dajani and Uddin, 2015), which is correlated with increased restricted interests and repetitive behaviors in ASD (Faja and Nelson Darling, 2019; Miller et al., 2015).

Finally, social skills, ranging from perception of social cues to more complex competencies like theory of mind (Morrison et al., 2017; Soto-Icaza et al., 2015), are recognized as a foundation for the development of social functioning (Klin et al., 2002). In the present study, Social skills subscale score was observed to be negatively linked to BOLD responses in the limbic systems (i.e., hippocampus and amygdala), and

dysfunction in these areas has been observed in ASD during social cognition, including eye contact (Stuart et al., 2023; Tottenham et al., 2014), emotion recognition (Schultz, 2005; Wei et al., 2025), and inferring other's mental states (Arioli et al., 2021). The SMA exhibited reduced activation with lower Social skills scores, which aligns with its role in observing, imitating, and monitoring movements (Delbruck et al., 2019). Such decreased activation may indicate a reduced ability to accurately perceive nonverbal communicative behaviors and to adaptively adjust behaviors across social contexts. The fusiform gyrus is a core region for identity recognition and expression recognition (Floris et al., 2025). Our results revealed increased activation in the fusiform gyrus associated with lower Social skills scores. This finding aligns with prior evidence showing that the fusiform gyrus is hyper-responsive in individuals with ASD during response inhibition to emotional faces (Duerden et al., 2013; Shafritz et al., 2015). One possible explanation is that individuals with diminished social skills may recruit additional neural resources to detect and interpret socially salient facial cues during movie watching.

Altogether, our study revealed both general and dimension-specific relationships between autistic traits and neural alterations during naturalistic social perception in the general population.

5. Limitations

As our study only involved neurotypical volunteers, and the AQ scores were distributed within the normal range, we cannot tell whether the similar patterns of AQ-dependent compensatory modulations to naturalistic social features extend to individuals clinically diagnosed with ASD. Future studies should include individuals with a formal ASD diagnosis to allow direct comparisons and to test the generalizability of the present findings across clinical and non-clinical populations. Second, caution is warranted when interpreting our results given the relatively low reliability of some AQ subscales, future studies would benefit from incorporating additional measures of autistic traits, such as the Social Responsiveness Scale (SRS) to evaluate the robustness and generalizability of these findings. Third, GLM and correlation analyses showed discrepancies in AQ-related modulations in neural responses to social features across datasets (Figs. 2 and 4), which may partly reflect variability in the naturalistic stimuli, such as the different scenarios, the richness of social features, language of the movies (English vs Finnish), and durations. Nonetheless, the convergent results from the consistency analysis identified regions most reliably engaged in perceiving social features across diverse naturalistic contexts. Finally, the absence of behavioral or perceptual measures during movie watching may limit the interpretability of the neural findings. Future studies may integrate eye-tracking measures to examine possible effect of autistic traits on visual exploration patterns during naturalistic social perception.

6. Conclusions

In sum, we demonstrated that individual differences in autism-like traits in neurotypical individuals are associated with neural responses to social features in regions involved in multisensory, social, and cognitive functions during naturalistic movie watching. Most consistent effects across features and datasets were observed in the temporal cortices. These associations indicate that neural alterations underlying social perception in ASD extend across a broader spectrum that includes typically developing individuals. Our findings may provide neurobiological evidence for the heterogeneous nature of autism-related traits.

Data and code availability

According to Finnish legislation, the original (even anonymized) neuroimaging data used in the experiment cannot be released for public use.

Code is available on GitHub (https://github.com/yqyUTU/Autistic-traits-modulate-neural-responses-to-social-signals-during-natural-vision).

In addition, cumulative results are available on NeuroVault (https://neurovault.org/collections/ZGEIACMW/).

CRediT authorship contribution statement

Qingying Ye: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Jinglu Chen:** Methodology, Writing – review & editing. **Severi Santavirta:** Methodology, Writing – review & editing. **Vesa Putkinen:** Conceptualization, Supervision, Writing – review & editing. **Juha Salmi:** Conceptualization, Writing – review & editing. **Lauri Nummenmaa:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2026.122121.

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