CORTEX 187 (2025) 159–171

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Research Report

Predictive responses in the Theory of Mind network: A comparison of autistic and non-autistic adults

Lucie Zimmer [a,*], *Hilary Richardson* [b], *Carolina Pletti* [c], *Markus Paulus* [a] *and Tobias Schuwerk* [a]

[a] *Department of Psychology, Ludwig-Maximilians-Universität München, München, Germany*
[b] *School of Philosophy, Psychology, and Language Sciences, The University of Edinburgh, Edinburgh, United Kingdom*
[c] *Department of Developmental and Educational Psychology, University of Vienna, Wien, Austria*

ARTICLE INFO

Article history:
Received 17 October 2024
Revised 1 April 2025
Accepted 1 April 2025
Action editor Punit Shah
Published online 30 April 2025

Keywords:
Autism spectrum disorder
Theory of mind
fMRI
Predictive coding
Narrative anticipation
Repetition suppression

ABSTRACT

Social cognitive processes, particularly Theory of Mind (ToM) reasoning, appear to differ between autistic and non-autistic individuals. This has been proposed to reflect the autistic core symptomatology of communication and social interaction difficulties. According to the predictive coding theory, autistic individuals' ToM reasoning difficulties arise from an attenuated use of prior information about others' mental states to explain and predict their behavior. This reduced use of prior assumptions makes the social world less predictable for autistic people, causing interactive mismatch and stress. Despite strong theoretical claims, robust and replicable neural differences in ToM brain regions remain elusive. Here, we investigated whether brain regions supporting ToM reasoning anticipate a narrative during repeated exposure (i.e., the narrative anticipation effect) in non-autistic adults (Experiment 1) and tested whether this effect was attenuated in autistic adults (Experiment 2). We presented a short movie with a plot including mental states with associated actions, twice, to 61 non-autistic adults who underwent functional magnetic resonance imaging [Experiment 1: $M(SD)_{age} = 25.9(4.4)$ years]. In Experiment 2, we used the same protocol with 30 autistic [$M(SD)_{age} = 32.4(10.7)$ years] and 30 non-autistic adults [$M(SD)_{age} = 33.2(10.1)$ years]. Analyses revealed no narrative anticipation effect in the ToM network in either group. Exploratory reverse correlation analyses identified a ToM scene that evoked a smaller difference in response between movie viewings (i.e., less repetition suppression) in autistic adults, compared to non-autistic adults. In sum, our study shows that predictive processing in the ToM network during a naturalistic movie-viewing experiment was absent in adults. Subtle differences in a key scene provide preliminary neural evidence for the predictive coding theory and open a promising avenue for future research to better understand the nature of differences in social interaction in autistic adults.

* *Corresponding author*. Ludwig-Maximilians-Universität, Leopoldstr. 13, 80802, München, Germany.
E-mail address: lucie.zimmer@psy.lmu.de (L. Zimmer).

https://doi.org/10.1016/j.cortex.2025.04.006

1. Introduction

According to DSM-5, Autism Spectrum Disorder (ASD, hereafter *autism*) is primarily characterized by two core symptoms: difficulties in social interaction and communication, and stereotyped behavior (American Psychiatric Association, 2013). Cognitive research focused on the social aspect of these core symptoms often examines differences in basic social cognitive processes between autistic and non-autistic individuals. For instance, autistic individuals can face difficulties in ascribing mental states, such as desires and beliefs, to explain and predict the behavior of others (Frith, 2012), the core of Theory of Mind (ToM) reasoning. It is believed that these difficulties are caused by altered social cognitive processes (Kennedy & Adolphs, 2012). However, difficulties of autistic individuals are observable in some but not all ToM tasks (Gernsbacher & Yergeau, 2019) indicating that applying typical ToM tasks may not fully reveal the origins of the challenges experienced by autistic individuals.

The predictive coding theory (Clark, 2013) offers a comprehensive framework for understanding the core autism symptoms, including social difficulties. In particular, others' actions can be predicted from mental states ascribed based on available prior information about the acting person, the corresponding situation and/or people in general. Similarly, mental states of others can be actively predicted (Koster-Hale & Saxe, 2013). Following this hypothesis, social difficulties in autism may arise from weakened social cognitive predictions, which lead autistic individuals to perceive social interactions as unpredictable, cause interactive mismatch (i.e., interactions in which behaviors and expectations of individuals involved do not align), and create stress (Bolis et al., 2017; Pellicano & Burr, 2012; Sinha et al., 2014).

While it has been suggested that predicting others' actions is generally atypical in autism, autistic children appear to attribute goals to others (e.g., Cattaneo et al., 2007; Somogyi et al., 2013). Recent research reported that autistic people do anticipate actions, make correct action predictions, and apply the same cognitive strategies (e.g., goal-directed eye movements) as individuals without autism (Falck-Ytter, 2010; Schuwerk & Paulus, 2018). Moreover, autistic adults learn quickly from action-outcome contingencies, allowing them to make accurate predictions upon subsequent encounters (Schuwerk et al., 2015). Although autistic individuals are able to anticipate another's action goal, evidence suggests that they use prior information less, thereby requiring more time compared to non-autistic individuals (Ganglmayer et al., 2020). Given these observations, the differences between autistic and non-autistic individuals appear to be subtler than previously assumed, indicating that the difficulties may lie in the nuanced use of prior experience and contextual cues. Investigations of predictive ToM reasoning in more complex and naturalistic situations may be important for capturing subtle differences in autistic individuals, but such investigations remain rare.

Following Clark's (2013) original neural examination of predictive coding, exploring the predictive coding theory in a naturalistic context at a neural level using functional magnetic resonance imaging (fMRI) could reveal underlying cognitive differences in autism. For instance, neurotypical adults' prior knowledge of a narrative seems to enable neural anticipation of event patterns (i.e., brain regions were recruited earlier in time indicating an anticipation of the narrative during repeated exposure; Baldassano et al., 2017); brain regions that show this effect include those in the *Theory of Mind network* (bilateral temporoparietal junction, precuneus, and medial prefrontal cortex; Tamir & Thornton, 2018). Anticipation effects reach further into the future in higher-order, anterior brain regions compared to lower-order, posterior brain regions - suggesting that higher-order brain regions may be involved in *narrative* anticipation, rather than anticipation of lower-level stimulus features (Lee et al., 2021). Further, ToM regions use current mental state information to predict future social states (Thornton et al., 2019). Predictive responses during short narratives that involve ToM reasoning have also been repeatedly evidenced in the right temporoparietal junction (rTPJ: Koster-Hale & Saxe, 2013) - a core brain region within the predictive social brain (Geng & Vossel, 2013; Saxe & Wexler, 2005; Schuwerk et al., 2017). In sum, these findings highlight the role of higher order brain regions (e.g., the ToM network) in social cognitive prediction processes in neurotypical adults.

To our knowledge, this kind of research has not yet been extended to autistic adults. This would provide a unique opportunity to test the predictive coding theory. In neurotypical participants, prior research found that unexpected outcomes compared to expected outcomes elicited a stronger response in ToM regions, given prior information about an agent's behavior (Heil et al., 2019), with the magnitude of this effect inversely related to autistic-like traits across participants (Dungan et al., 2016). Moreover, existing research on neural differences in the ToM network in autism yields conflicting results. For instance, studies have observed reduced TPJ activation and weaker functional connectivity during social cognition tasks (i.e., intentional causal attributions; Kana et al., 2014), as well as similar brain activation in ToM tasks (Dufour et al., 2013; Moessnang et al., 2020) and during passive viewing of movie scenes known to evoke ToM reasoning when presented once (Mangnus et al., 2024). Assessing predictive activity of the mentalizing network while autistic participants try to make sense of other's interactions is a promising way to increase ecological validity (Sonkusare et al., 2019) and test the predictive coding theory.

In developmental neuroscientific research this naturalistic approach has been applied using a novel paradigm in a fMRI study (Richardson & Saxe, 2019). Three-to-7-year-old neurotypical children were shown the Disney Pixar's movie *Partly Cloudy* twice in a row, while undergoing fMRI. The study tested the hypothesis that predictive responses in ToM brain regions of children might manifest as temporally earlier responses during the second viewing of the movie (reflecting, e.g., less information required to form predictions and/or less violation of expectations during the second viewing of the movie). Results demonstrated that as children got older, they recruited the ToM network (including bilateral temporoparietal junction, precuneus, medial prefrontal cortex) earlier during the second viewing compared to the first - suggesting that these brain regions increasingly anticipated the narrative of the movie (*narrative anticipation effect*). There was no such effect in

a control network of brain regions recruited for reasoning about bodily sensations (the *pain matrix*). This exact approach has not yet been applied to adults. Here, we aim to investigate whether differences in social interactions between autistic and non-autistic individuals may arise from less reliable neural predictions, thereby testing the predictive coding theory using Richardson and Saxe's (2019) approach.

Thus, the aim of the present study was two-fold. First, we attempted to find predictive coding processes by extending Richardson and Saxe's (2019) findings of a narrative anticipation effect to adults, applying their paradigm with the exact same fMRI stimuli and analysis procedures. Second, we tested open questions concerning predictive processing in the ToM network of autistic individuals. In Experiment 1, we expected to find a narrative anticipation effect in the ToM network but not in the pain matrix control network, indicating predictive coding processes in non-autistic adults (Richardson & Saxe, 2019). In Experiment 2, we planned to replicate Experiment 1 and compare the narrative anticipation effect in autistic and non-autistic adults, hypothesizing that the narrative anticipation effect would be attenuated (i.e., no/less anticipation of the narrative in the ToM network) in autistic compared to non-autistic adults (cf., Pellicano & Burr, 2012).

2. Methods

2.1. Participants

Experiment 1 included 61 non-autistic adults (30 women, 31 men, $M_{age} = 25.9$ years, $SD_{age} = 4.4$ years). An additional 3 non-autistic participants were tested but excluded due to technical issues during data collection ($n = 2$) and data preprocessing ($n = 1$).

Experiment 2 included 30 autistic adults (16 women, 12 men, 2 non-binary, $M_{age} = 32.4$ years, $SD_{age} = 10.7$ years) and 30 non-autistic adults (18 women, 12 men, $M_{age} = 33.2$ years, $SD_{age} = 10.1$ years). All autistic participants had been diagnosed by a qualified clinical psychologist or psychiatrist on average at the age of 27.2 years (SD = 12.22, range = 5–52 years; age of diagnosis was self-reported), with over 70% ($n = 22$) receiving their autism diagnosis in adulthood; the subtle presentation of this group should be considered when interpreting the generalizability to populations diagnosed earlier, particularly in childhood. The autism diagnosis was verified through medical documentation provided by the participants. Participants specified their autism diagnosis via self-report according to the International Classification of Diseases– 10th Revision (ICD-10) criteria: Asperger's syndrome ($n = 23$), high-functioning autism ($n = 2$), atypical autism ($n = 1$), multiple autism diagnoses ($n = 3$), and no specification provided ($n = 1$). Group assignment was further validated by two additional self-assessment measures of autistic traits [*Autism Quotient* (AQ; Baron-Cohen et al., 2001) & *Broad Autism Phenotype Questionnaire* (BAPQ; Hurley et al., 2007)], which confirmed significant differences between the autistic and non-autistic groups. The groups were matched based on gender, chronological age, and verbal and nonverbal intelligence (see Table 1). In the autistic group 30% ($n = 9$) had at least a university degree; this proportion was higher in the non-autistic group 70% ($n = 21$).

Table 1 – Demographic characteristics of the autistic and non-autistic group of Experiment 2.

	autistic group ($N = 30$)		non-autistic group ($N = 30$)		*Cohen's d*
	M	*SD*	*M*	*SD*	
Age	32.4	10.7	33.2	10.1	−.07
Verbal IQ (MWT)	111.0	14.6	115.5	18.0	−.28
Non-verbal IQ (CFT 20 R)	111.4	13.3	116.7	8.8	−.46
Autistic traits (AQ)	39.7	7.2	19.4	18.4	1.18 ***
Autistic traits (BAPQ)	4.5	.7	2.6	.7	1.63 ***

M, means; SD, standard deviation; MWT, Multiple Choice Vocabulary Intelligence Test (German: Mehrfachwahl-Wortschatz-Test); CFT 20 R, Culture Fair Test; AQ, Autism Quotient; BAPQ, Broad Autism Phenotype Questionnaire; ***, $p < .001$.

Over 75% ($n = 23$) of the autistic participants reported having at least one comorbidity. According to ICD-10 criteria, half ($n = 16$) of the autistic participants reported comorbid depression, one-third reported Anxiety Disorder ($n = 10$) and Attention Deficit Hyperactivity Disorder ($n = 10$), and one-fifth ($n = 6$) Post-Traumatic Stress Disorder. Over 80% ($n = 25$) have been or are currently in psychotherapy. To account for high comorbidity rates in autistic participants (e.g., Mannion & Leader, 2013), non-autistic participants with a psychiatric condition were included in the sample to reach a closely matched comparison group (Schwartz & Susser, 2011). Because we did not collect detailed information about comorbid conditions in the comparison group, we are unfortunately unable to report this here. However, this does not compromise our matching procedure with respect to comorbid conditions.

Autistic adults were recruited via local networks including clinics, practitioners and autism organizations. Non-autistic adults from the comparison group were consecutively recruited to match the individuals in the autism group via Ludwig-Maximilians-Universität (LMU) München's mailing list and postings on social media. All of the participants gave written informed consent prior to their participation and received payment for participating. The study was approved by the Ethics Committee of the Department of Psychology and Education of the Ludwig-Maximilians-Universität München.

2.2. Procedure and measures

2.2.1. Self-assessment measures

Before coming to our lab the participants in Experiment 2 were asked to complete a demographic questionnaire (asking about age, gender, autism diagnosis, comorbid psychiatric diagnoses, etc.) via an online survey tool. To support group assignment, we additionally assessed autistic traits via the self-assessment measures *Autism Quotient* (AQ; Baron-Cohen et al., 2001) and *Broad Autism Phenotype Questionnaire* (BAPQ; Hurley et al., 2007). In both questionnaires (AQ and BAPQ),

higher scores indicate more autistic traits, ranging from 0 to 50 in the AQ (cut-off criterion: score ≥32), and from 1 to 6 in the BAPQ (cut-off criterion: score ≥3.15).

2.2.2. *Assessment of verbal intelligence*

Verbal intelligence was measured with the German version of the *Multiple Choice Vocabulary Intelligence Test* (German: Mehrfachwahl-Wortschatz-Test MWT; Lehrl, 2005) and nonverbal intelligence with the *Culture Fair Test* (German: Grundintelligenztest CFT 20-R; Weiβ, 2019) after the fMRI scan.

2.2.3. *fMRI data acquisition*

The study was conducted at the NeuroImaging Core Unit Munich at LMU Munich using a 3-T MRI scanner. Participants used the standard Siemens 32-channel head coil. T1-weighted structural images were collected in 208 interleaved sagittal slices with isotropic voxels of .80 mm (GRAPPA parallel imaging, acceleration factor of 2; standard coil: FOV: 256 mm). Functional data were collected using a gradient-echo EPI sequence sensitive to Blood Oxygen Level Dependent (BOLD) contrast with 48 interleaved near-axial slices, 3 mm isotropic voxels, and a 10% slice gap, aligned with the anterior/posterior commissure, covering the entire brain (EPI factor: 70; TR: 1s, TE: 30 msec, flip angle: 45°). A total of 360 volumes were acquired per run, with the two movie viewings being collected across two separate runs.

In order to minimize stress and sensory overload in autistic participants, we adjusted the experimental setup (e.g., reduced number of staff involved, reduced waiting time, exact communication of time per scan and highlighting the remaining examination time between the scans, etc.) and customized the communication according to recent person-centered recommendations (Stogiannos et al., 2022).

2.2.4. *fMRI paradigm*

Following prior research (Richardson & Saxe, 2019), participants viewed the 5.6-min Disney Pixar's animated short movie *Partly Cloudy*, twice, while undergoing fMRI. The movie is about two main characters: a lonely grey cloud named Gus, who constantly creates dangerous baby animals like crocodiles, hedgehogs, and electric eels, and his loyal partner Peck, a stork, who delivers these animals to their parents. While the other storks deliver only sweet baby animals like puppies and kittens, Peck's job becomes increasingly challenging. When Peck flies away from Gus instead of delivering a baby shark, Gus becomes furious, believing Peck has abandoned him. To Gus's relief, Peck eventually returns with protective football gear that he had obtained during his absence to enable him to continue to work with Gus.

The movie was presented silently. Participants were asked to stay still and pay attention to the movie.

2.2.5. *fMRI data analysis*

Preprocessing procedures were identical to those used in Richardson and Saxe (2019), implemented using the same software (SPM8) and analysis scripts (Matlab 2017a). Functional images were registered to the first image of the run; that image was registered to each participant's anatomical image, and each participant's anatomical image was normalized to the Montreal Neurological Institute (MNI) template. Registration of each individual's brain to the MNI template was visually inspected, including checking the match of the cortical envelope and internal features like the Anterior-Posterior Commissures and major sulci. All data were smoothed using a Gaussian filter (5 mm kernel) and underwent SPM's global image scaling.

The realignment parameters were used to identify artifact timepoints, using the Artifact Detection Tool (Whitfield-Gabrieli et al., 2011). Artifact timepoints were defined as timepoints where composite motion exceeded 2 mm, relative to the previous time point, and/or the global signal deviated more than 3 standard deviations from the average global signal. Runs would have been excluded if one-third or more of the acquired timepoints were identified as artifacts; this resulted in zero exclusions (for our pre-registered exclusion criteria see https://osf.io/cqnmf).

Participant motion was relatively low [number of artifact timepoints: Experiment 1: M(SD) = 9.6(11.1); Experiment 2, autistic participants: M(SD) = 11.9(9.7); Experiment 2, non-autistic participants: M(SD) = 8.7(5.3); mean translation across all timepoints: Experiment 1: M(SD) = .03(.01) mm; Experiment 2, autistic participants: M(SD) = .04(.02) mm; Experiment 2, non-autistic participants: M(SD) = .03(.01)mm]. Number of artifact timepoints positively correlated with mean translation in the autistic sample [Experiment 2, autistic participants: $r(28) = .38$, $p = .039$], and did not correlate in the two non-autistic samples [Experiment 1: $r(59) = .01$, $p = .941$; Experiment 2, non-autistic participants: $r(28) = .08$, $p = .672$]. In Experiment 2, the size of effect of group (autistic versus non-autistic) on motion revealed a small effect in the number of artifact timepoints [Cohen's $d = .41$, 95% CI (−.11, .93)], and medium effect in the mean translation [Cohen's $d = .52$, 95% CI (−.01, 1.04)]. We included the amount of motion (i.e., mean translation) as a covariate of no interest in regressions that involve neural measures. We additionally defined five regressors using the CompCor method (Behzadi et al., 2007) in eroded white matter masks. These regressors were defined on white matter signal after interpolating over timepoints previously identified as artifact timepoints, such that these regressors were maximally independent from the artifact timepoint regressors.

Primary analyses were run on timecourses extracted from group functional regions of interest (ROIs) encompassing the ToM network [bilateral temporoparietal junction (R/LTPJ), precuneus (PC), and dorso-, middle- and ventromedial prefrontal cortex (D/M/VMPFC)] and the pain matrix (bilateral medial frontal gyrus, secondary sensory motor cortex, insula, and dorsal anterior cingulate cortex). Group ROIs were previously defined in neurotypical adults ($n = 20$; see Richardson et al., 2018 for details) and used in Richardson and Saxe (2019). ROIs are publicly available for download (https://openneuro.org/datasets/ds000228).

From each group ROI, we extracted the preprocessed timecourse from each voxel, applied nearest-neighbor interpolation over artifact timepoints, and regressed out (1) motion spikes and (2) five CompCor regressors (see above for details on motion artifact). Residual timecourses were high-pass filtered (threshold: 1 cycle/100s). Timecourses across voxels within each ROI were averaged and artifact timepoints

were excluded (NaNed). ROI timecourses were averaged per network (ToM network, pain matrix), such that there was one timecourse per network, movie-viewing, and participant.

We then calculated the correlation between each participant's timecourses during the first and second viewings for the ToM network and pain matrix in two temporal shifting schemes. Since the narrative anticipation effect was strongest at 2s time difference in Richardson and Saxe (2019), we used this time lag between the *anticipation* and *no shift* schemes. Thus, in the anticipation scheme, we calculated the correlation between timepoints 3–360 in the first viewing to timepoints 1–358 in the second viewing. In the no shift scheme, we calculated the correlation between timepoints 1–360 in the first and second viewings.

3. Statistical analyses

3.1. *Confirmatory analyses*

All statistical analyses were carried out in R (version 4.1.1, R Core Team, 2021). The anticipation effect was assessed by the *anticipation-no shift* correlation difference (CD; for graphs depicting correlation in anticipation and no shift schemes, see Fig. 1). All measures were normally distributed.

To confirm that the expected ToM regions were recruited during the movie across groups and viewings, we used a general linear model to analyse BOLD activity of each participant and run (separately) as a function of scene-type (for details see Supplementary Material).

3.1.1. *Experiment 1: Narrative anticipation in non-autistic adults (extension of Richardson & Saxe, 2019)*

In Experiment 1, we first tested for a narrative anticipation effect in non-autistic adults using a one-tailed one sample *t*-test, testing the anticipation-no shift CD in the ToM network of non-autistic adults.

Second, we tested whether the narrative anticipation effect was larger in the ToM network as compared to the pain matrix using a one-tailed paired *t*-test. As a follow-up analysis we tested for a narrative anticipation effect in the pain matrix using a two-tailed one sample *t*-test.

3.1.2. *Experiment 2: Narrative anticipation in autistic adults (replication of experiment 1 and extension of Richardson & Saxe, 2019)*

In Experiment 2, we first repeated Experiment 1 analyses with non-autistic and autistic samples. We expected to replicate Experiment 1 results with the non-autistic sample in Experiment 2, and planned to test whether the anticipation effect was larger in the non-autistic adults, as compared to the autistic adults. We conducted a linear mixed effects model using the lme4 package 1.1–33 (Bates et al., 2015) to test for an effect of group (autistic versus non-autistic) on the anticipation-no shift CD. We also included motion as a fixed effect, to account for potential effects of data quality [i.e., lm(CD-ToM ~ group + motion)]. Finally, we planned to test whether such a group difference in narrative anticipation effect was specific to the ToM network, by using another linear regression model to test for a network (ToM network versus pain matrix)-by-group (autistic versus non-autistic) interaction [i.e., lm(CD ~ network + group + network*group + motion)].

3.2. *Exploratory analyses*

To foreshadow our results: our planned analyses did not reveal a narrative anticipation effect in the ToM network of non-autistic adults in either Experiment 1 or 2. Given this, we conducted a series of exploratory analyses to ensure that we did not miss the predicted narrative anticipation effect. For the sake of clarity, we include the plan for these additional analyses here. First, to ensure that we did not miss predicted narrative anticipation effects due to adults having faster/more efficient predictive responses (relative to children; Richardson & Saxe, 2019), we ran the same analyses using a different temporal shift (i.e., 1s rather than 2s), which was afforded by the faster acquisition time of the fMRI sequence used in the present study. Second, following Richardson and Saxe (2019; Supplementary Figure 6), we explored narrative anticipation effects in all six regions of interest of the ToM network separately (DMPFC, LTPJ, MMPFC, PC, RTPJ, VMPFC), to ensure that the effect was absent in every region (rather than present in a subset of regions but obscured by the network average timecourse). Third, following Richardson and Saxe (2019; Supplementary Figure 8), we tested whether a narrative anticipation effect was present in neural response patterns – which can at times be more sensitive than univariate approaches. Fourth, we tested for an overall repetition suppression effect (i.e., a lower response magnitude in second viewing compared to first viewing, on average across all timepoints in the response timecourse, following Richardson and Saxe (2019); Supplementary Figure 9].

We then conducted two exploratory analyses to test for a local – i.e., content-specific – narrative anticipation or repetition suppression effect – in case predictive effects in ToM brain regions were specific to scenes in the movie that evoke ToM reasoning. First, we tested for a narrative anticipation effect (i.e., earlier response during second movie-viewing) specifically during all ToM scenes (using a concatenated timecourse), as defined in Richardson et al. (2018; for an overview of corresponding timepoints see Supplementary Fig. 8). Second, we used data-driven reverse correlation analyses (see Hasson et al., 2004; Richardson et al., 2018) to identify scenes (>4s) in a continuous naturalistic stimulus, in which there was a reliable difference across participants in response magnitude across viewings, per network and sample (i.e., Experiment 1 non-autistic, Experiment 2 non-autistic, and Experiment 2 autistic, separately). Reduced responses during the second viewing of the movie were defined as repetition suppression effects. After identifying scenes that evoked a different response (positive or negative) during the second viewing in non-autistic adults of Experiment 1, we tested for a replication in non-autistic adults in Experiment 2, and compared results with autistic adults in Experiment 2. Specifically, we ran a linear regression with Experiment 2 data to test for group, viewing, and group-by-viewing interaction effects on the response magnitude to a scene that reliably showed repetition suppression in non-autistic adults [i.e., lm(response.magnitude ~ group + viewing + group* viewing + motion)].

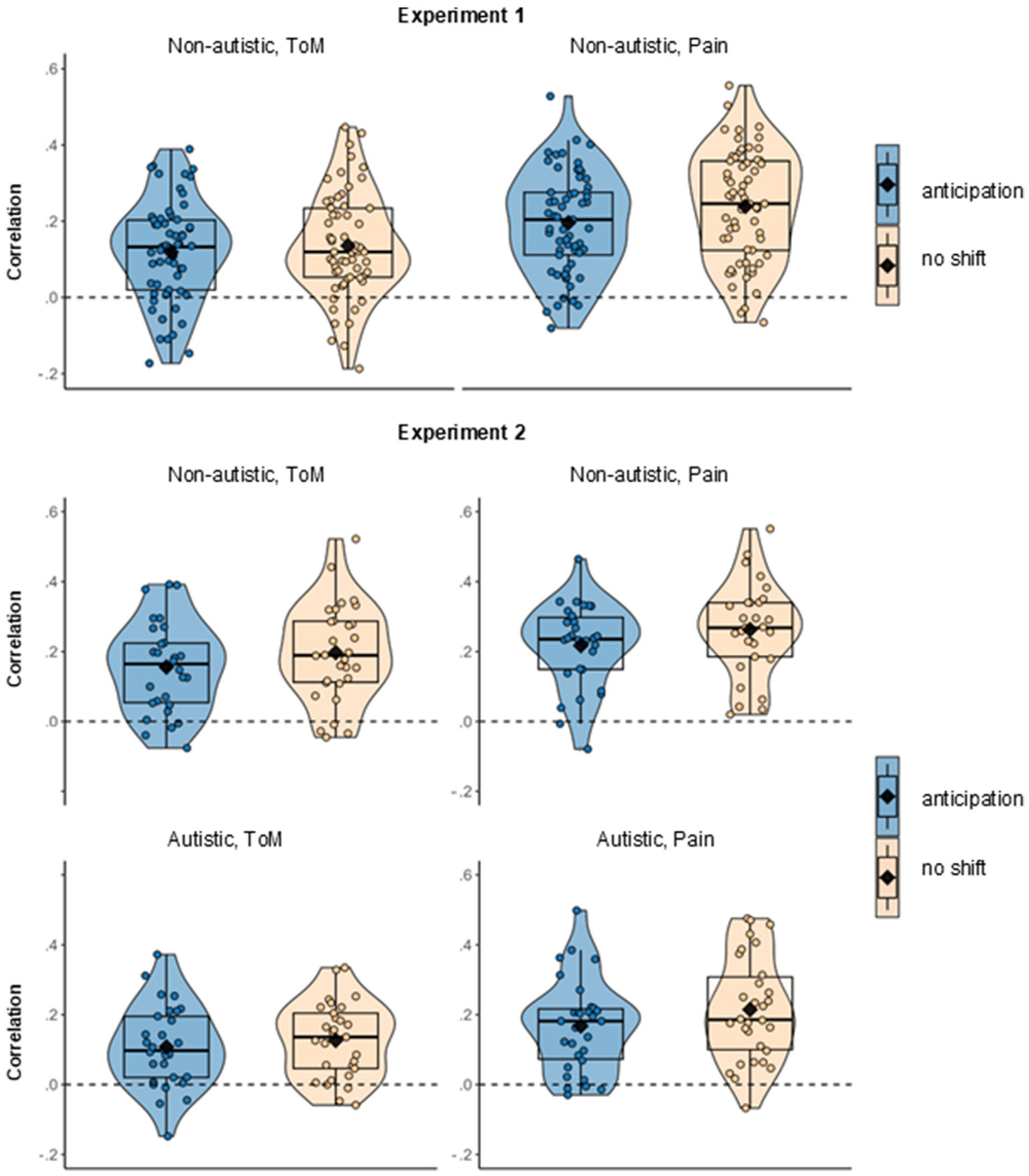

Fig. 1 – Graph depicting the z-scored correlation (y-axis) in the anticipation (blue) and no shift (orange) correlation schemes for the ToM network (x-axis, left) and the pain matrix (x-axis, right) in Experiment 1 (upper plot) and in Experiment 2 (lower plot) for both groups (non-autistic: upper plot in Experiment 2 and autistic: lower plot in Experiment 2).

4. Results

4.1. *Confirmatory analyses*

ToM movie scenes evoked responses in the ToM network in all groups (Experiment 1: non-autistic adults; Experiment 2: autistic and non-autistic adults) and in both movie viewings (see Supplementary Fig. 1).

4.1.1. *Experiment 1: Narrative anticipation in non-autistic adults (extension of Richardson & Saxe, 2019)*

In non-autistic adults, temporally misaligning the ToM time-courses from the first and second viewings into the

anticipation scheme reduced the correlations between them [$M = -.02$, $SE = .01$; one-tailed one sample t-test (mu = 0): $t(60) = -2.03$, $p = .977$], indicating that the non-autistic participants did not show narrative anticipation in the ToM network during the second presentation of the movie. When comparing the anticipation effect in the ToM network to the pain matrix using a one-tailed paired t-test, the effect significantly differed between both networks, $t(60) = 2.50$, $p = .008$, such that the effect was smaller (more negative) in the pain matrix. In a follow-up analysis, a one sample two-way t-test revealed that the anticipation effect in the pain matrix ($M = -.04$, $SE = .01$) was significantly negative relative to 0, $t(60) = -5.25$, $p < .001$ (see Fig. 2; for graph depicting the average timecourses by network, and viewing, see Supplementary Fig. 2). This negative effect was predicted as any temporal shift in timecourses (in absence of a narrative anticipation effect) should lead to a reduced correlation between the timecourses.

4.1.2. *Experiment 2: Narrative anticipation in autistic adults (replication of experiment 1 and extension of Richardson & Saxe, 2019)*

First, we replicated the results above with our second non-autistic sample. In non-autistic participants, the anticipation effect in the ToM network ($M = -.04$, $SE = .01$) was again not significantly positive relative to 0, $t(29) = -3.02$, $p = .997$, indicating that adults did not show anticipation in the ToM network during the second presentation of the movie. Unlike in Experiment 1, when comparing the anticipation effect in the ToM network to the pain matrix using a one-tailed paired t-test, the effect did not significantly differ between the networks, $t(29) = .93$, $p = .180$. As in Experiment 1, a one sample two-way t-test revealed that the anticipation effect in the pain matrix ($M = -.06$, $SE = .01$) was significantly negative relative to 0, $t(29) = -3.93$, $p < .001$ (see Fig. 2; for graph depicting the average timecourses by network, and viewing, see Supplementary Fig. 2).

We observed the same pattern of results in autistic adults. Using a one-tailed one sample t-test, the anticipation effect in the ToM network ($M = -.02$, $SE = .01$) of the autistic participants was not significantly positive relative to 0, $t(29) = -1.65$, $p = .945$, indicating that the autistic participants did not show anticipation in the ToM network during the second presentation of the movie. When comparing the anticipation effect in the ToM network to the pain matrix using a one-tailed paired t-test, the effect significantly differed between both networks, $t(29) = 2.00$, $p = .027$, such that the effect was smaller (more negative) in the pain matrix. In a follow-up analysis, a one sample two-way t-test revealed that the anticipation effect in the pain matrix ($M = -.05$, $SE = .01$) was significantly negative relative to 0, $t(29) = -3.83$, $p < .001$ (see Fig. 2; for graph depicting the average timecourses by network, and viewing, see Supplementary Fig. 2).

To test for a group difference in the anticipation effect in the ToM network, we fit a linear mixed model and found no significant main effect of group ($ß = -.02$, $t = -1.28$, $p = .207$), indicating that the anticipation effect in the ToM network was not larger in the group of non-autistic participants compared to the autistic participants. Finally, we used a linear mixed effects model to simultaneously test for effects of brain network (ToM network versus pain matrix), group (autistic versus non-autistic), and the group-by-network interaction term on the correlation difference. We found no significant interaction effect of group-by-network ($ß = -.01$, $t = -.52$, $p = .610$), and also no significant main effects of network ($ß = .03$, $t = 1.64$, $p = .104$) or group ($ß = -.01$, $t = -.40$, $p = .688$).

4.2. *Exploratory analyses*

To ensure that predicted effects did not go unnoticed, we conducted a series of exploratory analyses, as detailed in the Methods and Supplementary Material. Briefly, the pattern of results remained unchanged with a 1s temporal shift (instead of 2s shift; see Supplementary Fig. 3). Second, the narrative anticipation effect was not present in any individual ToM

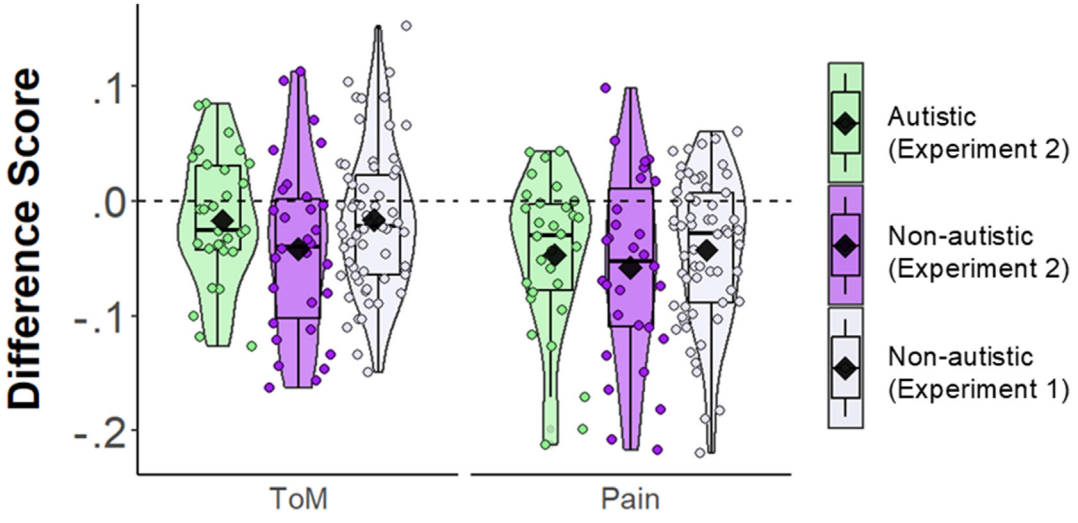

Fig. 2 – Graph depicting the difference score (y-axis) in the ToM network (x-axis, left) and pain matrix (x-axis, right) in Experiment 1 and 2 (green: autistic participants (Experiment 2); purple: non-autistic participants (Experiment 2); light purple: non-autistic participants (Experiment 1). A positive difference score would evidence a narrative anticipation effect.

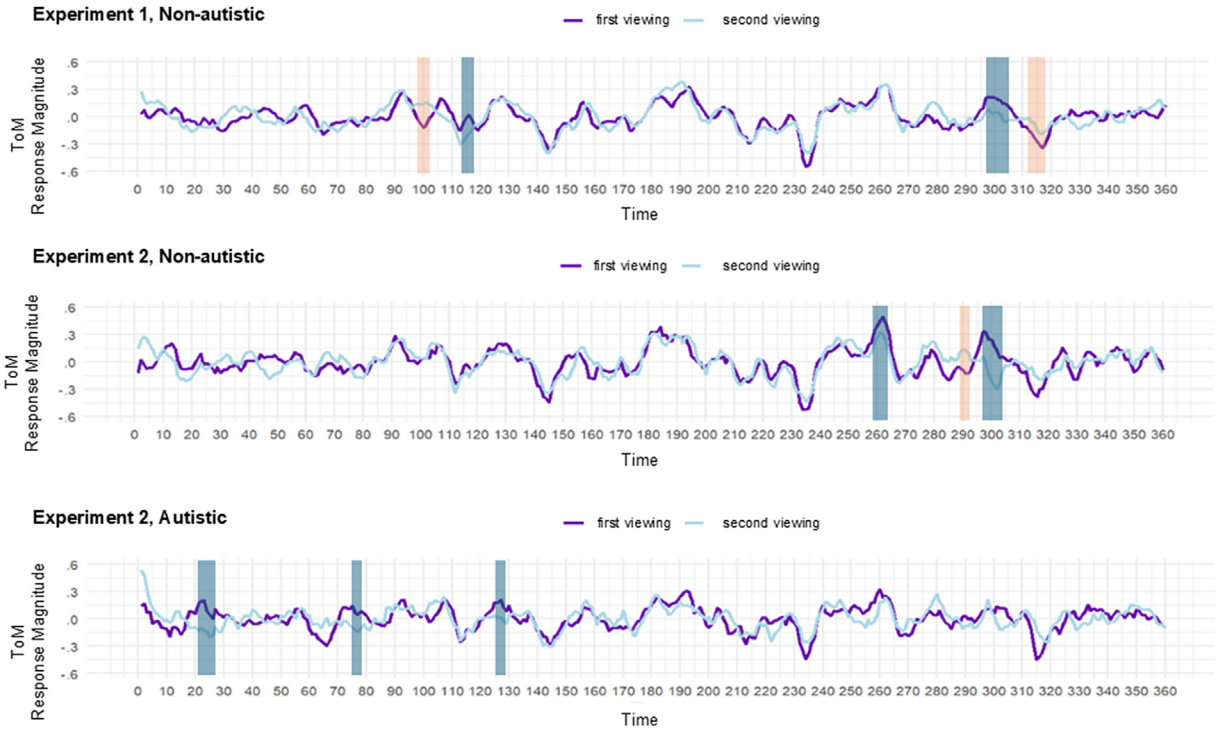

Fig. 3 – Average timecourses in the ToM network for each experiment (Experiment 1 versus Experiment 2), group (in Experiment 2: autistic versus non-autistic), and viewing (purple: 1st viewing, light blue: 2nd viewing) with response magnitude (*y*-axis) and timecourse (*x*-axis). Scenes with significant positive values marked in blue, scenes with significant negative values in orange.

network ROI (for a graph depicting the difference score in each ROI, see Supplementary Fig. 4, and for the average timecourses by ROI and viewing, see Supplementary Fig. 5). Third, we found no evidence for a narrative anticipation effect in the multivariate pattern of response (see Supplementary Fig. 6). Fourth, there was no positive evidence for repetition suppression across the full timecourse, in either experiment (see Supplementary Fig. 7). We also did not observe a narrative anticipation effect in the ToM network specifically during concatenated ToM scenes, as identified in Richardson et al. (2018; for details see Supplementary Material).

4.2.1. *Exploratory reverse correlation analyses in the ToM network*

Finally, we conducted data-driven reverse correlation analyses (Hasson et al., 2004) to discover scenes in which the response magnitude reliably differed across viewings. In non-autistic adults in Experiment 1, we identified two scenes that evoked smaller responses during the second viewing, relative to the first viewing (i.e., timepoints 98–102, and 297–305) and two scenes that evoked larger responses during the second viewing, relative to the first viewing (i.e., timepoints 113–117, and 312–318). We repeated analyses in non-autistic adults in Experiment 2 and replicated the reduced response to one scene during the second viewing (i.e., timepoints 297–304); we also identified a novel scene that evoked a smaller response during the second viewing (i.e., timepoints 259–264) and a novel scene that evoked a larger response during the second viewing (i.e., timepoints 289–292).

In autistic adults in Experiment 2, we identified three scenes that evoked smaller responses during the second viewing, only (i.e., timepoints 21–27, 75–78, and 125–128); autistic adults did not show reduced responses to the one scene we identified in both Experiments with non-autistic adults during the second viewing (see Fig. 3). The range of repetition suppression effects between autistic and non-autistic participants, illustrated by individual subject response difference values, was similar across groups (see Supplementary Fig. 9).

We conducted similar analyses in the pain matrix to understand the specificity of the apparent repetition suppression effects. In Experiment 1, we identified three scenes that evoked smaller responses during the second viewing, relative to the first viewing (i.e., timepoints 97–100, 233–236, and 274–277) and one scene that evoked larger responses during the second viewing, relative to the first viewing (i.e., timepoints 49–52). In Experiment 2, we did not identify any scene in autistic nor non-autistic samples that evoked differential response magnitude across viewings. Taken together, we did not find evidence for robust, replicable repetition suppression effects in the pain matrix.

Interestingly, the scene that evoked reduced responses in the ToM network during the second viewing across both experiments in non-autistic adults was previously identified as a scene that drives responses in ToM brain regions in (non-

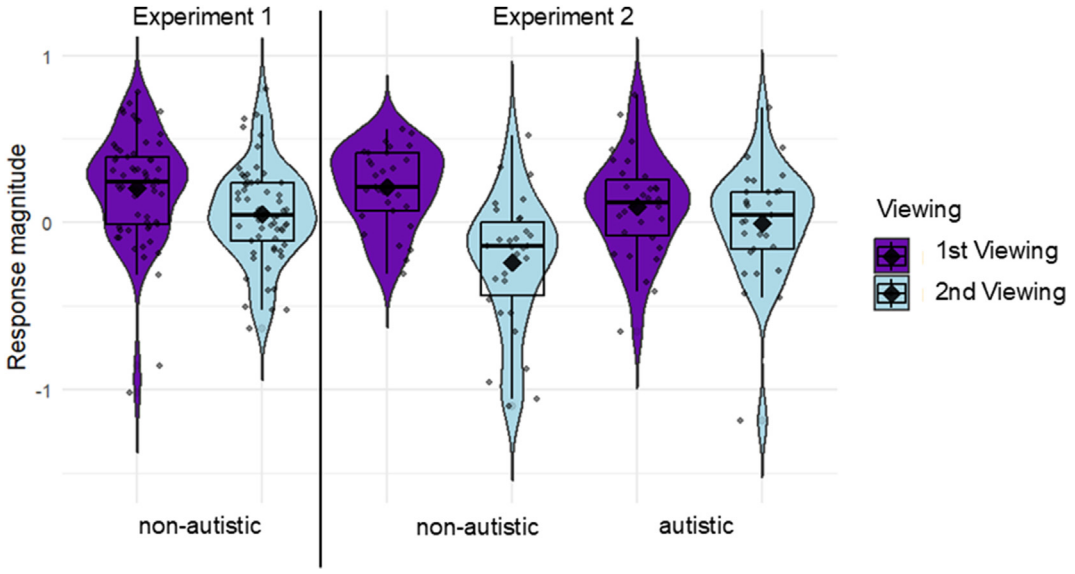

Fig. 4 – Graph depicting the response magnitude to a key ToM scene (T04; y-axis) per group (Experiment 1: non-autistic participants; Experiment 2: non-autistic and autistic participants; x-axis) and viewing (purple: 1st; light blue: 2nd viewing) in the ToM network.

autistic) adults in Richardson et al., 2018 (referred to as scene T04). In this scene, one character initially holds false beliefs about the other's intentions but feels relieved upon discovering the truth. Further, among 3–12-year-old children, ToM network response magnitude during this scene correlated with Theory of Mind behavior, controlling for age. Given these prior results, we tested whether the extent to which responses to T04 were reduced during the second viewing differed significantly between groups in Experiment 2. We extracted the response magnitude to the previously-defined peak timepoint of this scene (timepoint 150 in Richardson et al., 2018; which corresponded to timepoints 300 & 301 in this study) from each individual in each viewing. We found a significant main effect of group ($ß = .44$, $t = 2.31$, $p = .023$), indicating that there was, overall, a reduced response in the ToM network in autistic adults, relative to non-autistic adults, to this scene. There was also a significant group-by-viewing interaction effect ($ß = -.34$, $t = -2.85$, $p = .005$), such that non-autistic adults showed more repetition suppression (i.e., reduced response to T04 during the second viewing) relative to autistic adults (see Fig. 4).

5. Discussion

In this study, we examined predictive coding processes in brain regions associated with Theory of Mind reasoning in non-autistic and autistic adults. We investigated a narrative anticipation effect (i.e., ToM responses shifted earlier in time during the second movie viewing) that was previously described in children by Richardson and Saxe (2019) in three samples of adults (Experiment 1: non-autistic adults; Experiment 2: non-autistic and autistic adults) by applying the exact same paradigm. First, we aimed to find a narrative anticipation effect in non-autistic adults (Experiment 1) and attempted to replicate it in a new sample of non-autistic adults (Experiment 2). Second, we aimed to extend this effect to autistic adults (Experiment 2) to compare predictive coding processes in autistic and non-autistic adults. We expected to find differences between autistic and non-autistic individuals in this effect that could contribute to difficulties in social interaction in autism.

In contrast to our expectations, in our confirmatory analyses, we did not find evidence for narrative anticipation in the ToM network in either non-autistic or autistic adults. Further, we did not find a significant difference in narrative anticipation between non-autistic and autistic adults. Rather, our study showed that the neural responses in the ToM network during a short, naturalistic movie-viewing experiment are highly similar between autistic and non-autistic adults. In all adult samples, response timecourses across viewings were more correlated when temporally aligned than when the second timecourse was shifted earlier in time. In two samples (non-autistic adults in Experiment 1 and autistic adults in Experiment 2), we observed higher correlations in the ToM network, relative to the pain matrix, under the narrative anticipation time scheme - which is consistent with Richardson and Saxe (2019) - but in both cases these higher correlations were still lower than the aligned timecourse correlations. Narrative anticipation effects were also not observed at a faster timescale, in individual ToM regions, or in the multivariate response patterns. These findings of our main analysis may indicate either that a narrative anticipation effect exists, but our task is not sensitive enough to capture it in adults – meaning we cannot draw any conclusions about a group difference (or its absence) – or that adults do not show a narrative anticipation effect when watching this movie. Consequently, our findings show that autistic adults do not differ from non-autistic adults. This would

suggest that the core interaction difficulties observed in autism may not lie in an attenuation of prediction processes or may not be captured throughout an anticipation of an entire narrative. Instead, these social difficulties may be measurable in specific situations and/or located in other areas or processes. Moreover, these similar neural responses may suggest that autistic individuals understand narratives similarly to neurotypical individuals but face difficulties more at a level of execution, which is consistent with literature finding no measurable differences between autistic and non-autistic adults in ToM network activation during mentalizing (Dufour et al., 2013; Mangnus et al., 2024; Moessnang et al., 2020). From a theoretical perspective, our confirmatory results would speak against the theoretical explanation of a circumscribed and profound Theory of Mind deficit causing interaction and communication problems in autistic adults (Gernsbacher & Yergeau, 2019).

In exploratory analyses we used data-driven reverse correlation analyses to identify scenes that evoked reliable response differences between the first and second viewing. In both non-autistic samples, we identified a crucial scene at the end of the movie that evoked smaller responses in the ToM network, but not in the pain matrix, during the second viewing, relative to the first viewing. In autistic adults, this key scene evoked a smaller response overall and did not evoke a reduced response during the second viewing (i.e., there was no repetition suppression effect across viewings of this scene); the magnitude of repetition suppression to this scene differed significantly across autistic and non-autistic groups. We did not find global repetition suppression effects - across the whole timecourse - in any sample or networks. This suggests that the observed repetition suppression effect in the ToM network appears to be specific to this key scene.

In comparison to other social scenes in the movie, that also show social interactions involving mental states and emotions, this key scene specifically evokes a more complex reasoning about the false beliefs of the characters: it shows Gus, the grey cloud, revising his beliefs about the intention of his partner Peck, the stork. Because of Peck's absence, Gus became furious, believing that Peck had abandoned him after constantly creating dangerous creatures for Peck to deliver. When Peck returned with protective gear, Gus felt relieved and happy upon realizing Peck's true intentions. In a previous study this same scene drove responses in ToM brain regions in (non-autistic) adults and response magnitude during this scene correlated with ToM behavior in 3- to 12-year-old children, controlling for age (Richardson et al., 2018). Our results might indicate that when complex ToM reasoning is required, different neural processing within the ToM network becomes evident in autistic adults, which is in line with recent findings showing that differences between autistic and non-autistic individuals emerge only when ToM processes become demanding (Schuwerk & Sodian, 2023). Potentially, non-autistic adults benefit more from the initial viewing of this ToM scene, reflected in a more efficient processing (i.e., less response magnitude) during the repeated viewing of the ToM scene. In contrast, autistic adults did not show differences in processing this ToM scene (i.e., the response magnitude was similar) between the first and second viewings, which might indicate that processing demands remained consistent regardless of repetition, suggesting a potential difference in adaptive strategies when processing complex social information. Although this key scene involves a clear false belief and empirical evidence underpins the association between ToM network responses to this scene and ToM reasoning, its emotional content may also contribute to the observed group difference. Future studies could explore the role of empathetic reasoning in processing this scene.

In sum, our confirmatory analyses leave open whether predictive processing is at work in non-autistic and autistic adults when processing social scenes. Additionally, we find no evidence for differential processing in autism. Using a data-driven reverse correlation approach, we identified one scene that evoked differential predictive processes between autistic and non-autistic adults - in line with previous literature. This scene evoked complex ToM reasoning. Thus, we only find exploratory evidence which is not supported by the main analysis, and may either indicate a subtle difference or no difference. But, it is up to future research to confirm this exploratory finding and to better understand this effect.

5.1. *Limitations*

In 3–7-year-old children, the presence of a narrative anticipation effect increased with age (Richardson & Saxe, 2019), which led us to predict that this effect would be evident in neurotypical adults. Speculatively, it is possible that narrative anticipation effects are more present/observable in age-appropriate movie stimuli. That is, movie stimuli that evoke complicated reasoning may be more likely to be processed differently across viewings. As a result, children might benefit more from seeing the complete movie, leading to larger temporal shifts in their responses between the viewings. This is in line with prior evidence for narrative anticipation effects among adults, which tend to use longer movies (Baldassano et al., 2017) designed for adult audiences (Baldassano et al., 2017; Lee et al., 2021). Future research is needed to clarify the extent to which predictive processes differ/depend on stimulus complexity - and how this varies by age and population.

As our study focused on Theory of Mind reasoning from a third-person perspective, our findings cannot be readily generalized to all forms of Theory of Mind reasoning. Early neuroscientific studies on Theory of Mind were limited in ecological validity and explanatory power, as they typically involved processing abstract stimuli from a third-person perspective. In response to this, second-person approaches emerged, focusing on social cognition during real-time interaction—including hyperscanning paradigms in which brain activity from two interaction partners is simultaneously recorded (Misaki et al., 2021; Redcay & Schilbach, 2019). Future neuroscientific studies addressing social interactions that require flexible attunement between partners (Bolis et al., 2023) may be important for understanding the differences in mechanisms underlying differences in social interactions in autistic individuals. This approach could be further extended to the idea that social difficulties are mutual and occur on both sides of social interactions (see Milton, 2012 for double empathy problem), offering a promising direction for future neurocognitive research.

However, in everyday life, humans engage in both types of reasoning: Theory of Mind from a second-person perspective during interactions, and more *offline* Theory of Mind from a third-person perspective—for instance, when observing others or reflecting on past encounters. In fact, a prior experience sampling study found that participants thought more about others' mental states when they were alone, and during interaction, their thoughts were more focused on others' actions rather than mental states (Schuwerk et al., 2019). To investigate this type of offline Theory of Mind reasoning while addressing the limitations of earlier paradigms, researchers have increasingly turned to naturalistic stimuli such as movies (Sonkusare et al., 2019). This is the approach we followed in our study.

While we measured activity in the Theory of Mind network in response to naturalistic interactions depicted on screen—thus increasing ecological validity—we acknowledge that the use of animated stimuli and a fictional narrative remains an artificial scenario that cannot be equated with real–world interactions. Nonetheless, we chose this format because the exaggerated emotional expressions and dense narrative structure were expected to enhance Theory of Mind network activation. We see our study as a step forward in this direction, with future research needed to bridge the remaining gap toward more realistic, ecologically valid settings.

5.2. *Implications*

This study suggests several directions for future research. First, conducting fMRI studies in adults, including non-autistic and autistic samples, using this approach but with stimuli more suited for adults (e.g., the stimuli used in Baldassano et al., 2017 and Lee et al., 2021) could be a next step in testing the predictions of the predictive coding theory of autism. Second, exploring how perceived stimulus complexity and narrative comprehension interact with predictive responses and narrative anticipation is crucial. This research could reveal how these factors influence cognitive processing in both autistic and non-autistic adults. Third, future studies should aim to scale up investigations of scenes that evoke reasoning processes observed in our key ToM scene and systematically examine any potential differences between autistic and non-autistic adults. Finally, to gain further insights into the development of predictive coding processes, it would be beneficial to try to extend Richardson and Saxe's (2019) findings in 3- to 7-year-old children with adolescents (using a movie that is more suitable for this age group). Such an extension could help validate the presence of an anticipation effect in children and clarify the development of this effect across the life span.

6. Conclusion

Confirmatory analyses did not provide evidence for a narrative anticipation effect, as previously defined by Richardson and Saxe (2019), in adults, nor differences in this effect between neurotypical and autistic adults. Both groups showed comparable neural responses within the ToM network during a short, naturalistic movie-viewing experiment. However, exploratory, data-driven analyses revealed a difference in repetition suppression to one particular ToM scene between non-autistic and autistic adults - providing preliminary neural evidence for differences in predictive coding between autistic and non-autistic adults. Yet, this finding should not be readily generalized without further cross-validation in a follow-up study.

CRediT authorship contribution statement

Lucie Zimmer: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Hilary Richardson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Carolina Pletti:** Writing – review & editing, Project administration, Investigation. **Markus Paulus:** Writing – review & editing, Resources. **Tobias Schuwerk:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization.

Funding

The study was done using the NICUM Siemens Prisma scanner supported by German Research Foundation (DFG; Deutsche Forschungsgemeinschaft) [grant number INST 86/1739-1 FUGG].

Declaration of competing interest

The authors declare that they have no competing interests.

Acknowledgements

The authors would like to thank all participants for their contribution to this work, and the student assistants Sarina Drexler, Paula Kirchner, An Thuy Nguyen and Cui Ci Voon for their support in data acquisition. Thanks to Adrian Steffan for technical support.

Scientific transparency statement

DATA: Some raw and processed data supporting this research are publicly available, while some are subject to restrictions: https://osf.io/2uckn/.

CODE: All analysis code supporting this research is publicly available: https://osf.io/2uckn/.

MATERIALS: Some study materials supporting this research are publicly available, while some are subject to restrictions: https://saxelab.mit.edu/theory-mind-and-pain-matrix-localizer-movie-viewing-experiment/, https://osf.io/2uckn/, References for AQ (Baron-Cohen et al., 2001) and BAPQ (Hurley et al., 2007) are contained in the manuscript or supplemental files. Please contact Hogrefe for CFT 20-R and

MWT, and The Walt Disney Company for the Pixar movie *Partly Cloudy*.

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: At least part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted: https://osf.io/cqnmf At least part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted: https://osf.io/cqnmf The analyses that were undertaken deviated from the preregistered analysis plans. All such deviations are fully disclosed in the manuscript.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.04.006.

REFERENCES

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders: DSM-5* (5). American Psychiatric Publishing.

Baldassano, C., Chen, J., Zadbood, A., Pillow, J. W., Hasson, U., & Norman, K. A. (2017). Discovering event structure in continuous narrative perception and memory. *Neuron, 95*(3), 709–721. https://doi.org/10.1016/j.neuron.2017.06.041

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *Journal of Autism and Developmental Disorders, 31*(1), 5–17. https://doi.org/10.1023/A:1005653411471

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Behzadi, Y., Restom, K., Liau, J., & Liu, T. T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage, 37*(1), 90–101. https://doi.org/10.1016/j.neuroimage.2007.04.042

Bolis, D., Balsters, J., Wenderoth, N., Becchio, C., & Schilbach, L. (2017). Beyond autism: Introducing the dialectical misattunement hypothesis and a bayesian account of intersubjectivity. *Psychopathology, 50*(6), 355–372. https://doi.org/10.1159/000484353

Bolis, D., Dumas, G., & Schilbach, L. (2023). Interpersonal attunement in social interactions: From collective psychophysiology to inter-personalized psychiatry and beyond. *Philosophical Transactions of the Royal Society B, 378*, Article 20210365. https://doi.org/10.1098/rstb.2021.0365

Cattaneo, L., Fabbri-Destro, M., Boria, S., Pieraccini, C., Monti, A., Cossu, G., & Rizzolatti, G. (2007). Impairment of actions chains in autism and its possible role in intention understanding. *Proceedings of the National Academy of Sciences, 104*(45), 17825–17830. https://doi.org/10.1073/pnas.0706273104

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *The Behavioral and Brain Sciences, 36*(3), 181–204. https://doi.org/10.1017/S0140525X12000477

Dufour, N., Redcay, E., Young, L., Mavros, P. L., Moran, J. M., Triantafyllou, C., Gabrieli, J. D., & Saxe, R. (2013). Similar brain activation during false belief tasks in a large sample of adults with and without autism. *Plos One, 8*(9), Article e75468. https://doi.org/10.1371/journal.pone.0075468

Dungan, J. A., Stepanovic, M., & Young, L. (2016). Theory of mind for processing unexpected events across contexts. *Social Cognitive and Affective Neuroscience, 11*(8), 1183–1192. https://doi.org/10.1093/scan/nsw032

Falck-Ytter, T. (2010). Young children with autism spectrum disorder use predictive eye movements in action observation. *Biology Letters, 6*(3), 375–378. https://doi.org/10.1098/rsbl.2009.0897

Frith, U. (2012). The 38th Sir Frederick Bartlett lecture why we need cognitive explanations of autism. *Quarterly Journal of Experimental Psychology, 65*(11), 2073–2092. https://doi.org/10.1080/17470218.2012.697178

Ganglmayer, K., Schuwerk, T., Sodian, B., & Paulus, M. (2020). Do children and adults with autism spectrum condition anticipate others' actions as goal-directed? A predictive coding perspective. *Journal of Autism and Developmental Disorders, 50*, 2077–2089. https://doi.org/10.1007/s10803-019-03964-8

Geng, J. J., & Vossel, S. (2013). Re-evaluating the role of TPJ in attentional control: Contextual updating? *Neuroscience and Biobehavioral Reviews, 37*(10), 2608–2620. https://doi.org/10.1016/j.neubiorev.2013.08.010

Gernsbacher, M. A., & Yergeau, M. (2019). Empirical failures of the claim that autistic people lack a theory of mind. *Archives of Scientific Psychology, 7*(1), 102–118. https://doi.org/10.1037/arc0000067

Hasson, U., Nir, Y., Levy, I., Fuhrmann, G., & Malach, R. (2004). Intersubject synchronization of cortical activity during natural vision. *Science, 303*(5664), 1634–1640. https://doi.org/10.1126/science.1089506

Heil, L., Colizoli, O., Hartstra, E., Kwisthout, J., van Pelt, S., van Rooij, I., & Bekkering, H. (2019). Processing of prediction errors in mentalizing areas. *Journal of Cognitive Neuroscience, 31*(6), 900–912. https://doi.org/10.1162/jocn_a_01381

Hurley, R. S. E., Losh, M., Parlier, M., Reznick, J. S., & Piven, J. (2007). The broad autism phenotype questionnaire. *Journal of Autism and Developmental Disorders, 37*(9), 1679–1690. https://doi.org/10.1007/s10803-006-0299-3

Kana, R. K., Libero, L. E., Hu, C. P., Deshpande, H. D., & Colburn, J. S. (2014). Functional brain networks and white matter underlying theory-of-mind in autism. *Social Cognitive and Affective Neuroscience, 9*(1), 98–105. https://doi.org/10.1093/scan/nss106

Kennedy, D. P., & Adolphs, R. (2012). Perception of emotions from facial expressions in high-functioning adults with autism. *Neuropsychologia, 50*(14), 3313–3319. https://doi.org/10.1016/j.neuropsychologia.2012.09.038

Koster-Hale, J., & Saxe, R. (2013). Theory of mind: A neural prediction problem. *Neuron, 79*(5), 836–848. https://doi.org/10.1016/j.neuron.2013.08.020

Lee, A., Aly, M., & Baldassano, C. (2021). Anticipation of temporally structured events in the brain. *eLife, 10*, Article e64972. https://doi.org/10.7554/eLife.64972

Lehrl, S. (2005). *Mehrfachwahl-Wortschatz-Intelligenztest MWT-B*. Spitta.

Mangnus, M., Koch, S. B. J., Cai, K., Greidanus Romaneli, M., Hagoort, P., Bašnáková, J., & Stolk, A. (2024). Preserved spontaneous mentalizing amid reduced intersubject variability in autism during a movie narrative. *bioRxiv*. https://doi.org/10.1101/2024.03.08.583911

Mannion, A., & Leader, G. (2013). Comorbidity in autism spectrum disorder: A literature review. *Research in Autism Spectrum*

Disorders, 7(12), 1595–1616. https://doi.org/10.1016/j.rasd.2013.09.006

Milton, D. E. (2012). On the ontological status of autism: The 'double empathy problem'. *Disability & Society, 27*(6), 883–887. https://doi.org/10.1080/09687599.2012.710008

Misaki, M., Kerr, K. L., Ratliff, E. L., Cosgrove, K. T., Simmons, W. K., Morris, A. S., & Bodurka, J. (2021). Beyond synchrony: The capacity of fMRI hyperscanning for the study of human social interaction. *Social Cognitive and Affective Neuroscience, 16*(1–2), 84–92. https://doi.org/10.1093/scan/nsaa143

Moessnang, C., Baumeister, S., Tillmann, J., Goyard, D., Charman, T., Ambrosino, S., Baron-Cohen, S., Beckmann, C., Bölte, S., Bours, C., Crawley, D., Dell'Acqua, F., Durston, S., Ecker, C., Frouin, V., Hayward, H., Holt, R., Johnson, M., Jones, E., Lai, M. C., … EU-AIMS LEAP group. (2020). Social brain activation during mentalizing in a large autism cohort: The longitudinal European autism project. *Molecular Autism, 11*(1), 17. https://doi.org/10.1186/s13229-020-0317-x

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': A bayesian explanation of autistic perception. *Trends in Cognitive Sciences, 16*(10), 504–510. https://doi.org/10.1016/j.tics.2012.08.009

R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nature Reviews Neuroscience, 20*(8), 495–505. https://doi.org/10.1038/s41583-019-0179-4

Richardson, H., Lisandrelli, G., Riobueno-Naylor, A., & Saxe, R. (2018). Development of the social brain from age three to twelve years. *Nature Communications, 9*(1), 1027. https://doi.org/10.1038/s41467-018-03399-2

Richardson, H., & Saxe, R. (2019). Development of predictive responses in theory of mind brain regions. *Developmental Science, 23*(1), Article e12863. https://doi.org/10.1111/desc.12863

Saxe, R., & Wexler, A. (2005). Making sense of another mind: The role of the right temporo-parietal junction. *Neuropsychologia, 43*, 1391–1399. https://doi.org/10.1016/j.neuropsychologia.2005.02.013

Schuwerk, T., Kaltefleiter, L. J., Au, J. Q., Hoesl, A., & Stachl, C. (2019). Enter the wild: Autistic traits and their relationship to mentalizing and social interaction in everyday life. *Journal of autism and developmental disorders, 49*, 4193–4208. https://doi.org/10.1007/s10803-019-04134-6

Schuwerk, T., & Paulus, M. (2018). Action prediction in autism. In F. R. Volkmar (Ed.), *Encyclopedia of autism spectrum disorders*. New York: Springer. https://doi.org/10.1007/978-1-4614-6435-8_102206-1.

Schuwerk, T., Schurz, M., Mueller, F., Rupprecht, R., & Sommer, M. (2017). The rTPJ's overarching cognitive function in networks for attention and theory of mind. *Social Cognitive and Affective Neuroscience, 12*(1), 157–168. https://doi.org/10.1093/scan/nsw163

Schuwerk, T., & Sodian, B. (2023). Differences in self-other control as cognitive mechanism to characterize theory of mind reasoning in autistic and non-autistic adults. *Autism Research: Official Journal of the International Society for Autism Research, 16*(9), 1728–1738. https://doi.org/10.1002/aur.2976

Schuwerk, T., Vuori, M., & Sodian, B. (2015). Implicit and explicit theory of mind reasoning in autism spectrum disorders: The impact of experience. *Autism: the International Journal of Research and Practice, 19*(4), 459–468. https://doi.org/10.1177/1362361314526004

Schwartz, S., & Susser, E. (2011). The use of well controls: An unhealthy practice in psychiatric research. *Psychological Medicine, 41*(6), 1127–1131. https://doi.org/10.1017/S0033291710001595

Sinha, P., Kjelgaard, M. M., Gandhi, T. K., Tsourides, K., Cardinaux, A. L., Pantazis, D., Diamond, S. P., & Held, R. M. (2014). Autism as a disorder of prediction. *Proceedings of the National Academy of Sciences, 111*(42), 15220–15225. https://doi.org/10.1073/pnas.1416797111

Somogyi, E., Király, I., Gergely, G., & Nadel, J. (2013). Understanding goals and intentions in low-functioning autism. *Research in Developmental Disabilities, 34*(11), 3822–3832. https://doi.org/10.1016/j.ridd.2013.07.039

Sonkusare, S., Breakspear, M., & Guo, C. (2019). Naturalistic stimuli in neuroscience: Critically acclaimed. *Trends in Cognitive Sciences, 23*(8), 699–714. https://doi.org/10.1016/j.tics.2019.05.004

Stogiannos, N., Carlier, S., Harvey-Lloyd, J. M., Brammer, A., Nugent, B., Cleaver, K., McNulty, J. P., Dos Reis, C. S., & Malamateniou, C. (2022). A systematic review of person-centred adjustments to facilitate magnetic resonance imaging for autistic patients without the use of sedation or anaesthesia. *Autism: the International Journal of Research and Practice, 26*(4), 782–797. https://doi.org/10.1177/13623613211065542

Tamir, D. I., & Thornton, M. A. (2018). Modeling the predictive social mind. *Trends in Cognitive Sciences, 22*(3), 201–212. https://doi.org/10.1016/j.tics.2017.12.005

Thornton, M. A., Weaverdyck, M. E., & Tamir, D. I. (2019). The social brain automatically predicts others' future mental states. *The Journal of Neuroscience, 39*(1), 140–148. https://doi.org/10.1523/JNEUROSCI.1431-18.2018

Weiß, R. H. (2019). *CFT 20-R Grundintelligenztest Skala 2 – Revision*. Hogrefe.

Whitfield-Gabrieli, S., Nieto-Castanon, A., & Ghosh, S. (2011). *Artifact detection tools (ART), release version 7:11*. Cambridge, MA: Artifact Detection Tools.