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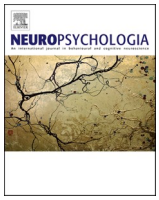

Special treatment of prediction errors in autism spectrum disorder

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ABSTRACT

For autistic individuals, sensory stimulation can be experienced as overwhelming. Models of predictive coding postulate that cortical mechanisms disamplify predictable information and amplify prediction errors that surpass a defined precision level. In autism, the neuronal processing is putting an inflexibly high precision on prediction errors according to the HIPPEA theory (High, Inflexible Precision of Prediction Errors in Autism). We used an apparent motion paradigm to test this prediction. In apparent motion paradigms, the illusory motion of an object creates a prediction about where and when an internally generated token would be moving along the apparent motion trace. This illusion facilitates the perception of a flashing stimulus (target) appearing in-time with the apparent motion token and is perceived as a predictable event (predictable target). In contrast, a flashing stimulus appearing out-of-time with the apparent motion illusion is an unpredictable target that is less often detected even though it produces a prediction error signal. If a prediction error does not surpass a given precision threshold the stimulation event is discounted and therefore less often detected than predictable tokens. In autism, the precision threshold is lower and the same prediction errors (unpredictable target) triggers a detection similar to that of a predictable flash stimulus. To test this hypothesis, we recruited 11 autistic males and 9 neurotypical matched controls. The participants were tasked to detect flashing stimuli placed on an apparent motion trace either in-time or out-of-time with the apparent motion illusion. Descriptively, 66% (6/9) of neurotypical and 64% (7/11) of autistic participants were better at detecting predictable targets. The prediction established by illusory motion appears to assist autistic and neurotypical individuals equally in the detection of predictable over unpredictable targets. Importantly, 55% (6/11) of autistic participants had faster responses for unpredictable targets, whereas only 22% (2/9) of neurotypicals had faster responses to unpredictable compared to predictable targets. Hence, these tentative results suggest that for autistic participants, unpredictable targets produce an above threshold prediction error, which leads to faster response. This difference in unpredictable target detection can be encapsulated under the HIPPEA theory, suggesting that precision setting could be aberrant in autistic individuals with respect to prediction errors. These tentative results should be considered in light of the small sample. For this reason, we provide the full set of materials necessary to replicate and extend the results.

1. Introduction

The predictive coding framework argues that the brain is constantly predicting the outcome of the events in the environment, and errors in our predictions are fed back up the neural hierarchy, where at each level they are weighted against the prediction. Our models about the world are then updated if enough weight is given to the error (Friston, 2010). Based on these models we create future predictions about incoming sensory information, which help us to navigate our environment more efficiently. This is achieved by developing generalisable models of the world allowing for some variability in the input. This is done by appropriately allocating uncertainty to different parts of the environment – i.e., discounting some information as noise, and appropriately emphasizing genuine signals indicating a change (Friston, 2010).

A recent interpretation of autism through the predictive coding framework suggests that autistic individuals[1] develop models that are

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[1] The authors recognise the lack of consensus within the autistic community in response to the use of person first and diagnosis first language (Botha et al., 2021; Bury et al., 2020; Kenny et al., 2016). Within this article, we use 'autistic person' and 'person on the autism spectrum' to acknowledge this lack of consensus and acknowledge both sides.

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too narrow, turning small inconsistencies between their prediction and the environment into an error signal (Van de Cruys et al., 2014, 2017). Van de Cruys et al. (2014) argue, that the differences in the neurocognitive processes in autism come from difficulties with meta-learning – knowing when the variability in the environment and its associated uncertainty is a genuine change in the rule and when it should be discounted as noise (Van de Cruys et al., 2014, 2017). Following this line of reasoning, Van de Cruys et al. (2014) propose the theory of High Inflexible Precision of Prediction Errors in Autism (HIPPEA), which postulates that individuals on the autism spectrum put higher precision on prediction errors than their neurotypical counterparts. Weighing prediction errors consistently high will lead to the development of models that are based on infrequent contingencies due to the noisiness of the environment, creating narrow models of the world.

Individuals on the autism spectrum are consistently reported as having a perceptual style that focuses more on details than the holistic percept (Simmons et al., 2009; Van der Hallen et al., 2015). Having a processing style that focuses on the parts will inevitably facilitate the development of narrow models through assigning too much weight or precision to sensory information that does not fit the already narrow predictions. Hence, many prediction errors will be registered by individuals on the autism spectrum, which will break down the perception of holistic information (Van de Cruys et al., 2014). Importantly, the HIPPEA theory also argues, that individuals on the autism spectrum can form predictions, but those are often low-level. Unless specifically instructed autistic individuals will not automatically direct their attention to holistic representations, as low-level features will be easier to predict (Koldewyn et al., 2013; Van de Cruys et al., 2014). One of the proposed mechanisms through which precision allocation occurs is through attention (Feldman and Friston, 2010) and thus, HIPPEA argues that autism is a disorder of attention allocation.

One way to test whether prediction errors are weighted with higher precisions is to utilise an already established paradigm, which rests on a predictive context, where the amount of sensory information - predictable and unpredictable, is varied and attention is controlled. One such paradigm is the apparent motion paradigm as used by Alink et al. (2010). The illusion of motion is created when two identical objects are flickered in rapid succession, thus creating the illusion of a single moving token. This illusory filling-in of the empty frames between the flickering objects impairs the detection of stationary targets shown on the illusory moving token's path (Yantis and Nakama, 1998). This motion masking effect has been shown to vary in strength with the spatial-temporal characteristics of the flashed targets. Targets that appear in-time with the illusory motion token are perceived more readily than those presented out-of-time with it (Alink et al., 2010; Schwiedrzik et al., 2007). The perception of these in-time stimuli invokes smaller activation in the primary visual cortex (V1) which will be expected if the human brain anticipates incoming visual stimuli and thus uses less neural activity to process them (Alink et al., 2010). In contrast, out-of-time targets produce larger V1 activation, which would correspond to stimuli being unexpected, resulting in the brain allocating additional resources to process them (Alink et al., 2010). The behavioural results, whereby predictable (in-time) targets are better detected than unpredictable (out-of-time) ones, indicate that increased activation for the unpredictable targets cannot be attributed to attention and should be viewed as prediction error activation (De-Wit et al., 2010). This is further corroborated by transcranial magnetic stimulation (TMS) studies. TMS disruption of motion processing brain area V5, before the appearance of the in-time targets, eliminates the advantage in their detection when compared to the out-of-time targets (Vetter et al., 2015). This disruption would be expected under the predictive coding framework as it suggests that higher order areas are responsible for the perception of more holistic stimuli – in this case the perception of motion, and for feeding forward the predictions about where the illusory moving token should be at each point in time.

The apparent motion paradigm has also been tested on schizophrenic individuals (Sanders et al., 2012), which is a condition commonly associated with autism. Sanders et al. (2012) found that schizophrenic patients showed the same advantage in detecting in-time stimuli as neurotypical individuals and greater motion masking than neurotypicals – i.e. lower hit rates. These results indicate that schizophrenic individuals were able to form and utilise the prediction created by the apparent motion, and show no differences in the processing of prediction errors. Although it has often been suggested that ASD and schizophrenia have a similar underlying mechanism, Van de Cruys et al. (2014) make an important distinction between the two conditions. They argue that the perceptual-cognitive style – local vs global processing, is an underlying reason for their HIPPEA model. This becomes important in light of findings like those from Russell-Smith et al. (2013) where they showed that individuals with high levels of schizotypy have a more global focus, whereas those with high autistic traits have a more local focus. The global focus in neurotypically developing individuals and individuals with high levels of schizotypy would support the similar performance in the two groups in Sanders et al. (2012) study. Additionally, a study also looking at autistic and schizotypy traits showed that in a visual statistical learning paradigm, higher autistic traits led to more veridical processing and less influence of expectations, which was due to increased weighting of sensory representations rather than weaker prior formation (Karvelis et al., 2018). This was not true for increase in schizotypy traits. Moreover, Sterzer et al. (2018) put forward the idea that in psychosis/schizophrenia the affected component as explained by the predictive coding framework is the prior. Whereas substantial research is required to tease apart at what levels it is a weak or a stronger prior, the argument that Van de Cruys et al. (2014) are making for autism in HIPPEA is that in ASD the prediction error is more heavily weighted, rather than having lower/larger weighting on the priors. Thus, we argue that schizophrenic patients should show more 'typical' performance than ASD participants on account of their different processing styles.

It is important to note that it has been argued that individuals on the autism spectrum have difficulty perceiving illusions, however, the findings have been contradictory (Simmons et al., 2009) and it has been shown that the susceptibility to illusions is dependent on the type of illusion used (Ishida et al., 2009). Specifically, David et al. (2010) investigated differences in horizontal and vertical apparent motion perception in ASD. They used the metastable motion quartet, which is a stimulus consisting of two dots alternately presented at four locations – the four corners of a hypothetical square, and thus creating apparent motion illusions in the vertical or horizontal direction. Autistic participants showed reduced horizontal binding in the apparent motion but not reduced vertical binding. Furthermore, individuals on the autism spectrum readily perceive first-order motion - based on luminance (Bertone et al., 2003). Hence, the apparent motion paradigm suggested here should be readily perceived as it is dependent on luminance – i.e., flashing lights with a specific frequency.

Following the discussion above, we propose investigating whether autistic adults show the same advantage in detecting predictable targets over unpredictable as neurotypical participants and whether autistic participants treat prediction errors differently than neurotypicals as proposed by HIPPEA. In this experiment, autistic adults and neurotypical individuals pressed a button every time they detected a target, which was presented either in-time (predictable) or out-of-time (unpredictable) with the illusory motion token's path created by two vertically aligned squares flashing in rapid succession. If prediction errors are more highly weighted in autistic individuals as proposed by HIPPEA, then they will perceive predictable and unpredictable events with the same rate, or unpredictable at a higher rate, whereas neurotypical participants will show an advantage for detecting predictable targets. Thus, as attention appears to be controlled in neurotypical individuals (De-Wit et al., 2010), this task will also allow us to see whether unpredictable targets attract greater levels of attention in autistic individuals.

2. Materials and methods

2.1. Participants

Twenty participants took part in the present experiment – 9 neurotypical (NT) and 11 autistic (ASD). All participants were biologically male. Participants were group-wise matched on age. To avoid confounds with cross hemisphere communication, we attempted to recruit only right-handed participants, however, two ambidextrous participants on the autism spectrum also took part in the experiment. Participants were also group-wise matched on Full-Scale IQ (FSIQ) as measured by the Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999). NT participants were screened using the Autism-Spectrum Quotient (AQ) before taking part in the original experiment as it has been shown to provide a good distinction between NT and ASD individuals (Baron--Cohen et al., 2001; Ruzich et al., 2015). A score of 26 was used as a cut off for the NT participants to account for the larger spread of scores in neurotypical populations in Ruzich et al. (2015). Additionally, NT participants needed to have no neurological or clinical/psychiatric conditions/diagnoses. This was not required for ASD individuals as ASD has been found to show high comorbidity with different conditions (Tye et al., 2019). ASD individuals with a history of epilepsy were excluded as the stimulation involved flickering stimuli which may risk inducing seizures. From our sample, one autistic participant reported an Anxiety Disorder diagnosis and another indicated a possible Anxiety Disorder. Additionally, one participant reported cerebellar atrophy of the vermis and sulci. They reported that they do not have a problem with motion perception and fixation. They also informed us that they have had surgery to correct for a drifting eye.

All participants' basic vision capabilities were checked for acuity using the Freiburg Vision Test ('FrACT') before any further testing (Bach, 2007). We attempted to confirm the diagnosis of all autistic individuals using the Autism Diagnostic and Observation Schedule (ADOS) by a trained clinical researcher (Lord et al., 2000). Due to the researcher's availability, two individuals did not participate in the interview. The clinical researcher did not provide us with complete scoring from the ADOS and provided us with a binary classification of the results (would/would not be considered autistic). All individuals reported having received an official autism diagnosis; for nine of those, the diagnosis was confirmed with the ADOS.

2.2. Measures

All participants filled in a short demographics and screening questionnaire. It inquired about age, sex, eyesight, and neurological/psychological conditions.

Edinburgh Handedness Inventory (EHI). The EHI (Oldfield, 1971) consist of 10 tasks/activities which involve using one or both hands. Participants are asked to indicate a preference for the right or left hand.

FrACT. The FrACT is an automated, self-paced measurement of visual acuity (Bach, 2007; Brosnan et al., 2012). It consists of a 4-alternate forced-choice task, where using a button press participants indicate the orientation of the gap of a Landolt C (contrast 98%), the size of which depends on the correctness of the response. There were 36 trials, where every 6th trial is an 'easy' trial. No auditory feedback was provided. Participants had to have visual acuity of at least 0.5 decimal, which is the legal driving requirement by the Driver & Vehicle Licensing Agency of the UK (https://www.gov.uk/driving-eyesight-rules).

AQ. The Autism-Spectrum Quotient was originally developed for investigating autistic traits in individuals. It consists of 50 items to which individuals have to indicate their agreement (Baron-Cohen et al., 2001). NT individuals with scores of or above 26 (Ruzich et al., 2015) were excluded from further testing (N = 3).

WASI. The WASI (Wechsler, 1999) is an individually administered assessment of intelligence and is applied to individuals aged between 6 and 89 years of age. It provides composite scores of verbal, perceptual and full-scale IQ. It contains four subtests – Vocabulary, Block Design, Similarities, and Matrix reasoning. Both the ASD and NT participants undertook the assessment. As we are looking for individuals of neurotypical IQ, FSIQ scores below 70 were not included in any further testing. No participants scored below 70. The test was administered either by the ADOS administering researcher or the primary researcher.

ADOS. The ADOS (Lord et al., 2000) is used to assess and diagnose ASD across age and is used for ages between 12 months to adulthood. It takes up to 60 min to administer and it consists of semi-/structured tasks, that assess the social and communicative abilities of the individual. A researcher trained to score and administer the ADOS interviewed the participants using Module 4 for adults.

Stimuli. The stimuli replicated the paradigm used by Sanders et al. (2012) with schizophrenic patients. Stimuli were presented using PsychoPy (v1.84) (Peirce et al., 2019) on a CRT monitor (1024 × 768, 75 Hz). The presentation was on a uniform grey background (24.1–29.3 cd/m^2) with a white (97.35–103.5 cd/m^2) fixation cross (1.2° × 1.2°) displayed in the centre of the screen. The apparent motion stimuli consisted of two white squares (2.35° × 2.35°), which flashed to the right of the fixation cross (eccentricity = 7.72°) and above/below the centre fixation cross (Apparent motion trace = 16.45°). The stimuli alternated between the two positions, with an inter-stimulus interval equal to the stimuli presentation (7 frames). Presentation frequency was 2.68 Hz with one cycle representing one full bi-directional 'motion' - assuming starting from the bottom: $target_{bottom}$ (93 ms) + ISI(93 ms) + $target_{top}$ + ISI. This is more clearly visualised in Fig. 1. Targets were white squares (2° × 2°). Predictable targets appeared in-time with the illusory motion – i.e., a target appearing closer (±4.7° from centre) to the first flashed stimulus after a short delay will be more predictable than one appearing at a longer delay. As the apparent motion presents a movement of up and then down, this created 4 different target presentations: two in-time (one down and one up) and two out-of-time (one up and one down). Every target was followed by 4–9 apparent motion cycles without a target to maintain the motion illusion. There was a total of 80 predictable and 80 unpredictable targets.

Additionally, one control condition was performed by the participants. The control condition used the same stimuli, but it showed simultaneously blinking apparent motion stimuli instead of the temporally displaced ones from the experimental condition. The control condition kept the timing of the targets. In this way, all stimuli appeared at the same locations as before and the targets appeared at the same times, but the illusory motion component was removed by the simultaneously flashing apparent motion stimuli.

2.3. Power analysis

Power calculations were done using the PANGEA (v.02) applet (Westfall, 2016; https://jakewestfall.shinyapps.io/pangea/) as it allows one to take into account the number of replicates i.e. how many trials each participant has in each condition.

For the between-group comparisons, each participant in each motion condition (apparent motion vs no apparent motion) for each predictability level (predictable vs unpredictable) will see 80 targets i.e. 80 trials. The sample size calculated for the interaction of interest (Group x Condition x Predictability) was performed with an estimated effect size of $d = 0.45$ as recommended by Westfall (http://jakewestfall.org/publications/pangea.pdf, 2016) as no other estimate is available. The recommendation is based on the meta-analysis of meta-analyses in social psychology by Richard et al. (2003). We were not able to find another study that compared an autistic and a neurotypically developing population on a similar task. Additionally, although Sanders et al. (2012) have used the same paradigm to study schizophrenia, the effect size needed was not reported, because the group interaction was not significant i.e. schizophrenic and neurotypical volunteers showed the same predictability effect. Moreover, Sterzer et al. (2018) and Van de Cruys et al. (2014) call for more research to distinguish between the two

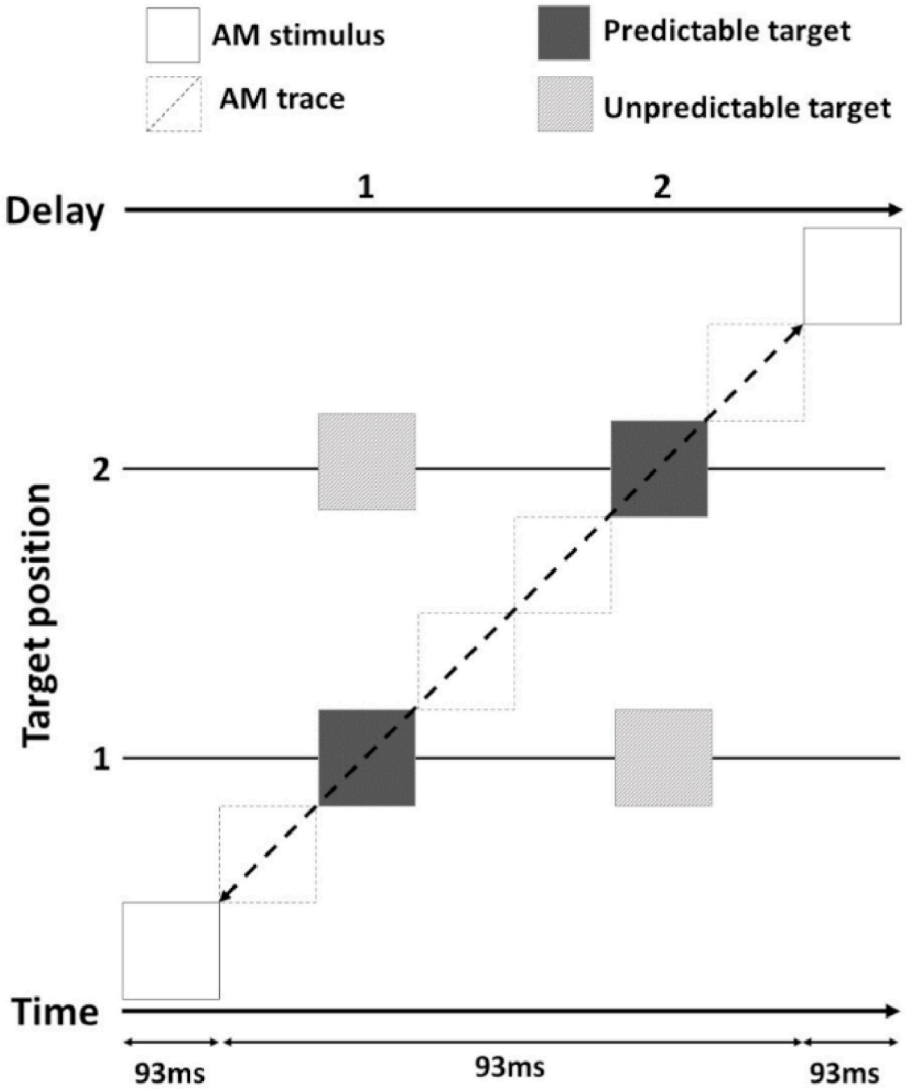

Fig. 1. Stimuli setup. Predictable targets appeared in time with the motion – i.e., assuming 'motion' starting from the bottom moving up, delay 1 at position 1 and delay 2 at position 2. All stimuli were presented on the right side of the screen. Modified from Sanders et al. (2012).

conditions, hence, it is not appropriate to generalise between these two conditions. Thus, using a moderate effect size ($d = 0.45$) as a guideline, we calculated that with 20 participants in each group we will reach power above 0.95.

Nevertheless, using a smaller effect size of 0.33 found in a meta-analysis of overall coherent motion perception difference between ASD and neurotypically developing individuals (Van der Hallen et al., 2019), we found that with the same number of participants (20 per group) we will still reach a power of ~0.93.

In terms of replicating previous findings in neurotypical participants, the effect of condition consistently shows strong effects - i.e. $\eta^2 = 0.853/d = 4.8$ [N = 8] (Schwiedrzik et al., 2007); and $\eta^2 = 0.565/d = 2.27$ [N = 31 per group] (Sanders et al., 2012). For the interaction condition*predictability, effect sizes have also been consistently large – i.e. $\eta^2 = 0.952/d = 8.9069$ [N = 8, condition*delay*position interaction] or position*delay at the apparent motion condition only $\eta^2 = 0.816/d = 4.2118$ (Schwiedrzik et al., 2007); $\eta^2 = 0.067/d = 0.536$ for condition*predictability*position [N = 31] or $\eta^2 = 0.109/d = 0.6995$ for condition*predictability interaction (Sanders et al., 2012). When decomposing into simple effects, the predictability effect in the apparent motion condition has been found to be $d = 1.086$ [N = 8, only apparent motion condition, one target position (bottom)] in Edwards et al. (2017) and $d = 0.494$ [N = 31, only apparent motion condition for neurotypical participants, two target positions (top & bottom)] (Sanders et al., 2012). The smallest effect size of 0.494 suggests that our initial sample size of 20 participants per group would only reach power of 0.719. To reach power of at least 0.80, a minimum of 25 participants will be required.

Thus, the sample size for both groups was chosen to be 25 to ensure that we could detect the effect in the neurotypically developing group. However, due to the COVID-19 pandemic and the national lockdown in Scotland associated with it, the study was stopped before the full sample could be reached, and we were only able to recruit 11 autistic and 9 non-autistic individuals. Therefore, we are publishing this work along with all analysis and experiment set-up scripts to allow other groups to build upon the data we have collected.

2.4. Procedure

Participants performed the FrACT, EHI, AQ, WASI before the beginning of the experiment. Participants took part in the ADOS before or after the experimental task depending on participant/clinical researcher availability. If participants did not meet inclusion criteria on the AQ, WASI or FrACT they did not continue with further testing.

Afterwards, we seated the participants at a viewing distance of 70 cm and asked them to fixate on the fixation cross at the centre of the screen throughout the experiment, while allowing for brakes in fixation

between trials. We monitored the fixations by tracking the eye movements of the right eye of the participant throughout the experiment using a remote eye-tracker EyeLink 1000 v4.51 at a 250 Hz sample rate. We presented one block per condition (experimental/control), and we counterbalanced the order across participants. We calibrated the eye-tracker with a standard 9-point calibration with each subject. The participants maintained their head position throughout the experiment with the help of a chin rest. Between the blocks, we encouraged the participants to take a break and rest their eyes. Participants performed a short practice of 12 target presentations at the start of each block. We asked the participants to respond as quickly as possible to the perception of the target by pressing the space bar on a standard keyboard. A total of 160 targets were presented across the two blocks with a 30s break after every 15th target where participants free-viewed nature scenes presented on the screen, without moving from the chin rest. Every response between 150 and ~1500 ms (4 apparent motion cycles) after target presentation was considered as a hit and everything else as an erroneous response. Each block lasted approximately 15 min.

2.5. Analysis

The analysis was carried out in R (v4.0.4) (R Core Team, 2020) using RStudio (v1.3.1093) (RStudio Team, 2016) using lme4 (v1.1-26, Bates et al., 2015) and tidyverse (v1.3.0) and attached packages (Wickham et al., 2019).

For a target to be coded as detected the key press should have occurred between 150 ms and 1500 ms after the target onset. This response window was selected based on previous research (Sanders et al., 2012; Schwiedrzik et al., 2007).

Trials, where the participant performed a blink when the target was presented were excluded (N = 43 across participants (apparent motion = 24, control = 19)). Additionally, 90 more trials were removed (all from the ASD group) where participants either misunderstood the task or there were problems with the eye-tracking equipment. Despite reporting that they have had corrective surgery for their eye, the participant that reported cerebellar atrophy had large shifts in their eye movements, for which they performed consistent corrective eye movements. For two additional participants, eye-tracker calibration was not possible (1- both condition, 1- apparent motion condition only) and a verbal reminder was given about maintaining fixation at the beginning of each set of 15 trials (after the break). For that reason, their eye-movement data is not included in the descriptive analysis below.

Due to the small sample size, the data are presented and interpreted descriptively. For completeness, binomial regression (for performance data) and gamma regression (for reaction time (RT) data) were also used for fitting the data, without the inclusion of random intercepts and slopes. The initial pre-registered analysis resulted in many convergence failures resulting from too many parameters and not enough data points. The analysis here deviates from the pre-registered one, to provide a complete description of the data. The original pre-registered analysis can be found at OSF (https://osf.io/729cr) and analysis scripts and data can be found at ReShare: https://dx.doi.org/10.5255/UKDA-SN-854905. Significance of all effects was done through model comparison of the full model, with a reduced model that excluded the effect of interest.

Initially, to check if we could replicate previous findings in neurotypically developing individuals and to confirm the paradigm performed as expected, we ran a logistic regression with condition (apparent motion vs no apparent motion) and predictability (predictable vs unpredictable) for only the NT group.

Next, to directly test the hypotheses, logistic regression was used to check for interaction between condition (apparent motion vs no apparent motion), predictability (predictable vs unpredictable) and group (ASD vs NT) – 3-way interaction. Finally, the ASD group's performance was analysed to investigate any potential differences in the control/apparent motion condition.

As an exploratory measure, reaction time was also explored to tap into any processing delays within the ASD population. An analysis was run with reaction times (for the detected targets) as the outcome variable rather than the responses.

Finally, we investigated whether Age and FSIQ were significant covariates to the model.

2.6. Ethics

Ethical approval was obtained from the Ethics Committee at the College of Science and Engineering, University of Glasgow. All participants provided informed consent for taking part in all parts of the study and for their data to be shared. All participants were allowed to take a copy of their scores.

3. Results

3.1. Descriptive statistics

As seen in Table 1, the two groups were not significantly different on age or FSIQ but were significantly different in AQ scores. Percentage of fixations within the 2° window away from the centre of the screen were compared between the groups for each condition. Comparisons were performed using Welch's Two-Sample t-tests.

Table 2 describes the participants' performance based on condition and predictability. Overall, it appears that the control condition was easier than the apparent motion condition, which indicates that the apparent motion introduced motion masking (see Fig. 2). Additionally, the NT participants performed better in both conditions. From Table 2 it appears that performance was better for the predictable than the unpredictable targets in the apparent motion condition for both groups, with 66% (6/9) of NT participants and 64% (7/11) of ASD participants detecting more predictable than unpredictable targets. This can more clearly be seen in the lower panel of Fig. 2.

Looking at the RTs, from Fig. 3 and Table 2 we can see that NT individuals were slower at detecting unpredictable targets, whereas ASD participants were faster. The lower panel of Fig. 3 more specifically highlights that while 22% (2/9) of NT participants had shorter median reaction times for the unpredictable targets, more than half of ASD participants (55% - 6/11) had shorter median reaction times, indicating faster detection of unpredictable targets in the ASD group.

3.2. Performance analysis

3.2.1. Replicating previous findings in neurotypicals

In the first instance, the effects only in the neurotypical population were analysed. A comparison between the full model and model without the main effect of condition (apparent motion vs control) showed that there was a significant effect of condition – $X^2(1) = 220.34$, $p < 0.001$. NT participants were able to detect a larger proportion of targets in the control condition ($M_{Apparent\ motion} = 0.540$ [SD:0.499], $M_{Control} = 0.801$

Table 1
Descriptive sample statistics.

Group	ASD	NT	*t*	*df*	*p*
Mean Age (SD)	33.73 (13.84)	29.78 (12.74)	0.66	17.71	0.52
Mean AQ (SD)	35.27 (7.34)	12.00 (5.50)	8.10	17.9	<0.001
Mean FSIQ (SD)	115 (14.90)	118.44 (12.61)	−0.56	17.96	0.58
Mean % fixations out of centre, apparent motion (SD)	15.50 (14.82)	4.96 (3.21)	1.97	7.59	0.09
Mean % fixations out of centre, control (SD)	6.83 (7.16)	4.7 (2.75)	0.83	10.31	0.42

Table 2
Participants' performance by condition and target type for each group.

Condition	Target	Group	Mean detection rate (SD)	Median reaction time (ms) (MAD*)
Apparent Motion	Predictable	NT	0.56 (0.5)	478 (152)
		ASD	0.47 (0.5)	510 (200)
	Unpredictable	NT	0.52 (0.5)	519 (157)
		ASD	0.44 (0.5)	501 (180)
Control	Predictable	NT	0.81 (0.39)	418 (83)
		ASD	0.73 (0.44)	416 (95)
	Unpredictable	NT	0.79 (0.41)	420 (91)
		ASD	0.74 (0.44)	418 (101)

*MAD – Median Absolute Deviation.

[0.399]) where there was no apparent motion illusion present. Unfortunately, the interaction effect between condition and predictability was not replicated – $X^2(1) = 0.02$, $p = 0.88$. As the simple effect of predictability would not provide us with any information because it will be across conditions, the effect was not explored.

3.2.2. *Overall analysis*

There was an overall effect of group, indicating that participants on the autism spectrum were less likely to detect the targets overall (M_{ASD} = 0.596 [0.491], M_{NT} = 0.672 [0.470]) - $X^2(1) = 29.26$, $p < 0.001$. There was no effect of the group and condition interaction - $X^2(1) = 0.03$, $p = 0.86$. This is also evident from Table 2. Additionally, there was no three-way interaction between group, condition, and predictability - $X^2(1) = 0.65$, $p = 0.42$. No further effects were looked at. After removing the one outlier evident in Fig. 2 from the ASD group, the effect main effect of group was no longer significant X^2 (1) = 9.42, $p = 0.05$. This

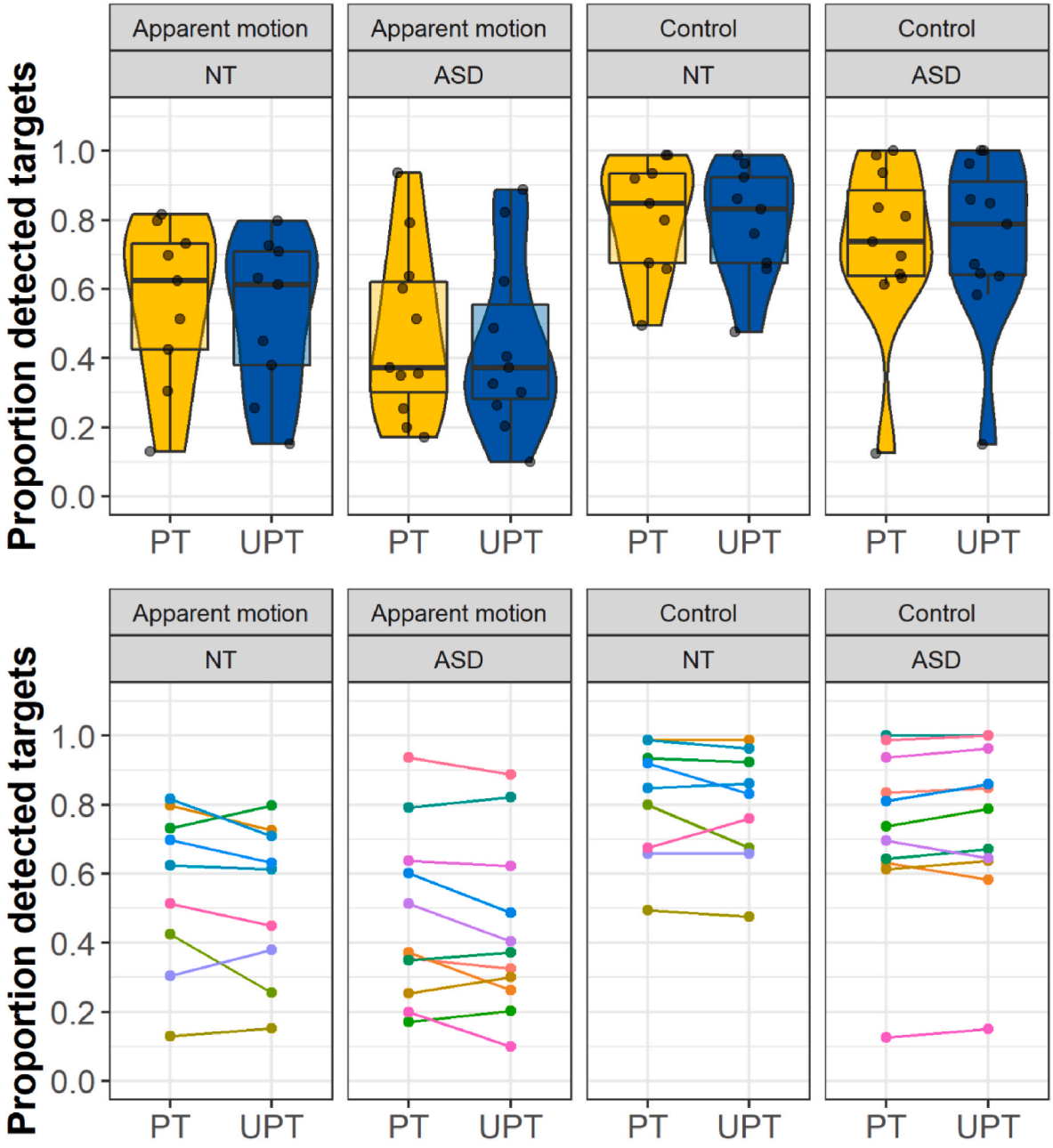

Fig. 2. Average performance per person for each group per condition. PT - Predictable Target; UPT - Unpredictable Target. Top panel present the overall performance per group with individual data points for each participant. Bottom panel shows the data as pairs of observations for each participant between target conditions.

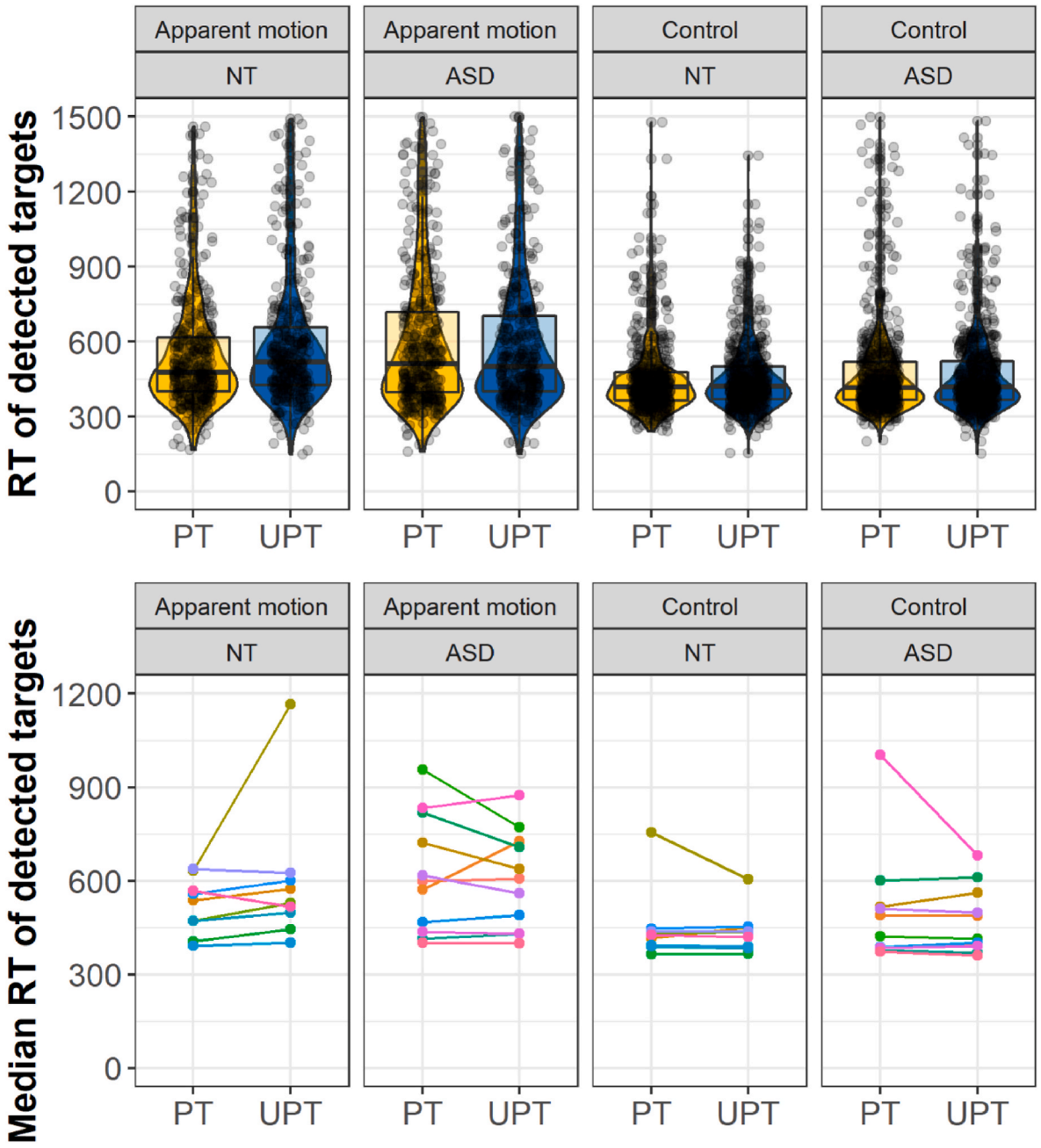

Fig. 3. Reaction time (ms) for each group per condition. PT - Predictable Target; UPT - Unpredictable Target. Top panel presents violin and boxplots of reaction time per target and condition with reaction time point superimposed for each participant and trial for each condition. Bottom panel shows the paired median RT for each individual between target conditions.

suggests that overall both groups were able to detect similar number of targets. No other effects were qualitatively affected.

3.2.3. Performance in the ASD group only

Finally, as there was not a significant effect in the neurotypically developing group for predictability, but most participants detected a higher proportion of predictable than unpredictable targets, to maximise power, and to establish any effects of predictability in the apparent motion condition for ASD participants only, we ran a model, where the ASD group and the apparent motion condition were coded as reference levels via dummy coding. In this way, the 'main effects' of the model become simple effects at the reference conditions. However, the simple effect of predictability was not significant when comparing the modified model, and the same model without the predictability variable - $X^2(2) = 2.27$, $p = 0.32$. Removing the outlier mentioned above did not qualitative change this result.

3.2.4. Covariates

There was no significant effect of age at the omnibus model - $X^2(1) = 0.06$, $p = 0.81$. However, FSIQ was a significant covariate - $X^2(1) = 72.21$, $p < 0.001$. This indicates that higher FSIQ was associated with higher detection rates. After removing the outlier mentioned above, there was no longer a significant effect of FSIQ $X^2(1) = 1.66$, $p = 0.20$.

3.3. Reaction times

3.3.1. Overall analysis

There was an overall effect of group, which was driven by NT having

faster reaction times on average (M_{NT} = 498 [198] (median:442 [114]), M_{ASD} = 517 [228] (442 [126])) - $X^2(1) = 1.91$, $p = 0.01$. There was a significant effect of condition - $X^2(1) = 45.58$, $p < 0.001$, indicating faster detection in the control condition ($M_{Apparent\ motion}$ = 579 [257] (502 [174]), $M_{Control}$ = 464 [169] (418 [92])). This is also evident from Table 2. The group and condition interaction was not significant - $X^2(1) = 0.05$, $p = 0.56$. Additionally, there was no three-way interaction between group, condition, and predictability - $X^2(1) = 0.31$, $p = 0.15$. No further effects were explored. After exclusion of the 2 participants (one in the NT group and one in the ASD group) that showed outlier RTs in Fig. 3, the results remained qualitatively the same.

3.3.2. Covariates

There was not a significant effect of age at the omnibus model - $X^2(1) = 0.50$, $p = 0.07$. However, FSIQ was a significant covariate - $X^2(1) = 9.36$, $p < 0.001$. This indicates that higher FSIQ of individuals was was associated with faster reaction times. After exclusion of the 2 participants mentioned above, the effect of age became significant, indicating that RT increased with the increase in age $X^2(1) = 2.84$, $p < 0.001$.

4. Discussion

This experiment aimed to investigate whether predictable and unpredictable targets are detected differently in an apparent motion paradigm between individuals with and without autism. According to the HIPPEA theory proposed by Van de Cruys et al. (2014), individuals on the autism spectrum allocate more precision to prediction errors than neurotypicals. Therefore, unpredictable targets should be more easily detected by autistic individuals. The descriptive results observed in the present experiment show that the illusory motion made the task more difficult for both the NT and ASD groups. This suggests that both groups were able to experience motion masking. However, there were no effects of predictability in either group and there were no interaction effects with group on performance. The only effects of group showed that autistic individuals detected fewer targets and were slower in their responses, although the former disappeared after removing the one present outlier. However, a descriptive examination of the data shows that precision for prediction errors as represented by unpredictable targets is set differently in autistic individuals in comparison to neurotypicals.

The descriptive results, although incomplete, highlight some important trends in the data. By count, it is evident that most of the participants in both groups detect more predictable than unpredictable targets. This supports HIPPEA's argument, that individuals on the autism spectrum can form predictions. In the present case, the formation of a prediction about the 'movement' of the token facilitated performance in both groups for the predictable targets and led to a decreased ability in detecting unpredictable targets. These results mirror the findings from Alink et al. (2010) and Schwiedrzir et al. (2007).

Yet, significant effects of predictability have been seen with similar and even smaller sample sizes than the present NT one (i.e., n = 9 in Edwards et al., 2017; and n = 8 in Schwiedrzik et al., 2007). One possible explanation could be the differences in the control conditions between the present task and the ones previously used. Specifically, Schwiedrzik et al. (2007) flashed only one of the apparent motion rectangles (top or bottom), keeping the target positions the same. In our task, the control condition flashed the top and the bottom apparent motion squares simultaneously while the targets maintained their timing as in the experimental condition. This could have obscured the size of the three-way interaction effect in our study. Further, Schwiedrzik et al. (2007) looked at miss rate, rather than accuracy, which could have contributed to larger effects in their study. Alternatively, the design by Edwards et al. (2017) showed the paradigm in the centre of the screen, rather than lateralised and also asked participants explicitly after each trial if they detected the target. In comparison, we used continuous trial presentation, which could have put more pressure on participant's performance. On the other hand, Sanders et al. (2012) used the same apparent motion structure in the experimental condition as us, and looked at hit rates, however, they had a much larger sample (n = 31) and showed a smaller effect size than the previous two studies. Thus, the absence of an interaction in the NT sample could be due to design or measurement choices. Hence, although the apparent motion paradigm shows consistent results, there is inevitably going to be variability in the results dependent on variability in design choices. Thus, it remains important to extend and replicate these results to develop a better understanding of the effects in autism.

The descriptive results that we observe are similar to the finding by Sanders et al. (2012) with schizophrenic patients. However, in the present study autistic participants additionally showed a faster detection for the unpredictable targets, which could be indicative of the higher precision given to prediction errors as suggested by HIPPEA (Van de Cruys et al., 2014). As Feldman and Friston (2010) emphasise, attention will have a spotlight effect on prediction errors, assisting in their propagation up the processing hierarchy. Thus, although participants on the autism spectrum still experienced the motion masking effect created by the apparent motion paradigm, and the prediction appears to assist them with the detection of predictable over unpredictable targets, unpredictable targets appear to be given special treatment. Moreover, the fact that attention is not modulated in this paradigm (De-Wit et al., 2010) suggests that attention might be disproportionately affecting prediction errors, capturing the attention of autistic individuals to a higher degree, leading to faster reaction times.

Our results are to an extent in agreement with the results seen in individuals with higher autistic traits in the work by Russell-Smith et al. (2013) and Karvelis et al. (2018). On the other hand, Tulver et al. (2019) found that the number of autistic traits did not correlate with the performance on a variety of predictive tasks (except with the Mooney task, before correction). One of the possible reasons for this is that the autism traits in Tulver et al. (2019) were in the lower end of the spectrum, ranging between 5 and 27, whereas in both Russell-Smith et al. (2013) and Karvelis et al. (2018) the participants scores ranged between 20-33 and 6–41, respectively, showing a much larger range with higher scores. Thus, the lower range in Tulver et al. (2019) could have obscured any larger effects. Hence, the present descriptive results could be indicative of an effect that is more pronounced in individuals with an official diagnosis. However, this can only be determined after looking at the results with the full sample.

The paradigm we are presenting here looks at only one facet of predictive processing. In fact, Tulver and colleagues (2019) who looked at several paradigms that investigate the effects of priors on behaviour show that paradigms that investigate different priors do not necessarily show high correlations and they do not cluster around the same underlying factor. Although Tulver et al. (2019) replicated previous results showing that prior knowledge and noise affect behaviour in an expected manner, this is not necessarily one underlying process. Instead, each paradigm could be tapping into a slightly different process that can additionally be at a different level of the processing hierarchy. Thus, the paradigm we present can only focus on the specific case, where attention is not modulated, but directly allocated to the centre and the targets recruit the exogenous attention. The descriptive results suggest that there might be some special treatment of unpredictable events in autism but this generalisation is limited to the current setting. Although, we propose that the use of the GMM once the full sample is recruited would allow for generalisability above the specific sample, the interpretation would still be limited to the present paradigm.

There are some further limitations to this study that need to be considered when moving forward. Above and beyond the insufficient sample size, we only recruited male participants to avoid any interaction effects with sex. It has been shown that the brains of autistic individuals have differing connectivity between the sexes and in comparison to their neurotypical counterparts (Alaerts et al., 2016; Lawrence et al., 2020). However, to be able to characterise the complete ASD profile, we need to know whether HIPPEA can explain differences in both sexes. Samples

with only male, only female and comparison between the two are necessary to achieve this. Thus, we are making available the analysis and experiment scripts along with the pre-registration of the analysis for future researchers to add to this dataset. Datasets from multiple sites with diverse samples will allow for the establishment of more robust findings. This in turn will allow for future research to have a clearer path moving forward when testing HIPPEA's predictions.

Further, it is noteworthy that there is research suggesting that autistic individuals tend to use compensatory brain networks to show similar behavioural responses (McKay et al., 2012; Philip et al., 2012). Therefore, our sample of autistic males might show similar behavioural performance to the neurotypical population because they are using compensatory brain networks. Thus, this task may be too simplistic to show differences in the ability of individuals with autism to form and utilise predictions to guide their behaviour. Hence, apart from adding more data points to this study, it will be important to consider more complex stimuli which also control for attention and expectation at the same time. Moreover, research that uses multiple paradigms such as the study by Tulver et al. (2019) might provide a more in-depth understanding of the predictive processing in autism.

5. Conclusions

The present results suggest that there is a special treatment of prediction errors in autism as expected under HIPPEA. However, it is important to point out that the formation of predictions as seen by the better detection of predictable targets along with the motion masking effects indicate that our autistic participants were able to form predictions, which is another pillar of HIPPEA. These results are promising and the recruitment of a sufficient number of participants, as suggested by the power analysis, will be necessary to establish how stable these results are. Nevertheless, the findings take us one step closer to finding out whether HIPPEA is a good candidate for explaining autism.

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CRediT author statement

GT: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – Original Draft, Writing – Review & Editing, Visualisation, Project administration, Funding acquisition. **FP**: Writing, Review & Editing, Supervision. **LM**: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

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