Rhythmic and interval#based temporal orienting in autism

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RESEARCH ARTICLE

Rhythmic and interval-based temporal orienting in autism

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Abstract

Individuals with autism spectrum disorder (ASD) may show secondary sensory and cognitive characteristics, including differences in auditory processing, attention, and, according to a prominent hypothesis, the formulation and utilization of predictions. We explored the overlap of audition, attention, and prediction with an online auditory "temporal orienting" task in which participants utilized predictive timing cues (both rhythmic and interval-based) to improve their detection of faint sounds. We compared an autistic ($n = 78$) with a nonautistic ($n = 83$) group, controlling for nonverbal IQ, and used signal detection measures and reaction times to evaluate the effect of valid temporally predictive cues. We hypothesized that temporal orienting would be compromised in autism, but this was not supported by the data: the boost in performance induced by predictability was practically identical for the two groups, except for the small subset of the ASD group with co-occurring attention deficit hyperactivity disorder, who received less benefit from interval-based cueing. However, we found that the presence of a rhythm induced a significantly stronger bias toward reporting target detections in the ASD group at large, suggesting weakened response inhibition during rhythmic entrainment.

Lay Summary

When we can predict the moment something important will likely happen, we can focus our attention on that moment in time to perceive it more accurately and respond to it faster. This process of "temporal orienting" plays an important role in social interaction and other day-to-day functioning. Based on previous literature, we hypothesized that temporal orienting would be less effective in autism, but our experiments indicated no difference in temporal orienting between autistic and nonautistic groups.

KEYWORDS
attention deficit hyperactivity disorder, attention, audition, autism, prediction, rhythm, temporal orienting

INTRODUCTION

Autism spectrum disorder (ASD), diagnostically defined as persistent deficits in social communication and interaction plus the presence of restricted and repetitive behaviors (American Psychiatric Association, 2013), is characterized by a wide range of cognitive and perceptual differences, including differences in low-level sensory sensitivity, higher-level perceptual judgment, attention, and learning (Marco et al., 2011; Park et al., 2016; Remington et al., 2009). Some of these differences may be epiphenomenal to the diagnostically relevant social differences or share genetic or environmental causal factors with them. However, a growing number of

researchers have proposed and explored "domain-general" accounts of autism in which the social differences result from cognitive and perceptual differences over the course of development (Northrup, 2017; Tager-Flusberg, 2010). These nonsocial characteristics of autism phenotypes are therefore relevant not only in their own right but also as possible causal contributors to social impairment and possible targets for intervention.

Several of these domain-general accounts of autism have focused on possible differences in the prediction of upcoming events (Sinha et al., 2014) and timing/time perception (Isaksson et al., 2018). In the nonautistic (NA) brain, learned patterns of temporal contingencies or cues can support deployment of attention to temporally predictable events for the purpose of improving perceptual sensitivity and speeding response processes (Nobre & Heideman, 2015). Various timing processes have been studied in autism (Allman, 2015; Casassus et al., 2019), but only a few have looked at time-based event expectancy. One recent study investigated "variable foreperiod effects": this study found that when participants were asked to respond quickly to a target that follows a cue with a variable foreperiod, autistic participants' reaction times were less affected by the foreperiod of the previous trial than those of nonautistic participants, indicating a possible difference in implicit temporal orienting (Girardi et al., 2021). A further pair of studies with autistic children used a task in which participants rapidly discriminated between two targets that could be partially predicted by the foreperiod preceding their appearance (Kunchulia et al., 2017, 2020). These studies found equal or superior performance in autistic children. However, the temporal orienting aspect of the task was complicated by the necessity of learning implicit time/target pairings, and the number of participants per group was small. Thus, whether explicit temporal orienting offers the same perceptual and response time advantages to autistic adults remains an open question.

Temporal orienting is particularly relevant in audition, where most intelligible stimulus structure unfolds in the time domain (Lange, 2013). Since humans are much more attuned to rhythmicity in the auditory stream than in vision (Grahn, 2012), the auditory domain is also especially useful for exploring temporal orienting through rhythm. Though the study of timing differences in autism has focused mainly on interval timing, recent evidence has also suggested differences in neural and motor entrainment to rhythmicity (Beker et al., 2021; Vishne et al., 2021). Temporal orienting via rhythmic cueing has been shown to draw on different subcortical neural mechanisms than temporal orienting through learned interval timing: the former is thought to be more dependent on cerebellum, while the latter is thought to draw more on the basal ganglia (Teki et al., 2011). Structural and functional differences associated with both of these areas have been hypothesized to underlie different aspects of autism phenotypes (Blaylock, 2010; Hampson & Blatt, 2015; Subramanian et al., 2017); thus, the study and comparison of intervallic and rhythmic temporal orienting could help to expose subcortical contributions to autism.

In this study, we explored temporal orienting in autism through an online cued auditory detection task. Our participants reported detection of faint auditory targets on a white noise background as quickly and accurately as possible with and without temporally predictive interval-based or rhythmic cues. Based on the rate of successful target detections and false positives, we calculated the signal detection measures of target detection sensitivity (ability to differentiate targets from nontargets) and response bias (tendency to report targets where none were presented). We also measured response time for successful detections. It has previously been shown that valid predictive temporal cues in the auditory domain improve perceptual sensitivity at the cued time (Rimmele et al., 2011) and reduce response times to cued targets (Lange & Röder, 2006; Rimmele et al., 2011); we therefore interpreted the boost in sensitivity and reduction in reaction time introduced by valid (relative to invalid) predictive temporal cueing as measures of the efficacy of temporal orienting. Our preregistered hypothesis was that autistic participants would demonstrate less of a boost in target sensitivity and less reduction in response time from valid predictive cues, indicating difficulties with cued auditory temporal orienting. We also planned to investigate target response bias, but we had no specific hypotheses about how this would differ between groups. We hypothesized that the group differences in sensitivity and response time benefit of temporal predictability would be specific to predictive orienting, and that there would be no such group difference when target timing was marked by concurrent visual cues.

MATERIALS AND METHODS

Participants

The 187 adults (94 nonautistic and 92 autistic) aged 18–39 years consented voluntarily to participate in this online research study (Table 1). Participants were given the opportunity to volunteer for several follow-up experiments for which we intended to investigate cross-task relationships with this experiment; these experiments are not discussed here. Our large sample size was intended to allow for analysis of interindividual correlations among tasks and measures, and also to provide a sufficient number of follow-up participants for follow-up experiments. The screening process and tasks were completed on each participant's personal computer. All participants self-reported English as their native language (including bilingual or multilingual individuals).

Autistic participants were recruited through the Simons Foundation Powering Autism Research (SPARK) database through a multi-step screening

TABLE 1 Group-level information of participant characteristics

	NA	NA (postexclusion)	ASD	ASD (postexclusion)
N	94 (46 M, 48 F)	83 (40 M, 43 F)	92 (47 M, 45 F)	78 (41 M, 37 F)
Age	30.5 (7.6)	30.5 (7.9)	28.5 (6.2)	28.4 (6.5)
IQ (test my brain)	28.5 (3.0)	28.5 (3.0)	28.6 (3.2)	28.5 (3.3)
Gender identity[a]	Cis $N = 92$ (98%)	Cis $N = 92$ (98%)	Cis $N = 75$ (82%)	Cis $N = 75$ (82%)
	GD $N = 2$ (2%)	GD $N = 2$ (2%)	GD $N = 17$ (18%)	GD $N = 17$ (18%)
ADHD[a]	$N = 0$ (screened out)	$N = 0$	$N = 27$ (13 M, 14 F)	$N = 23$ (12 M, 11 F)

Abbreviations: Cis, cisgender (gender identity consistent with sex assigned at birth); GD, gender diverse (nonbinary and/or transgender gender identity).
[a]Self-reported.

process. Participants were first identified as eligible through SPARK's existing characterization measures based on a clinical diagnosis of ASD, plus the criteria listed below. All ASD participants were located in the US and live independently.

A control group of NA participants were recruited through Prolific, an online portal to screen and recruit participants for online research. Prolific participants were recruited globally, although we only included participants who spoke English natively.

Exclusion criteria for both groups included self-report of any history of head trauma (resulting in concussion), seizures, uncorrected vision or hearing impairments, color-blindness, and prematurity. Additional screening criteria for the ASD group included a self-reported set of possible ASD diagnostic confounds: schizophrenia, cognitive fetal alcohol syndrome, brain infections like encephalitis or meningitis, insufficient oxygen at birth with NICU stay, and any developmental delays or impairment due to another medical condition or exposure. Additional screening criteria for the NA group included a self-report of any history of diagnosis of psychiatric, mood, or learning disorder, or medications to treat these conditions, including any antipsychotic medication. Importantly, participants self-reporting attention deficit hyperactivity disorder (ADHD) or being on medication to treat ADHD were excluded from the NA group but not from the ASD group (except for exploratory analyses, as described below). The 29% of the ASD group reported a concurrent ADHD diagnosis or being on medication to treat ADHD, consistent with the ~31% of ASD children meeting full criteria for ADHD reported in (Leyfer et al., 2006). We did not exclude ADHD in the ASD group because it is a notable part of the autism phenotype for a significant subset of autistic individuals, and we wanted to investigate this aspect of heterogeneity.

All participants completed the Test My Brain matrix reasoning subtest (Germine et al., 2012; Singh et al., 2021), a validated and normed measure of nonverbal intellectual ability comparable to IQ score. Test My Brain matrix reasoning scores are referred to below as "IQ" for easy interpretation. In the matrix reasoning subtest, participants must identify the image that completes an incomplete matrix based on a logical rule. Only individuals who achieved a score of 20 or above on the matrix reasoning subtest (~2.75 standard deviations below the mean of 28.8) were included in the study; 13 autistic and 3 nonautistic individuals were screened out due to IQ scores lower than this threshold.

After participation in the experiment, 14 ASD and 11 NA participants were excluded because they did not reach a reasonably low signal-to-noise ratio in the adaptive staircase procedure or because of self-reported distractions, as described in the *Methods Supplement*.

The research study was approved by the MIT Committee On the Use of Humans as Experimental Subjects, in accordance with the ethical standards in the Declaration of Helsinki. Participants could opt out of the study at any time and were compensated for the portion of the study that they completed. Compensation was not linked to accuracy of task performance. Participants who completed this study were then invited to complete two additional follow-up sessions on language perception and sequence learning that will be described in subsequent manuscripts.

Setup

Participants were instructed to complete the experimental session online from a computer in a quiet, distraction-free environment, and to use headphones/earphones that covered or rested inside both ears. Instructions and experiments were presented in full screen mode. Task instructions were delivered to participants through on-screen text and concurrent audio.

A series of auditory tasks described below were presented via the online experiment interface Pavlovia (https://pavlovia.org). Screening and characterization questionnaire responses were collected via Qualtrics (https://www.qualtrics.com).

Experimental tasks

In all of the tasks, participants were asked to listen for faint auditory targets on a background of white noise and report when they detected a target by promptly

pressing their space bar. Targets were 770 Hz pure tones lasting for 100 ms, including a 5 ms linear amplitude ramp-up and ramp-down.

Participants performed five different target detection tasks, described in detail below and schematized in Figure 1. Three were "nonrhythmic" tasks:

- Predictable nonrhythmic (PN)
- Unpredictable nonrhythmic (UN)
- Visually-cued nonrhythmic (VN)

Two were "rhythmic" tasks:

- Predictable rhythmic (PR)
- Unpredictable rhythmic (UR), or "somewhere in the gap"

Participants were first asked to adjust their computer volume to a comfortable level. They then performed a practice block for each task with clearly audible beeps, followed by a target volume staircase procedure to set the signal-to-noise ratio (SNR) of beeps relative to white noise for the rest of the experiment. See *Methods Supplement* for details on setting SNR.

Next, each participant performed four blocks of each of the five tasks. The order of the 20 blocks was randomized for each participant. Participants were informed of which task they would perform and given task instructions before each block. They were allowed to take breaks between blocks, and initiated each block with a button press.

The four blocks of a given task differed in terms of the *base interval* used. This was the exact (in predictable tasks) or average (in unpredictable and visual tasks) temporal separation between the cue and target. Each of the four blocks of each task used one of the four base intervals: 600 ms, 700 ms, 800 ms, and 900 ms.

Each block included 12 trials, of which eight were valid (containing a target) and four were invalid (without a target), presented in a random order. Within each

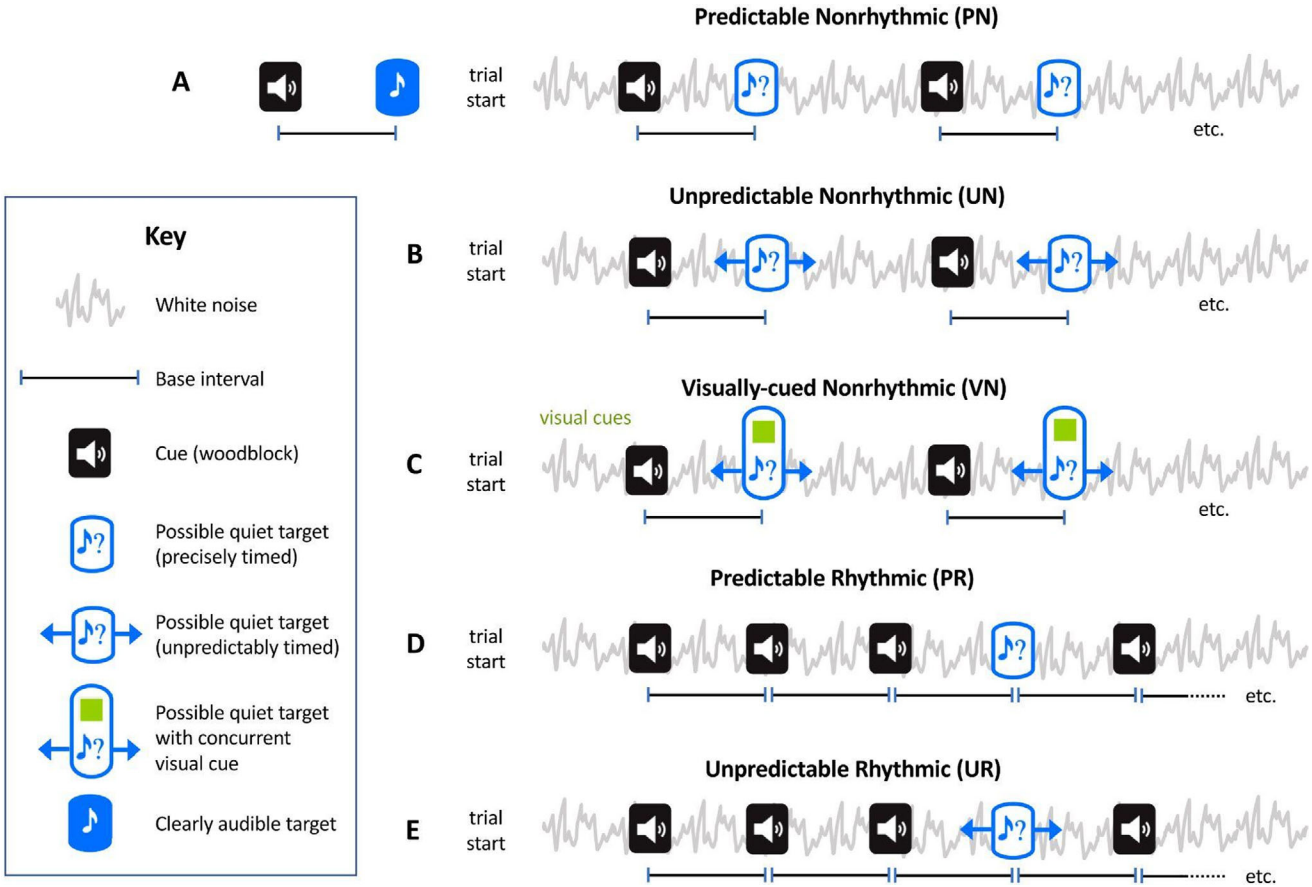

FIGURE 1 The five auditory detection tasks used in this study. All tasks asked participants to quickly press a key when they detected a target beep. (a) Predictable nonrhythmic (PN): A cue-to-target interval was presented before the start of the trial. In the subsequent trial, targets (when they occurred) followed the cue by that interval. (b) Unpredictable nonrhythmic (UN): Targets (when they occurred) followed cues by an uncertain interval. (c) Visually-cued nonrhythmic (VN): Like UN, but a visual cue followed every any auditory cue by an uncertain interval, and coincided in time with the target (when it occurred). (d) Predictable rhythmic (PR): An isochronous rhythmic stream consisted of three cues followed by a possible target at the time cued by the rhythm (when it occurred). (e) Unpredictable rhythmic (UR): Like PR, but target timing was uncertain after each isochronous sequence of three cues.

block, trials were presented uninterrupted over a continuous background of white noise. On each valid trial, the target's volume was randomly perturbed such that the SNR differed from the participant's baseline SNR by a uniform distribution of width 3 dB centered on +0.4 dB. Each participant received the same set of volume perturbations.

Nonrhythmic tasks

In the nonrhythmic tasks, each trial was initialized by a clearly audible cue (a "tap" sound). Trials were separated by a random delay uniformly distributed over the range 1.4 s–2.4 s. In the PN task (Figure 1a), targets followed cues at a delay equal to the base interval, and the base interval was instructed at the beginning of the block with a clearly audible cue-target pair; thus, target timing was predictable based on memory of the instructed interval. In the UN task (Figure 1b), on valid trials, targets followed cues at a delay drawn from a uniform distribution with width 0.84 s, centered on the base interval for that block. This width was chosen such that the target always followed the cue by at least 180 ms and therefore remained clearly perceptually distinct from the cue.

The VN (Figure 1c) task, was identical to the UN task except that on both valid and invalid trials, a simple visual icon (a small green square) was displayed. On valid trials, the visual icon appeared simultaneously with the target. On invalid trials, the visual icon followed the cue with delay equal to the base interval. Thus, in the VN task, the target timing was not predictable in advance, but the participant had the advantage of unambiguously knowing the possible target timing after the fact based on when the visual icon had appeared. This task was designed to distinguish the detection advantage provided by advance knowledge (presumably attributable to cognitive/attentional preparation) from any detection advantage that could be gained from timing information concurrent with the target (presumably attributable to a post hoc decision-making advantage).

Rhythmic tasks

In the rhythmic tasks, each trial was initialized by a series of three isochronous "tap" cues, with an inter-onset interval equal in duration to the base interval for that block. In the PR task (Figure 1d), targets followed the last cue with delay equal to the base interval; thus, the timing of the target could be determined by the rhythm of the three preceding cues. In the UR task (Figure 1e), target delays were drawn from a uniform distribution with width 0.84 s and centered on the base interval; thus, targets were still preceded by a rhythmic series of cues, but exact target timing could not be determined from this rhythm. In both rhythmic tasks, trials within a block were sequenced such that each trial continued the steady rhythm of the previous trial, creating the sense of an ongoing beat.

Analysis

Data analysis was performed in R using publicly available packages. Data and code are available at https://osf.io/2trnd/ and https://osf.io/v693s/. For each participant, data were pooled over all repetitions of each of the five tasks, producing a pooled hit count H_{task}, a pooled false alarm count F_{task}, a pooled miss count of M_{task}, and a pooled true negative count of T_{task}. Standard signal detection measures of sensitivity (d') and response bias (c) were calculated using the standard formulae, corrected for the presence of extreme values (e.g., participants achieving the maximum hit rate) using the log-linear rule as suggested in (Hautus, 1995).

$$d' = z(h_{task}) - z(f_{task}),$$

$$c = -\frac{z(h_{task}) + z(f_{task})}{2},$$

where $h_{task} = \frac{H_{task}+0.5}{32+1}$ is the corrected hit rate, $f_{task} = \frac{F_{task}+0.5}{16+1}$ is the corrected false alarm rate, and $z(\cdot)$ is the z-transform. We compared d' and c across groups with preregistered ANOVAs using the Geisser–Greenhouse correction where appropriate. The full preregistration was published prior to data collection at https://osf.io/hdyrm.

We hypothesized that we would see the NA group demonstrate a larger boost in sensitivity d' from unpredictable to predictable conditions than the ASD group. In order to evaluate the strength of evidence for the null hypothesis, we supplemented the preregistered ANOVA analysis with an exploratory Bayes Factor analysis comparing the predictive boost in d' across groups. For this analysis, a noninformative Jeffreys prior wass placed on the variance of the normal population, and a Cauchy prior was placed on the standardized effect size (Morey & Rouder, 2011; Rouder et al., 2009).

Reaction time RT was analyzed by collecting all reaction times to correct detections for each task and diagnostic group, excluding reactions with RT <0.1 s (which we assumed to be anticipations), and performing a preregistered 2×2×2 ANOVA over predictability, rhythmicity, and diagnosis, controlling for baseline SNR, age, IQ, and target volume. We hypothesized that we would see the ASD group get less reaction time advantage from temporal predictability than the NA group.

Since the ASD group included a substantial incidence of ADHD (~30%) while ADHD was excluded from the NA group, and since attention was highly relevant to our tasks, we conducted a post hoc exploration in which the

ASD group was separated into ADHD and non-ADHD subgroups. We compared task performance across these subgroups and the NA group using exploratory 3-group ANOVAs.

Community involvement

No autistic individuals or family members were involved in developing the research questions, study design, measures, implementation, or dissemination of these findings.

RESULTS

Signal detection analysis of predictive versus concurrent cues

We first compared the effect of concurrent visual timing cues (VN task) with the effect of predictive timing cues (PN task) across groups, with the invalid cueing condition (UN) as a control. We investigated detection sensitivity (d') and response bias (c) across groups with preregistered 2×3 (task × group) mixed ANOVAs. In Figure 2, we show d' for these tasks for both groups. Due to clear differences between the ASD participants with and without ADHD discussed below, we show the ASD group broken into ASD-ADHD and ASD-nADHD.

The ANOVA for d' showed a significant main effect of task ($F_{2,318} = 51.5$, $p < 0.0001$, $\eta_G^2 = 0.063$), but no significant effect of group ($F_{1,159} = 1.07$, $p = 0.30$, $\eta_G^2 = 0.005$) or task × group interaction ($F_{2,318} = 1.98$, $p = 0.14$, $\eta_G^2 = 0.003$). Post hoc pairwise t-tests showed that the PN condition (mean $d' = 2.14$, SE = 0.069) provided a significant predictability-related sensitivity boost over UN (mean $d' = 1.60$, SE = 0.062) ($p < 0.0001$) and over VN (mean $d' = 1.77$, SE = 0.073) ($p < 0.0001$), but that sensitivity did not differ significantly between UN and VN ($p = 0.24$), indicating that concurrent visual cueing was not sufficient to improve target sensitivity in either group.

The ANOVA for d' also showed a significant main effect of task ($F_{1.86,295} = 43.5$, $p < 0.0001$, $\eta_G^2 = 0.070$), but no significant effect of group ($F_{1,159} = 1.49$, $p = 0.22$, $\eta_G^2 = 0.007$) or task × group interaction ($F_{1.86,159} = 0.180$, $p = 0.82$, $\eta_G^2 = 0.0003$). Post hoc pairwise t-tests showed that both the PN condition (mean $d' = 0.27$, SE = 0.032) and the VN condition (mean $d' = 0.33$, SE = 0.041) introduced a considerable bias ($p < 0.0001$) toward reporting target detection relative to the UN condition (mean $d' = 0.55$, SE = 0.031), while bias did not differ significantly between the PN and VN conditions ($p = 0.20$).

As shown in Figure 2, the sensitivity of the ASD-nADHD subgroup was very similar to that of the NA group across conditions, whereas the ASD-ADHD

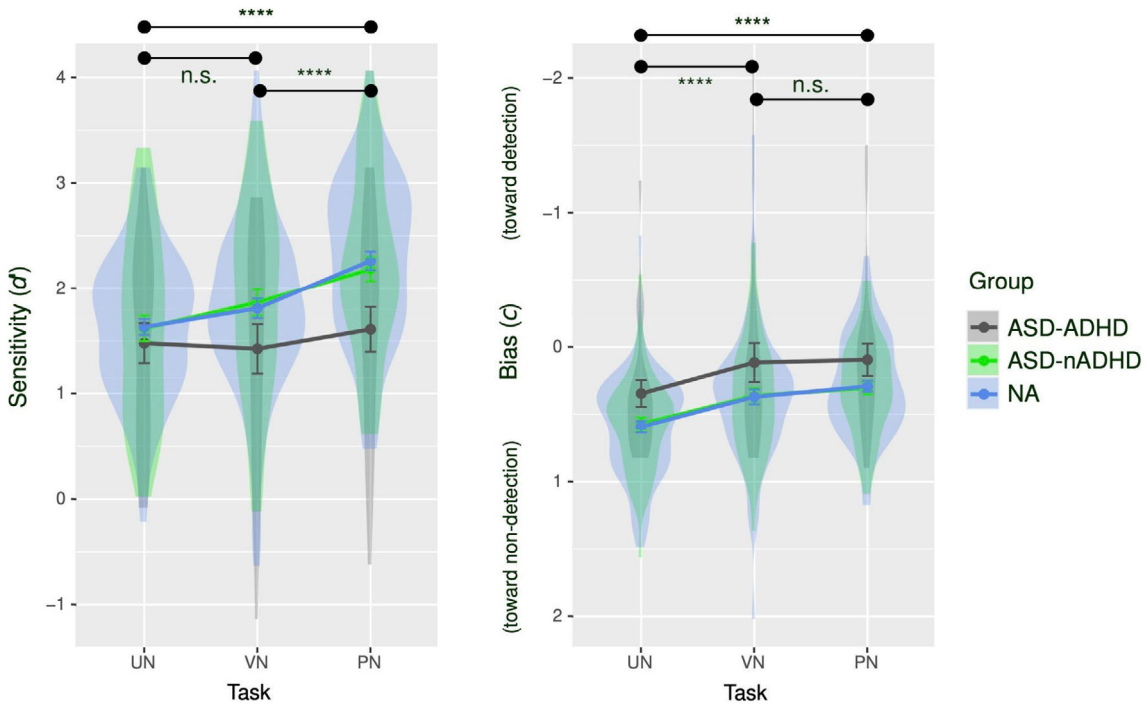

FIGURE 2 Effects of concurrent visual cue and predictive cue (nonrhythmic). (a) Across the population, a temporally predictive cue grants a highly significant advantage in target sensitivity d' over both the uncued and concurrently visually cued targets, while concurrent visual cueing offers no significant sensitivity advantage over uncued targets. (b) Across the population, both concurrent visual and predictive cueing induce a highly significant bias c toward reporting detections relative to uncued targets. No significant group differences were observed in the preregistered ANOVA, but an exploratory ANOVA separating out the ASD-ADHD group found that this group showed significantly higher response bias.

subgroup showed notably weaker sensitivity d' than the NA group in both the VN and PN conditions. An exploratory 3×3 ANOVA among the three subgroups showed a significant task by subgroup interaction ($F_{4,316} = 2.74$, $p = 0.029$, $\eta_G^2 = 0.007$). Similarly, the response bias c of the ASD-nADHD subgroup did not differ from that of the NA group, whereas the ASD-ADHD group showed significantly higher response bias than both other subgroups across all three tasks. This effect was apparent as a significant main effect of group in an exploratory 3×3 ANOVA ($F_{2,158} = 3.84$, $p = 0.023$, $\eta_G^2 = 0.034$).

Rhythmicity and predictability

Signal detection analysis across predictability and rhythmicity

We next excluded the visually-cued task such that the remaining four consisted of a predictable and an unpredictable version of a rhythmic and a nonrhythmic task. We compared signal detection measures across groups, investigating sensitivity d' and bias c with preregistered $2 \times 2 \times 2$ (predictability × rhythmicity × group) mixed ANOVAs (Figure 3).

The ANOVA for d' revealed significant main effects of rhythmicity ($F_{1,159} = 7.52$, $p = 0.007$, $\eta_G^2 = 0.004$) and predictability ($F_{1,159} = 185$, $p < 0.0001$, $\eta_G^2 = 0.098$), but no significant group effect ($F_{1,159} = 1.90$, $p = 0.17$, $\eta_G^2 = 0.009$) or interactions. Sensitivity was higher in the predictable than in the unpredictable condition, and higher in the nonrhythmic task than in the rhythmic task. We had hypothesized that we would see a predictability x group interaction indicating less of a sensitivity boost from predictive cues in the ASD group. We did see a difference in this direction (NA d' boost = 0.63, ASD d' boost = 0.52), but it did not rise to the level of significance ($F_{1,159} = 1.64$, $p = 0.20$, $\eta_G^2 = 0.0009$). The effect was even weaker when we controlled for baseline SNR, age, and IQ ($F_{1,156} = 0.98$, $p = 0.33$, $\eta_G^2 = 0.0006$).

The ANOVA for c revealed a significant main effect of diagnosis ($F_{1,159} = 5.59$, $p = 0.019$, $\eta_G^2 = 0.025$): participants in the ASD group had a higher bias toward reporting detections (NA mean $c = 0.48$, SE = 0.024; ASD mean $c = 0.34$, SE = 0.024). We also saw a significant main effect of predictability ($F_{1,159} = 295$, $p < 0.0001$, $\eta_G^2 = 0.13$) and an interaction of rhythmicity × predictability ($F_{1,159} = 6.16$, $p = 0.014$, $\eta_G^2 = 0.003$). Surprisingly, we saw a powerful interaction of rhythmicity × diagnosis ($F_{1,159} = 9.37$, $p = 0.003$, $\eta_G^2 = 0.006$) showing that rhythmic cueing conditions (regardless of cue validity) introduced bias toward reporting targets for the ASD group (mean c boost = −0.064, SE = 0.029) but introduced bias *against* reporting targets in the NA group (mean c boost = 0.067, SE = 0.028). This effect was even stronger when we controlled for baseline SNR, age, and IQ ($F_{1,156} = 10.4$, $p = 0.002$, $\eta_G^2 = 0.007$).

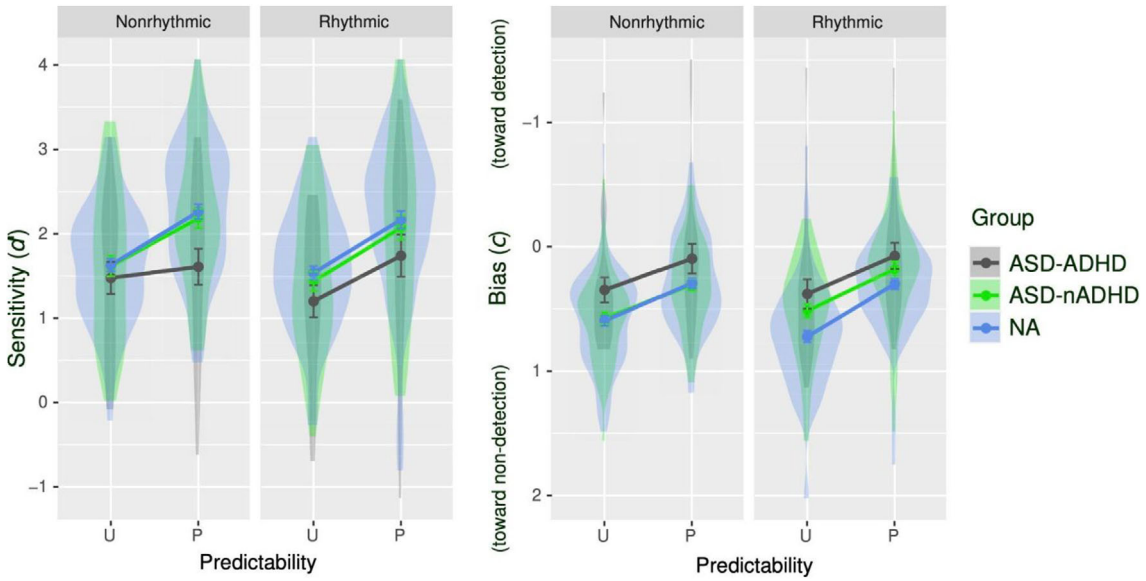

FIGURE 3 Effects of rhythmic and nonrhythmic predictive cueing. Lines connect the group means between unpredictable tasks and the corresponding predictable task, and bars show standard error within each group. (a) Across the tested groups, both rhythmic and nonrhythmic predictive cueing grant a significant advantage in detection sensitivity d'. Nonrhythmic cueing is marginally more effective for the NA group than for the ASD group. Separating out the ASD-ADHD subgroup from the larger ASD group showed that individuals with ASD and ADHD gained little advantage from nonrhythmic predictive cueing and showed less sensitivity during rhythmic streams. (b) Across the tested groups, both types of predictive cueing introduce a significant bias toward reporting target detections. A significant group by rhythmicity interaction indicates that the ASD group shows a larger bias than the NA group for rhythmic cues (in both the predictable and unpredictable target conditions), but not for nonrhythmic cues. Separating out the ASD-ADHD group showed that this interaction was driven by the subgroup without ADHD.

Exploratory Bayes factor analysis

To determine whether our data provided significant evidence *against* our hypothesis of weaker temporal orienting in ASD, we used a Bayes factor analysis to compare the predictive boost in d' between the NA and ASD groups across both rhythmicity conditions. We found moderate evidence supporting the null hypothesis (Bayesian *t*-test: BF = 0.31). Guided by the observation of substantial differences between the ASD-ADHD and the ASD-nADHD subgroups, we then repeated the analysis excluding the ASD-ADHD subgroup and found even stronger evidence supporting no difference in cued temporal orienting between the NA and ASD-nADHD subgroups (Bayesian *t*-test: BF = 0.14). The result was the same when the data was restricted to the nonrhythmic condition (Bayesian *t*-test: BF = 0.22) and to the rhythmic condition (Bayesian *t*-test: BF = 0.19). However, the interaction between diagnosis and rhythmicity in determining bias *c* only grew stronger when the ASD-ADHD group was excluded from analysis ($F_{1,156} = 11.3$, $p = 0.001$, $\eta_G^2 = 0.01$).

Analysis of reaction times

A preregistered ANOVA for *RT* on trials with successful target detection revealed a significant main effect of rhythmicity ($F_{1,13526} = 254$, $p < 0.0001$, $\eta_G^2 = 0.018$), with rhythmic conditions showing faster reactions (mean RT = 0.52 s, SE = 0.0022 s) than nonrhythmic (mean RT = 0.58 s, SE = 0.0024 s); a significant main effect of predictability ($F_{1,13526} = 225$, $p < 0.0001$, $\eta_G^2 = 0.016$), with predictable conditions showing faster reaction times (mean RT = 0.53 s, SE = 0.0021 s) than unpredictable (mean RT = 0.58 s, SE = 0.0026 s); and a significant main effect of ASD diagnosis ($F_{1,13526} = 62.0$, $p < 0.0001$, $\eta_G^2 = 0.005$), with the ASD group showing shorter reaction times (mean RT = 0.54 s, SE = 0.0024 s) than the NA group (mean RT = 0.56 s, SE = 0.0023 s) across tasks. We saw no significant interactions; in particular, we did not see our hypothesized significant interaction between diagnostic group and predictability ($F_{1,13526} = 0.10$, $p = 0.75$, $\eta_G^2 < 0.0001$) (Figure 4). When we separated out the ASD-ADHD subgroup from the ASD-nADHD subgroup in an exploratory analysis, we saw similar reaction times between the two groups except in the UN condition, where the ASD-ADHD subgroup showed slower reaction times (mean RT = 0.61 s, SE = 0.011 s) than the ASD-nADHD subgroup (mean RT = 0.58 s, SE = 0.0061 s).

Exploration of the effects of IQ

Our participant pool was limited to individuals with IQ above a threshold, and therefore did not represent the subset of autistic individuals with intellectual delays. As an exploratory analysis, we investigated the relationship between IQ and target detection sensitivity to give a sense of how the results might change if we were to include individuals with lower IQs in our sample. We found that d' across the four main tasks (not including visual cueing) showed positive Pearson correlation with IQ (Pearson's r(642) = 0.09, $p = 0.022$). However, the predictive boost in d' granted by valid predictive cues showed no significant correlation with IQ (Pearson's r(320) = 0.055, $p = 0.32$). Thus, it appears that IQ is not strongly related to the efficacy of temporal predictive cues for those above the threshold IQ score.

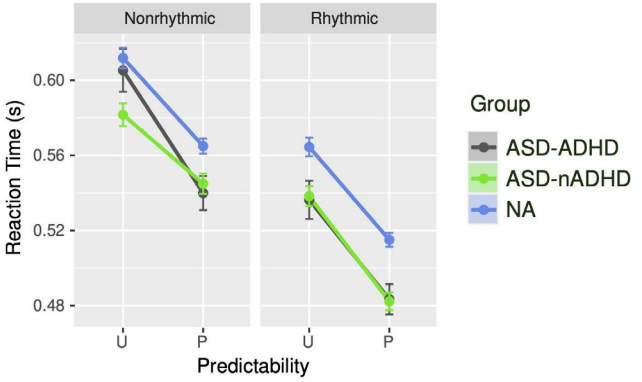

FIGURE 4 Reaction times across conditions and groups. Reaction times were lower for rhythmic than for nonrhythmic tasks, lower for predictable than unpredictable conditions, and lower for both ASD subgroups than for the NA group. Bars show standard error over all *hit* trials within each subgroup.

DISCUSSION

With this online experiment, we set out to investigate temporal orienting in autism by testing autistic participants' comparative ability to use temporally predictive cueing to improve auditory target detection in a large IQ-matched sample of autistic and nonautistic participants. Our hypothesis was that autistic participants would show less improvement at the task, as measured by target detection sensitivity and reaction time, when cues were introduced that could be used to predict the timing of possible auditory targets (i.e., less "predictive boost").

We did not find significant evidence supporting this hypothesis in our analysis of target detection nor in our analysis of reaction times. We saw a small reduction of the predictive boost in sensitivity in the ASD group — consistent with our hypothesis - but the difference was driven entirely by the ASD subgroup that reported concurrent ADHD. When we restricted our analyses to participants with no ADHD diagnosis, the two groups showed nearly identical mean sensitivity across all tasks, providing moderate evidence for the null hypothesis. We found that that predictable timing boosted target

sensitivity, whereas concurrent visual cueing did not; therefore, it seems that the detection advantage granted by predictive cues was not just a function of knowing the timing of potential targets, but instead was genuinely predictive, that is, dependent on knowledge of target timing with enough advance warning to adequately prepare attentional mechanisms to focus on the target time. We conducted these exploratory analyses with the ADHD-ASD subgrouping because ADHD affects approximately 30% of individuals on the spectrum, and because of the relevance of attentional factors in completing the task.

This result helps to constrain prediction-related accounts of autism, e.g. (Sinha et al., 2014), by restricting what forms of prediction may be impaired in autism: we find that the use of predictive timing cues to improve perceptual sensitivity does not seem to be impaired. This is consistent with a systematic review of prediction in autism (Cannon et al., 2021) that proposed that predictive impairment may be restricted to difficulty learning of subtle predictive relationships, differences in the neural signaling of low-level implicit predictions, and a relative absence of spontaneous engagement of prediction-related motor processes. A lack of impairment of predictive cue utilization suggests that social and language-learning difficulties in autism cannot be attributed to basic challenges attending to predictably important moments in spoken language or other social interaction; however, it leaves open the possibility of impairment in learning to recognize these important moments.

The ASD-ADHD subgroup showed greater bias toward reporting detections and reduced sensitivity on the predictive nonrhythmic task, consistent with weaker response inhibition in ADHD (Wodka et al., 2007); however, in this case we would expect the ASD-ADHD group to show faster reaction times, which was not the case. Our ADHD-specific differences highlight the importance of characterizing ADHD comorbidity in future explorations of perceptual and cognitive differences in ASD, especially in tasks with an attentional component. They also indicate that people with ASD and ADHD may have additional challenges in attending to predictably important moments in social interactions that could be relevant to interventions. However, we note that these findings were the results of exploratory, post hoc analysis and should therefore be replicated before they can be considered reliable.

A significant effect of diagnosis on reaction time revealed faster reaction times in the ASD groups with and without ADHD. The strength of the ASD group in this measure of task performance is unexpected in light of a previous large meta-analysis showing little difference in simple and choice reaction times in ASD across a wide range of tasks (Ferraro, 2016); however, this discrepancy is not especially noteworthy given the very small effect size associated with this group difference. One of the few studies of temporal orienting in autism did show decreased reaction times for predicted interval-response pairings in autistic children (Kunchulia et al., 2020), but this would not account for shorter reaction times in unpredictable conditions. We cautiously conclude that reaction time may be a strength for ASD individuals in some circumstances, but that more evidence is needed.

The most unexpected and robust result of our experiment was the substantial group difference (NA vs. ASD) in response bias during rhythmic cueing (valid or invalid) but not during nonrhythmic cueing, apparent for both the ADHD and the nADHD subgroups of the ASD sample. We hypothesize that the group difference in response in rhythmic conditions represents a group difference in response inhibition induced by ongoing rhythm. It has been repeatedly shown that people with autism struggle with response inhibition, and these difficulties seem to be linked to the diagnostic feature of repetitive movements (Mostert-Kerckhoffs et al., 2015; Schmitt et al., 2018). The group difference in the biasing effect of rhythm may be linked to group differences in basal ganglia function: response inhibition difficulties in autism have been linked to basal ganglia irregularities (Langen et al., 2012) and the detection of and entrainment to beat-based auditory rhythms draws heavily on the basal ganglia (Cannon & Patel, 2021; Grahn, 2009; Schwartze et al., 2011). Possible connections between auditory rhythm, basal ganglia differences, and atypical response bias in ASD should be explored further and more directly as one possible route to understanding the contribution of the basal ganglia to autistic phenotypes.

Limitations

The online format was not ideal in a number of ways: we lacked control of the auditory environment and the stimulus presentation headphones, and participants may not have been as motivated to perform as well as they would have been in a lab setting with a researcher observing. These limitations may have led to a wider range of baseline SNRs and therefore a wider range of performance than we would see in a lab. Further, we have no way to check whether participants ever adjusted their volumes after the adaptive staircase, though they were instructed not to and there was no monetary incentive to do so.

The decision to make our tasks speeded-response was a tradeoff. On the one hand, it allowed us to detect group differences related to response inhibition in the rhythmic condition, suggesting a future direction for research. On the other hand, it makes it more difficult to align our results with temporal orienting studies that do not use speeded response. We would expect to see a similar lack of NT/ASD-nADHD group differences in sensitivity if we ran similar tasks without speeded response; we leave this to future work.

This study excluded for psychiatric, mood, and learning disorders from the NA group but not in the ASD group. These conditions are common in ASD and their

prevalence increases with age (Havdahl & Bishop, 2019; Lai et al., 2019). By including individuals with ADHD in the ASD group, our intent was to achieve a more representative sample of the ASD phenotype. However, the exclusion of participants with ADHD from the NA group makes it difficult to interpret the ADHD-specific results: it is unclear whether task performance differences in the ASD-ADHD group were specific to the ASD-ADHD phenotype or general to ADHD. Further, by excluding participants with other psychiatric, mood, and learning disorders from the NA group and not specifically excluding those from the ASD group, we introduced a possible confound that might have influenced spurious group differences. Future research would benefit from comparing performance in an ADHD-only group.

Additionally, this study focused on autistic individuals within normal range nonverbal IQ as assessed by an online measure, and therefore does not represent autistic individuals with intellectual delays. Our exploratory analysis showed that IQ might influence overall performance on the target detection task, but gave us no reason to expect that the sensitivity boost granted by temporal predictability was strongly dependent on IQ. Future research should explore these abilities in autistic individuals with lower nonverbal IQ scores, as the IQ range in our intentionally-controlled sample does not represent the full spectrum of intellectual variability in ASD.

Lastly, this study did not involve members of the autism community in the conceptualization, design, or interpretation of the research. When done effectively, participatory research design can better reflect the needs and experiences of the ASD community, and account for certain biases that researchers may bring to the process (Zamzow, 2021).

CONCLUSION

We found no evidence supporting systematic differences in temporal orienting between IQ-matched autistic and nonautistic individuals without ADHD, and our results provided moderate evidence against any such differences. This finding helps to constrain the hypothesis that prediction is impaired in ASD by identifying one type of predictive process that seems to be intact. Temporal orienting in ASD with concurrent ADHD, or indeed in ADHD in general, requires more careful study. The unexpected ASD/NA group difference in response bias induced by rhythmic cueing, likely due to relatively lower response inhibition in the ASD group during ongoing rhythm, provides an exciting direction for further research.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Temporal auditory prediction (TAP) data at https://osf.io/2trnd/.

ETHICS STATEMENT

All research was approved by the MIT Committee On the Use of Humans as Experimental Subjects.

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SUPPORTING INFORMATION

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