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ORIGINAL PAPER

The Influence of Noise on Autonomic Arousal and Cognitive Performance in Adolescents with Autism Spectrum Disorder

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Abstract
This study examined the impact of noise on cognitive performance in autism spectrum disorder (ASD), while concurrently measuring sympathetic responses. Adolescents with and without ASD completed visually presented span tasks in a 2 × 2 experimental manipulation of noise (quiet vs. 75 dB gated broadband noise) and task difficulty (easier vs. harder). Analyses revealed a significant noise × difficulty interaction on performance, and a significant group × noise × difficulty interaction on sympathetic arousal. Correlational analyses indicated an adaptive effect of noise and increased arousal on performance in the easier condition for the control group and a detrimental effect of noise and increased arousal in the harder condition for the ASD group. Implications for sensory processing research and intervention development are discussed.

Keywords Autism spectrum disorder · Sensory processing · Cognitive performance · Autonomic arousal

Introduction

Individuals with autism spectrum disorder (ASD) experience social-communication impairments and restricted, repetitive interests and behaviors. Additionally, up to 95% of individuals with ASD are reported to experience some degree of sensory processing dysfunction (Baker et al. 2008; Tomchek and Dunn 2007), which has recently been recognized as a key diagnostic feature (American Psychiatric Association 2013). Sensory processing refers to the way the nervous system manages sensory stimuli, including responding in ways that increase adaptive responding in daily life (Ayres and Robbins 2005; Baker et al. 2008; Dunn et al. 2002). Disorders of sensory processing involve difficulties in perception and integration of stimuli, and can result in varying patterns of dysregulation. In individuals with ASD, overwhelming sensory input and atypical processing is related to maladaptive functioning throughout the lifespan, including deficits in social, emotional, and behavioral functioning (Ashburner et al. 2008; Baker et al. 2008; Lane et al. 2010; O'Donnell et al. 2012; Tomchek and Dunn 2007). Various theories of sensory dysfunction in ASD have conceptualized difficulty in cross-modal sensory integration, perceptual constancy, and/or arousal regulation; however more research is needed to continue to refine understanding of these complex processes (for reviews, see Cascio et al. 2016; Schauder and Bennetto 2016) and how these sensory problems impact *specific* areas of functioning. Identifying these specific consequences of sensory dysfunction, as well as mechanisms underlying these consequences, will further the development of interventions to improve daily functioning of individuals with ASD.

Characterizing Sensory Processing Difficulties in ASD

The nature of sensory processing problems in ASD has been investigated in a variety of ways, including questionnaires to capture sensory processing difficulties in daily life and controlled laboratory experiments to assess biologically based reactions to specific stimuli. Questionnaire-based reports of sensory impairments in ASD suggest significantly greater sensory processing problems across sensory domains compared to both neurotypical individuals and individuals with other developmental disorders (e.g., Ben-Sasson et al. 2009;

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Rogers et al. 2003; Schoen et al. 2009). Sensory dysfunction has also been found across the lifespan in individuals with ASD, from young children (e.g., Tomchek and Dunn 2007), to school-aged children and adolescents (e.g., Adamson et al. 2006), and through adulthood (e.g., Crane et al. 2009).

To expand upon and clarify findings from extant research that has relied on questionnaire data, researchers have examined specific mechanisms underlying sensory processing problems in ASD using laboratory-based methods and objective measures. One particular approach measures reactivity of the sympathetic nervous system to controlled sensory stimuli. Results across these studies have varied with findings suggesting sympathetic hyperresponsivity (e.g., Chang et al. 2012; Woodard et al. 2012) or hyporesponsivity (e.g., van Engeland et al. 1991), and there is also evidence of subgroups within ASD that represent each of these responsivity profiles (Schoen et al. 2008).

Importantly, past studies in ASD have examined dysregulated autonomic responses in isolation, without extending autonomic processes to the specific downstream *effects* of atypical response patterns. This extension is important as the broader psychophysiological literature has observed differential effects of autonomic processes on downstream outcomes, such as the impact of stress arousal on cognitive performance (Blascovich and Mendes 2010; Cahill and Alkire 2003; Quevedo et al. 2003). Therefore, it is important to comprehensively measure and link atypical autonomic arousal patterns in ASD to specific consequences to characterize the nuanced effects of these potentially harmful and/or compensatory mechanisms.

Application to Adaptive Functioning

Given the importance of education in the lives of children and adolescents, it is crucial to investigate the impact of sensory stimuli (e.g., noise) on the cognitive and academic performance of those with ASD. School is a key learning environment, but the degree of sensory stimuli in classroom settings may be over-stimulating and disruptive to learning. For example, the average noise levels in classrooms have been found to exceed the World Health Organization's noise-exposure and educational guidelines (for a review, see Shield and Dockrell 2003; Wålinder et al. 2007).

Past research into the effects of noise on cognition has found strong evidence for the detrimental effects of both chronic and acute noise exposure on cognition across the lifespan in neurotypical populations. Much of the research investigating the impact of chronic noise has examined the effects of airport noise on academic performance at nearby schools and has found detrimental effects on reading and short-term memory in school-age children (e.g., Haines et al. 2001; Hygge and Knez 2001; Stansfeld et al. 2005).

A meta-analysis of 242 studies investigating noise effects on performance in neurotypical populations found small-to-medium effects overall; however they also identified differential effects of specific noise characteristics on specific components of cognition (Szalma and Hancock 2011). The authors concluded that intermittent noise is often more disruptive than continuous noise, that speech noise (i.e., noise composed of multiple, overlaid speech streams) is more disruptive than non-speech noise, that louder noise is more disruptive than quieter/no noise, and that short durations of noise are more disruptive than long durations. A variety of cognitive domains were examined, including memory, reading comprehension, and attention, with findings indicating that tasks requiring greater levels of executive functioning were most vulnerable to the detrimental effects of noise. Additionally, several studies have established a consistent link between chronic and acute noise exposure and elevated stress levels in children and adults (e.g., Babisch 2006; Babisch et al. 2001; Evans et al. 1998, 2001; for a review, see Ising and Braun 2000). Notably, the majority of the studies conducted above focused on the negative impact of noise on performance and the stress response, with little attention paid to the potential for positive effects.

A critical gap in our understanding—particularly for ASD—is *how* noise influences performance. Existing attempts at understanding potential mechanisms have primarily focused on attentional and masking effects of the noise. In contrast, few studies have carefully examined the role of autonomic reactivity in the noise-performance relationship, despite the acute stress (increased arousal) that can result from having to process sounds while performing complex, cognitive tasks. The Yerkes–Dodson law stipulates a relationship between sympathetic arousal and performance, such that on simple tasks, increasingly higher levels of arousal improve performance (Cohen 2011; Diamond et al. 2007; Yerkes and Dodson 1908). However, when completing more difficult tasks, an optimal level of arousal exists for peak performance (depicted as an inverted-U curve), whereby both under- and over-arousal may hurt performance relative to this optimal level.

While optimal levels of arousal vary from person to person, this level may shift more substantially for specific populations that exhibit differences in stimuli perception, autonomic arousal, and/or task performance. Noise is an example of a stimulus that could be processed differently, resulting in differences in autonomic reactivity and subsequently in performance. Indeed, the differential effects of noise on cognitive performance have been documented in specific populations, including in individuals with certain personality characteristics and sensory sensitivities (for a review, see Belojevic et al. 2003), low cognitive abilities (Cohen et al. 1980), and ADHD (Söderlund et al. 2007). In these populations, noise had a greater impact on performance than

Table 1 Participant characteristics

	ASD		TD		F or χ^2	p
	M (SD)	Range	M (SD)	Range		
n	25		21			
Gender (M:F)	23:2		19:2		0.03	.86
Age	14.2 (1.4)	12.0–16.7	14.8 (1.2)	12.4–16.9	2.38	.13
FSIQ	110.0 (13.2)	84–133	114.4 (12.9)	84–139	1.25	.27
VCI	114.0 (16.3)	87–138	117.5 (14.1)	87–138	0.57	.45
PRI	103.5 (12.2)	78–122	108.6 (12.6)	78–122	1.90	.18
SRS total T-score	79.6 (10.6)	61–95	40.9 (4.1)	34–49	189.78	<.001
ADOS CSS	6.24 (1.7)	3–9	1.06 (0.2)	1–2	165.9	<.001

ASD autism spectrum disorder, *TD* typically developing, *FSIQ* Full Scale IQ, *VCI* Verbal Comprehension Index, *PRI* Perceptual Reasoning Index, *SRS* Social Responsiveness Scale, *ADOS CSS* Autism Diagnostic Observation Schedule Calibrated Severity Score

in typically developing (TD) controls, which could be due to differences in sensory and cognitive processing abilities. In several past studies, individuals with ASD have demonstrated increased arousal to sensory stimuli, including noise (e.g., Chang et al. 2012; Woodard et al. 2012). Thus, it is particularly important to study specific populations, like ASD, for whom autonomic arousal may serve as a mechanism between consistent and substantial sensory processing differences and specific adaptive consequences.

Despite the pervasiveness of atypical sensory processing in ASD and the importance of achieving optimal environments for learning and workplace success, no study has examined the relationship between sensory stimuli and cognitive performance in this group. Furthermore, no study has examined how autonomic responding plays a role in the relationship between sensory experiences and cognition in ASD. Better understanding this relationship is a critical next step in ASD research, with implications for education, learning, workplace performance, and intervention development.

The Present Study

The present study utilized a multi-method approach to investigate the effect of noise on cognitive performance, and examine how autonomic responses may play a mechanistic role in this relationship. To do this, we experimentally manipulated noise level and task difficulty while concurrently collecting sympathetic responses, in adolescents with ASD and TD peers matched on age, IQ, and gender composition. Based on the potential for the inverted-U curve from the Yerkes–Dodson law to be shifted for individuals with ASD, we hypothesized that participants with ASD would exhibit differentially increased sympathetic arousal—as assessed by measuring heart beats per minute and skin conductance level (SCL)—to the noise stimulus (relative to their TD peers) and that this hyperresponsivity would be linked to decreases in cognitive performance. Specifically, we predicted that this effect would occur during the more difficult cognitive task paired with noise, where the task and perceptual demands were highest. In this condition, individuals with ASD would show both greater arousal and worse performance compared to their TD peers.

Methods

Participants

Twenty-five adolescents with ASD (23 male) and 21 TD adolescents (19 male) completed this study. Based on the stabilization of both the autonomic nervous system (Benevides and Lane 2015) and working memory abilities (Schneider and Pressley 2013) by early adolescence, all participants were recruited to be between the ages of 12–17 years. The ASD and TD groups were matched on mean age and gender composition (see Table 1). Because of the demands of the cognitive task used, eligibility criteria included a Full Scale IQ (FSIQ) > 80 for all participants, as measured by an abbreviated version of the age-appropriate Wechsler scale (Wechsler 2003, 2008). The groups were matched on FSIQ; there were also no group differences on their Verbal Comprehension or Perceptional Reasoning Index scores.

Diagnoses were confirmed in the ASD group using the Autism Diagnostic Observation Schedule (ADOS; Lord et al. 2008) and the Autism Diagnostic Interview-Revised (ADI-R; Rutter et al. 2003b), plus clinician judgment. Results were ruled out in the TD group using the ADOS and the Social Communication Questionnaire (SCQ; Rutter et al. 2003a), plus clinician judgment. Parents of participants in both groups also completed the Social Responsiveness Scale (Constantino and Gruber 2002) as an additional measure of ASD symptomatology. All TD participants did not have any behavioral, learning, or psychiatric diagnoses by parent report, or first- or second-degree relatives with an ASD diagnosis. Additional eligibility criteria for all participants included absence of any history of seizures, and absence of any genetic, neurological, cardiac, vascular, visual, or auditory abnormalities. Participants in the ASD group were not excluded based on psychiatric comorbidities or medication usage. In this group, based on parent report, three participants (12.5%) had a speech or language diagnosis, one participant (4.2%) had a learning disability diagnosis, eight participants (33.3%) had an ADHD diagnosis, seven participants (29.2%) had an anxiety diagnosis, and one participant (4.2%) had an OCD diagnosis. Twelve participants with ASD were currently taking psychotropic medications (treating inattention, anxiety, depression, or difficulties sleeping).

All participants' hearing was evaluated at the time of their visit using audiometry (Maico Diagnostics; Eden Prairie, MN) to establish normal clinical thresholds ($\leq$20 dB SPL for frequencies 0.5–4 kHz; and $\leq$25 dB SPL for 8 kHz). Close distance vision was also assessed at the visit using a pocket vision screener; all participants had corrected vision at or better than 20/30 in both eyes.

All procedures were approved by the university's institutional review board. Informed consent was obtained from parents and assent from participants before beginning study activities.

Measures

The current study assessed the relationship between noise, autonomic arousal, and performance through a 2 × 2 experimental manipulation of cognitive task difficulty (forward span vs. backward span) and noise level (quiet vs. 75 dB intermittent broadband noise).

Cognitive Task

Working memory was assessed using a visually presented number span task, which required remembering increasingly long strings of numbers. Number span tasks have minimal practice effects; therefore, multiple versions of each span allowed for multiple noise conditions (Beglinger et al. 2005; McCaffrey et al. 1992). Additionally, past research suggests that individuals with ASD perform comparably to TD children on standardized digit span tasks (Bennetto et al. 1996; Williams et al. 2006; for a review, see; Boucher et al. 2012). Evidence from age-normed cognitive tests indicates a stabilization of performance on aurally presented number span tasks across adolescence, with minimal changes in performance expected across the current study's age range (Wechsler 2003). Our task was presented visually (vs. aurally) to avoid potential decrements in auditory perception during background noise, which may be a particular problem in ASD (Alcántara et al. 2004). Finally, the span task was presented at an easy and a more difficult level. Specifically, remembering numbers in their presented order (forward span) was the easier level, and remembering numbers in backward order (backward span), which required greater mental manipulation and cognitive demands, was the more difficult level.

This task was presented using an original program written in Matlab 2013b (The MathWorks, Inc. 2013) for this study. Number spans were originally created using random number generation. Each span was then examined and was excluded if it contained the same number repeated more than twice in that span or if it contained rhyming numbers (e.g., five and nine) within a single span. All participants were presented with the same finalized spans. Numbers were presented in white (font size 54) on a black background on a 22-inch LED monitor approximately 24 inches from the participant. Each number was presented for 1000 ms with an interstimulus interval of 750 ms. After each trial was completed, a dot appeared on the screen, indicating to the participant that it was time to respond. In forward span, participants were asked to, "Repeat the numbers you see in the same order they are presented." In backward span, participants were asked to, "Say the numbers you see in reverse order." Practice trials were administered prior to both the forward and backward conditions. The actual task began after the participants successfully completed these practice trials and indicated that they understood the task. The span length began at two numbers for the first trial, and increased by one for each level to a possible maximum of ten. Each level contained three trials of the same length, and the task ended when a participant failed all trials within a level. Task stimuli were piloted before the study to determine the appropriate number of spans per level and appropriate range of span lengths for this age group. Participants completed four number span conditions, in the following fixed order: forward span in quiet, forward span with noise, backward span in quiet, backward span with noise. Total scores were calculated for each task by summing the number of correctly recalled spans.

The evaluator was in the room during the number span tasks to record the participant's responses and to advance the trials, but did not interact with the participant beyond what was directly necessary to progress through the task. The participant wore noise-cancelling headphones throughout each condition, which delivered the noise stimulus (on noise conditions) and minimized any ambient noise in the room.

Auditory Noise Stimulus

Intermittent-gated broadband noise presented at 75 dB was used as the background sensory stimulus during the noise conditions. The noise level and type was chosen to mimic the average volume and intermittent nature of noise in a typical classroom of children working and talking (Dockrell 2006;

Shield and Dockrell 2004). Social noise (e.g., a multi-talker speech stream) was specifically avoided in the current study to prevent potentially confounding influences of a social stimulus for participants with ASD. The noise was created using Praat software (Boersma 2002) by randomly mixing short periods of broadband noise and silence. Each moment of noise and silence ranged from 0.3 to 1.5 s. The noise was presented using noise-cancelling Sennheiser HDA200 headphones. The noise level delivered through the headphones was calibrated using the fast scale of a Quest Model 1900 sound level meter with a ½ inch B&K microphone.

Physiological Measurement

Non-invasive measures of sympathetic reactivity were collected continuously during each visit. All signals were collected and integrated using Biopac M150 hardware (Biopac Systems Inc., Goleta, CA) and Acqknowledge software (AcqKnowledge software, Biopac Systems, Santa Barbara, CA, USA). Sympathetic responses were collected using electrocardiogram (ECG) and electrodermal activity (EDA). A trained evaluator attached ECG electrodes in a Lead III configuration and reusable EDA sensors on the participant's non-dominant hand.

After acclimating, the participant sat quietly for a 5-min baseline recording, followed by continued collection throughout each of the four task conditions. Additionally, there was a 2-min recovery period following each of the four task conditions to prevent any carryover effects of arousal from one condition to the next. The evaluator was not in the room during recovery periods. A research assistant continuously monitored the incoming signals on a computer in an adjacent room; the examiner working with the participant was immediately notified if signals looked atypical, at which point adjustments were made to the physical sensors to improve signal collection.

Quantification of Autonomic Measurements

Following data collection, physiological signals were visually inspected for artifacts and were processed using Mindware software (HRV v3.0.21, EDA v3.021; Mindware Technologies, Gahanna, OH) by trained personnel. Consistent with standard practices, data were ensembled in 1-min segments (for a similar approach, see Jamieson et al. 2012). All R-points in the ECG signal (indicating left ventricle contraction) were detected by Mindware HRV software and were also visually examined to correct for noise artifacts and inaccurate placements when necessary. SCL, which captures the varying electrical properties of the skin's eccrine sweat glands, was averaged across task conditions and was used in analyses as a tonic measure of EDA. There is a strong empirical basis for studying physiological arousal as indexed by changes in SCL (Dawson et al. 2000), including clinical populations (Nock and Mendes 2008).

Importantly, because changes in other sensory stimuli (e.g., lights, tactile stimulation) from one condition to the next could influence autonomic arousal and performance, all sensory input was held constant across all conditions (apart from the presence of noise). This included having all participants wear the same noise cancelling headphones during all four task conditions.

Analysis Strategy

Statistical analyses were performed using SPSS version 24 (IBM Corporation). A series of 2 × 2 × 2 mixed-model analyses of variance (ANOVA) were used to examine the relationship between task difficulty, noise level, and research group. This strategy was used for both performance and physiological data.

The dependent variables used for performance were the total scores from forward span-quiet, forward span-noise, backward span-quiet, and backward span-noise. The dependent variables used for physiological data were heart rate and SCL. Simple effects were tested via paired *t* tests using the least significant difference (LSD) correction. Pearson correlations were used to investigate the relationship between the change in performance and change in sympathetic arousal from the quiet to noise conditions.

All participants completed the number span tasks, however three participants (6.5%) were missing a section of their heart rate data due to a faulty ECG connection. One of these participants was missing heart rate data from forward span-quiet, one from both backward span-quiet and backward span-noise, and another from backward span-noise. Four participants' SCL (8.7%) was unusable due to equipment problems. Several other participants (ASD = 8; 32%; TD = 3; 14%) were determined to be electrodermal non-responders, meaning that their SCLs and reactions were not measurable (baseline EDA signals < 1 υS and no reactivity to stimuli) due to differences in the functioning of their eccrine sweat glands[1]. Approximately 10% of the population are electrodermal non-responders, however rates in ASD have been estimated at 30% (Schoen et al. 2008). Little is known about electrodermal non-responding in ASD and future work should aim to explore the mechanisms by which this occurs and the potential physiological and behavioral consequences.

[1] Electrodermal non-responders were not significantly different than electrodermal responders on demographic or outcome variables.

Results

Study findings are presented below, beginning with the performance results on the span task across quiet and noise conditions. Next, heart rate and skin conductance analyses across these same quiet and noise conditions are presented. Finally, the relationship between the change in performance scores and in arousal levels from quiet to noise conditions is presented.

Cognitive Performance

The effect of difficulty level and noise on cognitive performance across groups was examined with a difficulty level (forward span, backward span) × noise level (quiet, noise) × group (ASD, TD) mixed model ANOVA. This predicted three-way interaction was not significant, $F(1,44)=0.01$, $p=.94$, $\eta_p^2<0.01$. Because of this unanticipated null finding, we conducted post-hoc Bayes factor analyses (Dienes 2008, 2014) to address potential concerns regarding the likelihood of this null effect in a larger sample. Bayes factor values less than 0.33 are indicative of evidence in favor of the null hypothesis. Values greater than 3.0 are indicative of evidence in favor of the alternative hypothesis. Values between 0.33 and 3.0 remain inconclusive based on the data (Lee and Wagenmakers 2014). We calculated the Bayes factor comparing the change in performance with the addition of noise in forward span and in backward span for each group. These analyses revealed a Bayes factor (BF) of 0.07 for forward span and 0.05 for backward span, which indicates that our data strongly support the null hypothesis, whereby there are no group differences in the influence of noise on performance for either difficulty level of the task. Other interactions involving group were similarly not significant: group × noise, $F(1,44)=0.24$, $p=.24$, $\eta_p^2=0.01$, and group × difficulty, $F(1,44)=0.93$, $p=.34$, $\eta_p^2=0.02$, indicating that the ASD and TD participants showed a similar pattern of performance across conditions.

Analyses did, however, reveal a main effect of difficulty, $F(1,44)=68.51$, $p\leq.001$, $\eta_p^2=0.61$. Across both groups, participants obtained higher scores in forward span than backward span, providing support for the task difficulty manipulation. There was also a main effect of group, $F(1,44)=4.25$, $p=.045$, $\eta_p^2=0.09$, with individuals with ASD performing slightly worse than their TD peers (see Fig. 1).

There was not a main effect of noise, $F(1,44)=0.18$, $p=.68$, $\eta_p^2=0.004$; however, there was a significant noise × difficulty interaction, $F(1,44)=11.80$, $p=.001$, $\eta_p^2=0.21$ (Fig. 1). Across both groups, noise improved performance in forward span, $t(45)=-3.24$, $p=.002$, and marginally worsened performance in backward span, $t(45)=1.94$, $p=.06$.

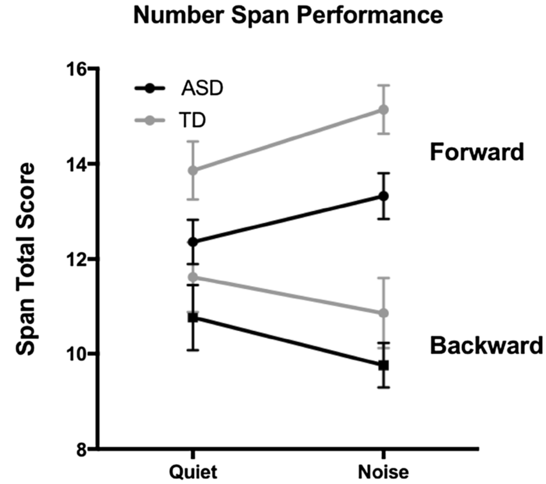

Fig. 1 Noise differentially affected performance based on task difficulty. Across groups, participants improved with the addition of noise on forward span ($p=.002$), and showed a marginal decrease in performance with the addition of noise on backward span ($p=.06$). All interactions involving group were non-significant

Physiological Arousal

Means and SDs for physiological measures during each condition are presented in Table 2.

Baseline

A preliminary one-way ANOVA revealed a marginally significant difference between groups in baseline heart rate, $F(1,44)=2.84$, $p=.10$, with the ASD group exhibiting a higher heart rate than the TD group. This marginal group difference was entered as a covariate in all subsequent heart rate analyses. Groups did not exhibit significantly different baseline levels of SCL, $F(1,29)=0.25$, $p=.62$.

Reactivity

Before analyzing reactivity, physiological data during recovery periods were compared to baseline levels to ensure that participants returned to homeostasis before beginning the next task. Paired t tests comparing each recovery to baseline were all non-significant (all $ps>.26$), suggesting no carry-over arousal effects from one condition to the next.

Physiological measures across cognitive conditions were then analyzed in a 2 (difficulty level) × 2 (noise level) × 2 (group) mixed-model ANOVA, with baseline heart rate entered as a covariate for all heart rate analyses. Results from

Table 2 Autonomic arousal during baseline and span conditions

	Baseline				Forward span-quiet				Forward span-noise				Backward span-quiet				Backward span-noise			
	ASD		TD		ASD		TD		ASD		TD		ASD		TD		ASD		TD	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
MHR	83.30	10.93	78.17	9.48	85.35	10.21	79.14	8.24	86.85	11.80	82.24	7.86	86.86	11.95	81.71	7.62	88.06	12.32	81.53	7.54
SCL	8.43	3.05	7.82	3.70	9.77	3.29	8.88	3.60	10.02	3.20	8.99	3.76	10.23	3.49	9.13	4.14	10.57	3.80	9.40	4.33

MHR mean heart rate (measured in beats per minute), *SCL* skin conductance level (measured in μS)

heart rate reactivity analyses revealed a significant three-way interaction, $F(1,40)=7.05$, $p=.01$, $\eta_p^2=0.15$ (see Fig. 2a). Follow-up analyses of simple effects showed that for forward span, both the ASD, $t(24)=-2.28$, $p=.03$, and TD group, $t(19)=-4.63$, $p<.001$, showed significant increases in heart rate with the addition of noise. However, in backward span, only the ASD group demonstrated continued increases in heart rate with the addition of noise, $t(22)=-2.38$, $p=.03$, while the TD group demonstrated no significant change, $t(20)=0.37$, $p=.71$. No main effects or two-way interactions were significant (all $ps \geq .16$).

We then examined SCL reactivity. Analyses indicated a significant main effect of difficulty level, $F(1,28)=8.40$, $p=.007$, $\eta_p^2=0.231$, with SCL lower in forward than backward span. There was also a significant main effect of noise, $F(1,28)=9.55$, $p<.004$, $\eta_p^2=0.25$, with SCL lower in the quiet than in the noise conditions. No interactions emerged (all $ps \geq .36$; see Fig. 2b). These analyses revealed a Bayes factor (BF) of 0.06 for the forward span interaction and 0.10 for the backward span interaction, which indicates that our data supports the null hypothesis, whereby there are no group differences in the influence of noise on SCL for either difficulty level of the task.

Relationship Between Physiological Arousal and Cognitive Performance

The relationship between the change in performance and the change in arousal across noise levels was directly examined using Pearson correlations. Performance change scores were calculated by subtracting the total score in quiet from the total score in noise (such that higher levels indicated better performance in noise relative to quiet). Arousal change scores were calculated by subtracting arousal (indexed via both heart rate and SCL) during quiet from arousal during noise (so that higher levels indicated more arousal during noise). When examining the effect of added noise, analyses revealed an association between increased arousal and increased performance on the easier task for the TD group only, and an association between increased arousal and decreased performance on the harder task for the ASD group only.

Heart Rate

Specifically, increased heart rate was associated with better performance on forward span when noise was added for the TD group only, $r(19)=.50$, $p=.03$. In the ASD group, however, increased heart rate was not related to performance on forward span, $r(23)=.03$, $p=.90$ (see Fig. 3a). The difference between these relationships was marginally significant when compared using Fisher's r-to-z transformation, $Z=-1.59$, $p=.06$. There was no relationship in either

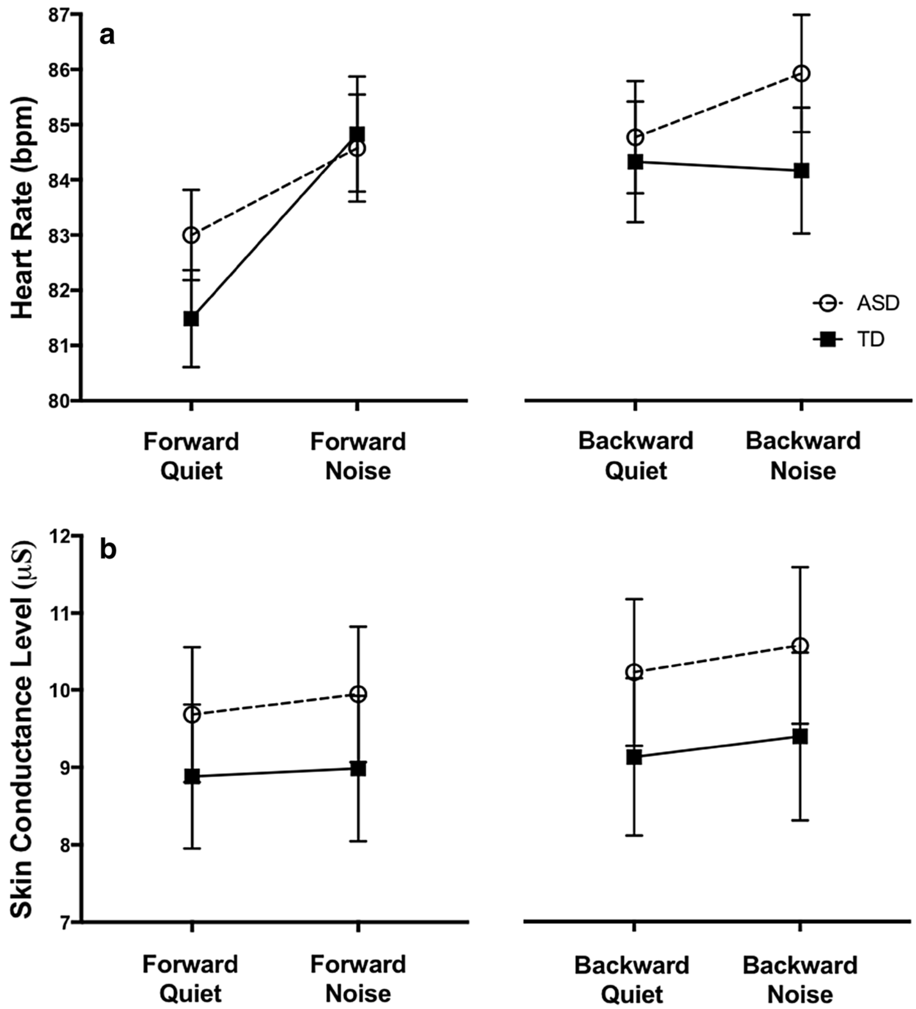

Fig. 2 Interactions of noise, difficulty level, and group depicted for heart rate and skin conductance level. **a** Heart rate analyses (controlling for baseline heart rate) indicate increased arousal across groups with the addition of noise in forward span, and a differential effect of arousal between groups in backward span. **b** Skin conductance analyses indicate significant main effects of difficulty and noise (supporting difficulty and noise manipulations), but no interactions with group

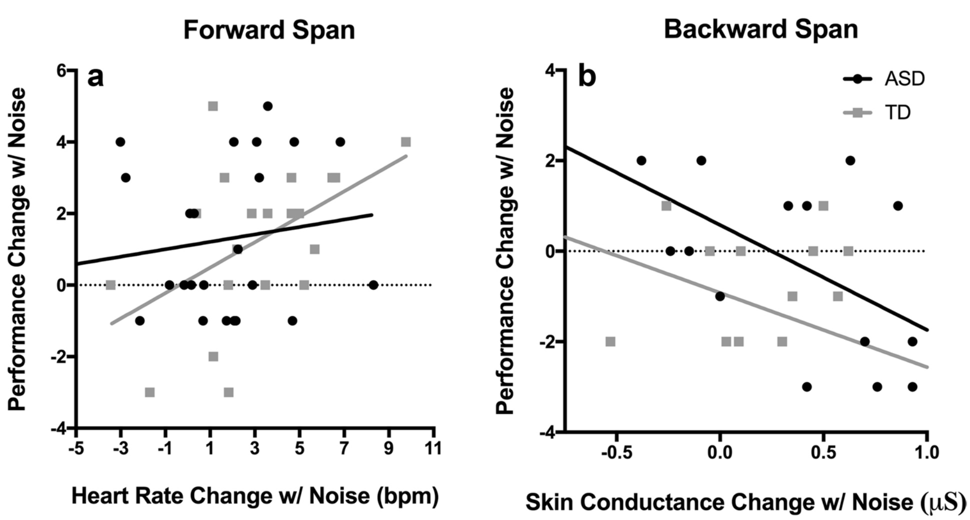

Fig. 3 Differential effects of arousal between groups based on task difficulty level. All axes represent the change score of the indicated variable (performance or arousal) from the quiet condition to the noise condition (i.e., noise value minus quiet value). **a** Change in heart rate with the addition of noise was related to improved performance from forward span-quiet to forward span-noise for the TD group only. **b** In the ASD group, change in skin conductance level with the addition of noise was related to decreased performance from backward span-quiet to backward span-noise

group between heart rate change and performance change in backward span, ASD: $r(21) = -.07$, $p = .76$, TD: $r(20) = .06$, $p = .80$.

Skin Conductance Level

A different pattern emerged for SCL, whereby increased SCL from quiet to noise conditions was related to significantly lower scores on backward span for the ASD group only, $r(14) = -.54$, $p = .04$. This detrimental effect of noise during the more difficult task was not significant in the TD group, $r(13) = -.37$, $p = .19$ (see Fig. 3b). The difference between these relationships was not significant when compared using Fisher's r-to-z transformation, $Z = -0.52$, $p = .30$. There was not a significant relationship between SCL change and performance change in forward span in either group, ASD: $r(15) = -.42$, $p = .12$, TD: $r(13) = .04$, $p = .89$.

Discussion

This study examined the relationship between sensory processing, arousal, and cognitive performance in adolescents with ASD and TD controls matched on age, gender, and Full Scale IQ. Results support a differential impact of noise on performance depending on task difficulty: all participants performed better in the easier condition and marginally worse in the more difficult condition paired with noise. Importantly, a differential impact of noise on autonomic reactivity emerged as a function of difficulty and ASD diagnosis. While both groups showed increases in heart rate with noise on the easier task, only those with ASD showed continued increases in heart rate with noise on the more difficult task. Furthermore, analyses identified a significant, *positive* relationship between arousal and performance under noise in the easier condition for the TD group, but a *negative* relationship been arousal and performance under noise in the more difficult condition for the ASD group.

Impact of Noise on Performance

Consistent with hypotheses, and the classic Yerkes–Dodson law (Yerkes and Dodson 1908), participants in both groups performed better with the addition of noise in the easier forward span task. This beneficial effect has been shown in past studies examining the impact of background noise on the performance of TD children and adolescents (for a review, see Erickson and Newman 2017). However, it has not previously been demonstrated in ASD. In fact, the majority of the existing literature on environmental noise and individuals with ASD focuses on hyperresponsivity to and avoidance of environmental noise. Importantly, the sensory literature in ASD almost exclusively views auditory hyperresponsivity as negatively impacting adaptive functioning (e.g., Ashburner et al. 2008; Suarez 2012) and, accordingly, recommends accommodations to limit noise exposure (e.g., Kanakri et al. 2017). The current results, however, suggest that individuals with ASD can experience a positive, energizing effect of predictable auditory stimulation during manageable tasks.

Based on the hyperresponsivity to noise seen in ASD, it was hypothesized that the Yerkes–Dodson law's inverted-U curve might shift for individuals with ASD such that the same objective level of noise would lead to higher arousal and subsequently more substantial decreases in performance compared to TD individuals. However, contrary to this notion, in the more difficult, backward span task, participants across *both* groups performed marginally worse with the addition of noise. This is consistent with the predicted downward slope portion of the inverted-U curve, but does not support a differentially greater impact of noise on *performance* for the ASD group. Thus, noise may not differentially worsen the performance of individuals with ASD compared to TD peers in all contexts, and particularly in controlled situations. Rather, a differential effect of noise on performance may occur with a more complex sensory stimulus and/or more difficult task.

Impact of Noise on Autonomic Arousal

Although we did not observe group differences in performance, autonomic response patterns did significantly diverge on the more difficult task, where only the ASD group demonstrated continued increases in heart rate with the addition of noise. As was hypothesized, this indicates that needing to manage background noise was a significant additional stressor, above and beyond the demands of the cognitive task, for the ASD group only.

These results may also suggest that the participants with ASD were capable of compensating for increases in sympathetic arousal during controlled and relatively straight-forward performance tasks. It is possible that by adolescence, these individuals, who had average or above average cognitive abilities, may have developed compensatory strategies to manage distressing sensory stimuli. Developmental trends in ASD suggest that sensory symptoms are most prevalent and severe earlier in development (Kern et al. 2006) and in individuals with higher levels of autistic symptoms (Ben-Sasson et al. 2009). It may be that the inverted-U curve is further shifted (requiring less noise for sub-optimal/diminished performance) in these specific sub-populations of ASD. While the present study's sample size, cross-sectional design, age range, and functioning level prevented us from examining developmental trajectories or patterns of responding within groups, it will be important for future studies to explore this.

Direct Relationships Between Arousal and Performance

Analyses examining the association between sympathetic arousal and performance, suggest that the TD group benefitted from increased arousal during this more manageable task. This beneficial effect was not present for individuals with ASD. Instead, higher arousal levels were associated with worse performance in noise on the more difficult task. Considering this pattern of results within the framework of the Yerkes–Dodson law, this would suggest that the combination of cognitive and sensory demands present on backward span with noise did not increase arousal levels enough to begin to negatively impact performance in the TD group. However, this pattern also suggests that, possibly due to a shifted inverted-U curve resulting from sensory sensitivity, the arousal levels in the ASD group were sufficiently elevated to be associated with worse performance.

While both of these relationships included sympathetic measures (heart rate and SCL), heart rate was associated with forward span performance, and skin conductance was associated with backward span performance. This pattern may be associated with possible differences in the psychological processes captured by these measures derived from different target organs. For instance, heart rate is often used to index task engagement (Blascovich 2013), but SCL has been more closely linked to attentional demands (Frith and Allen 1983; Kushki et al. 2013). It is also important to remember that there were many electrodermal non-responders in the current sample. While the proportion of non-responders in both the ASD and TD groups matches those found in other studies (Schoen et al. 2008) and there were no group differences in any study variables between responders and non-responders, it is possible that there are autonomic or behavioral features that are different in electrodermal non-responders. While we were unable to fully explore these differences in this study, it will be important to examine this in future research.

Our results, as well as the assumptions of the Yerkes–Dodson law (Cohen 2011), also suggest that the functional consequences of sensory dysfunction in ASD may become apparent when stimuli are more complex or overwhelming. Indeed, past research on the role of complexity in auditory processing concluded that individuals with ASD process simpler auditory input (e.g., a single pure tone) at comparable or superior levels to neurotypical individuals, but have a much more difficult time processing complex auditory information (e.g., multiple auditory stimuli at once, speech signals; for a review, see Samson et al. 2006). Additionally, past studies that used questionnaires to examine consequences of sensory dysfunction on daily life—where sensory environments and performance demands are exceedingly complex—have found significant, maladaptive effects (e.g., Ashburner et al. 2008; Baker et al. 2008; Lane et al. 2010). Similarly, a qualitative, interview study presented insights from adults with ASD about their experiences with complex auditory environments (Landon et al. 2016). For example, one participant from this interview study explained that noise is, "always an issue because it overloads you...all this stuff coming in at once and it's coming too fast for your brain to handle." Another participant shared her experience in a meeting, "there was music playing, people making coffee, people talking and so much noise and the lights were bright and there was just too much I couldn't concentrate." These experience along with the current data underscore the importance of investigating the complex nature of day-to-day experiences, and how these experiences are processed by individuals with ASD.

While it is clear that understanding the specific, functional impacts of *complex* sensory environments is needed, the current study provides important foundational information about this relationship using carefully controlled task and noise stimuli. However, to better approximate the performance demands of everyday life, it will be important to examine the impact of sensory stimuli on tasks that tap more complex forms of cognition and executive functioning (e.g., inhibitory control, dual-processing abilities, set-shifting abilities). For example, the task and sensory stimuli in the current study were presented in separate sensory modalities based on consistent findings that suggest that individuals with ASD are differentially impacted by the masking properties of sensory stimuli (i.e., detecting an auditory signal amongst background noise; e.g., Alcántara et al. 2004). However, it is common for multiple types of sensory stimuli (including those from the same sensory domain) to occur simultaneously in real-world environments. It is possible that, in addition to the masking effect of pairing target and interfering stimuli from the same sensory domain, this combination is more taxing on individuals with ASD, undermining their performance.

Furthermore, while the noise used in the current study mimicked the volume and intermittent nature of classroom noise, it was intentionally designed without speech sounds. While research in neurotypical populations suggests that speech sounds are more damaging to performance than non-speech sounds (Szalma and Hancock 2011), we did not include speech to avoid the potentially confounding nature of a social noise when studying this relationship in individuals with ASD for the first time. However, it will be important to determine the added impact of social noise on both performance and autonomic arousal given the social nature of many sensory environments in daily life.

Implications for Everyday Functioning

This work has important applications to educational and vocational settings. Our data suggest that it may be important to limit excessive background noise when students or employees are completing demanding tasks, particularly for individuals with ASD. Moreover, while the impact of noise on these more demanding tasks may not be directly apparent in an individual's performance, our study suggests that there are important, underlying physiological consequences of balancing sensory and task demands for individuals with ASD, which may have both behavioral and health-related implications.

Behaviorally, unmanaged stress in TD children and adolescents has been linked to increased risk of developing psychiatric diagnoses (e.g., depression and anxiety) and behavior problems, decreased school enjoyment and success, and worse social relationships (for reviews, see Compas et al. 2001; Lupien et al. 2009). In individuals with ASD, stress has been similarly linked to psychiatric comorbidities, social-communication challenges, and challenging behavior (for a review, see Baron 2006). Effects of unmanaged stress may also extend across the lifespan. For example, adults with ASD have consistently been found to be under-employed compared to their neurotypical peers, which is partially due to difficulties with sensory-related stress and lack of workplace accommodations (Van Wieren et al. 2008). Considering the results of the current study when creating and implementing appropriate accommodations may improve the experience of individuals in the workplace. Notably, many large companies, as well as the United States Department of Labor, have recently recognized the benefits of hiring neurodiverse individuals (including individuals with ASD) and are actively looking to adjust their recruitment processes and workplaces to best support employees with different needs (Austin and Pisano 2017; Bruyère 2017).

In addition to existing studies reporting increased sympathetic arousal in ASD (e.g., Chang et al. 2012; Kushki et al. 2013; Woodard et al. 2012), the current study found marginally higher heart rate at rest and significantly higher heart rate reactivity to a sensory stressor in the ASD group compared to the TD group. It is possible that higher baseline arousal measurements in individuals with ASD could result from sensory or social stressors specifically related to being in a laboratory. For example, individuals with ASD may be more sensitive to the tactile stimulation of the psychophysiological sensors. However, if this pattern of higher basal arousal and reactivity is present outside the laboratory as well, it may present potential long-term health risks for individuals with ASD. Over time, populations that have chronically elevated arousal or show increased and inefficient reactivity to stressors in their environment are likely to experience an allostatic load or "wear-and-tear" on the body (McEwen 1998), which has been linked to an increased risk for cardiovascular disease (Ho et al. 2014). Therefore, the increased arousal in ASD found in the current and previous studies should be addressed when possible to mitigate these immediate and future health risks as children with ASD age into adulthood.

One avenue to address autonomic dysregulation and reduce the impact of sensory difficulties on everyday functioning is to strengthen self- and emotion-regulation abilities in individuals with ASD. Notably, difficulty in emotion regulation in ASD has been linked to decreased participation in daily activities, including social peer-engagement and school participation (Jahromi et al. 2013). The paradigm used here is easily adaptable for testing self-regulation interventions in response to noise, as well as other sensory inputs (including multiple sensory inputs). These future studies may focus on improving recognition and communication of sensory stressors and arousal levels. Additionally, other prominent theories addressing stress and performance would suggest that self-regulation interventions could aim to help individuals reappraise situational demands and personal resources during overwhelming sensory experiences (please see Gross 2002; Jamieson et al. 2017 for reviews).

This study focused on daily, ever-present stimuli that impacts the ability of individuals with ASD to function in multiple settings throughout their lifetime. The results of the current study make several contributions to the ASD sensory literature by improving understanding of the relationship between sensory stimuli, autonomic arousal, and cognitive performance. The multi-method design of the current project also allowed for a novel understanding of this complex relationship with important implications for educational and workplace settings, as well as future research on the development and assessment of sensory and emotion regulation interventions in ASD.

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Author Contributions JMK conceived of the study, participated in its design, coordinated and ran all participant visits, performed data analyses, participated in data interpretation, and participated in writing the manuscript. LB participated in the design of the study, assisted with the recruitment and characterization of the participants, participated in the interpretation of results, and assisted in writing the manuscript. JPJ assisted in the design of the study, assisted with autonomic data collection and processing, participated in data interpretation, and assisted in writing the manuscript. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained for all individual participants included in the study.

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