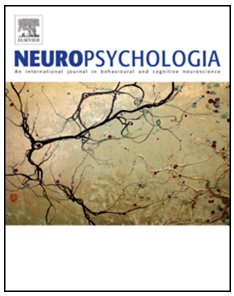

Multisensory integration and interactions across vision, hearing, and somatosensation in autism spectrum development and typical development

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Authors' contributions

The present study was designed by CDS, SMR, and YT. YT, IZ, SMR, and CDS contributed to data collection and processing. PD analyzed the data and drafted this manuscript, which was read, edited, and approved by all authors.

Multisensory Integration and Interactions across Vision, Hearing, and Somatosensation in Autism Spectrum Development and Typical Development

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Abstract

Most prior studies of multisensory integration (MSI) in autism have measured MSI in only a single combination of modalities – typically audiovisual integration. The present study used onset reaction times (RTs) and 125-channel electroencephalography (EEG) to examine different forms of bimodal and trimodal MSI based on combinations of auditory (noise burst), somatosensory (finger tap), and visual (flash) stimuli presented in a spatially-aligned manner using a custom desktop apparatus. A total of 36 autistic and 19 non-autistic adolescents between the ages of 11 – 14 participated. Significant RT multisensory facilitation relative to summed unisensory RT was observed in both groups, as were significant differences between summed unisensory and multisensory ERPs. Although the present study's statistical approach was not intended to test effect latencies, these interactions may have begun as early as ~45 ms, constituting "early" (<100 ms) MSI. RT and ERP measurements of MSI appeared independent of one another. Groups did not significantly differ in multisensory RT facilitation, but we found exploratory evidence of group differences in the magnitude of audiovisual interactions in ERPs. Future research should make greater efforts to explore MSI in under-represented populations, especially autistic people with intellectual disabilities and nonspeaking/minimally-verbal autistic people.

Keywords

Autism, ERPs, multisensory integration, audiovisual integration, audio-somatosensory integration, visuo-somatosensory integration

1. Introduction

Autism spectrum development (ASD)[1] is often conceptualized and assessed with a heavy focus on social-communication characteristics (see, e.g., Constantino et al., 2003; Lord et al., 2000; Timini et al., 2019), de-emphasizing sensory processing to the extent that a single sensory item was only added to the *DSM-5* diagnostic criteria for autism in 2013 (American Psychiatric Association). Despite this, there exists considerable evidence that autistic individuals often process and respond to sensory stimuli in an atypical manner (see review by Ben-Sasson et al., 2019). These differences in sensation and perception can manifest in different ways. For example, there is evidence that many autistic people experience sensory sensitivity and hyperacusis (Danesh et al., 2015; Khalfa et al., 2004; Rosenhan et al., 1999). Atypical sensory processing and perception can also be reflected in enhanced detail-oriented perception and reduced global integration (Booth & Happé, 2018; Mottron et al., 2006).

A number of studies (reviewed by Beker et al., 2018; Feldman et al., 2018; Meilleur et al. 2020; Zhang et al., 2019; Zhou et al., 2018) suggest that reduced integration of signals across

[1] Research indicates that few autistic individuals endorse the use of the terms "disorder" and "condition" to describe autism (Kenny et al., 2016). As these terms appear to reflect subjective value judgements, we chose to employ the more neutral term "development" (see Dwyer et al., 2022). Furthermore, there is controversy regarding whether identity-first (i.e., "autistic") or person-first (i.e., "person with autism") language should be used to describe autism (Bury et al., 2020; Kenny et al., 2016). In light of arguments that person-first language may reflect or accentuate stigma (Gernsbacher, 2017), we have chosen to use identity-first language.

sensory modalities such as vision, hearing, and touch – that is, reduced multisensory integration (MSI) – can be an aspect of atypical sensory processing in autism.

Reductions of MSI in ASD could emerge as early as infancy (Falck-Ytter et al., 2018), and reduced MSI in ASD might have a significant impact on social interaction and communication. In conversations, large amounts of information are simultaneously conveyed through multiple sensory modalities: speech and tone of voice (auditory) carry signals alongside lip movements and facial expressions (visual). Rapidly integrating these signals could help individuals better understand speech and other information, especially in fast-paced and noisy contexts. Reductions of MSI in ASD are related to characteristics of autism in the social-communication domain (Woynaroski et al., 2013) and to perception of speech in noise (Stevenson et al., 2018). Many autistic people appear to benefit less from visual information when attempting to perceive speech under noisy conditions (Foxe et al., 2015). Furthermore, some autistic people have aversions to touch (Jones et al., 2003; Robertson & Simmons, 2015); conceivably, reduced integration of tactile and visual inputs might make touch less predictable or more overwhelming, exacerbating these aversions. Indeed, it seems possible that reductions in MSI might, by reducing the degree to which multiple inputs are integrated into a single stimulus representation, contribute to autistic people's general susceptibility to sensory overload. Autistic accounts of sensory distress include descriptions of being overwhelmed by multiple inputs (MacLennan et al., 2021; Smith & Sharp, 2013). It is not clear that multisensory neural responses are associated with autistic sensory sensitivities (Brandwein et al., 2015), but children with sensory processing disorder do appear to exhibit atypical MSI (Molholm et al., 2020). Moreover, in extreme cases, autistic people with particularly low levels of MSI may be unable to

effectively process more than one sensory modality at a time (Bonneh et al., 2008; see also Jones et al., 2003), which could have widespread consequences for development and daily living.

1.1. Reaction Times (RTs) and the Race Model Inequality

MSI can be quantified using behavioural reaction times (RTs; Brandwein et al., 2013; Giard & Peronnet, 1999; Molholm et al., 2002). Admittedly, RTs to multisensory stimuli might be faster simply because having two independent, redundant unisensory signals might allow one of these signals to sometimes be processed more quickly by chance (the "race model inequality"). Consider: in a race where only a single runner from any team needs to reach the finish line for the team to win, a team with more runners will be more likely to win, even if the runners do not interact or support each other in any way. This "race model inequality" can be used to test whether RT facilitation is greater than expected from the redundant signals scenario (Miller, 1982; Gondan, 2010; Gondan & Minakata, 2016). If the cumulative probability distribution of RTs to multisensory stimuli exceeds the sum of the cumulative probability distributions of unisensory stimuli at any point, the "race model" can be said to be violated (Colonius & Diederich, 2006; Miller, 1982). Race model violation is taken to support a "coactivation model," in which cross-modal interactions and integration occur: that is, in which the stimuli from different modalities are not processed separately, but in which they interact and share common activations, leading to a faster response than could be expected simply due to chance and redundant signals (Miller, 1982).

1.2. Event-Related Potentials (ERPs)

Some studies suggest unisensory ERPs and event-related fields (ERFs) differ between autistic and non-autistic samples. For example, Williams and colleagues (2020) review the literature regarding auditory ERPs and ERFs in autism, reporting prolonged fronto-central auditory P1 latencies and reduced amplitudes of the temporal N1c/Tb and fronto-central N2

responses; amplitudes of the fronto-central N1b were only attenuated in studies of autistic individuals with co-occurring intellectual disabilities. Although relatively little research has examined ERPs and ERFs in the somatosensory modality, some prior studies variously suggest that somatosensory response latencies in ASD are either delayed (Demopoulos et al., 2017) or faster (Espenhahn et al., 2021) than those in TD; studies also suggest attenuated somatosensory response amplitudes (Marco et al., 2012; Russo et al., 2010) compared to TD. Similarly, some prior studies report that the amplitude of the visual P1 ERP is attenuated in autism (Boeschoten et al., 2007; Kovarski et al., 2019; Maekawa et al., 2011), which Kovarski and colleagues (2019) suggest could reflect elevated single-trial latency variability in ASD.

Although the majority of published studies of MSI in ASD are behavioural, some reports have used ERPs not only in the unisensory contexts described above but also to index brain responses to multisensory stimuli (e.g., Brandwein et al., 2013; Magnée et al., 2011; Russo et al., 2010; Stefano et al., 2020). If the sum of unisensory responses differs from multisensory responses, this may be evidence of cross-modal interactions: it would suggest the multisensory stimulus is not being processed as a simple additive combination of independent unisensory responses. The high temporal resolution of ERPs allows for examination of multisensory interactions at different stages of processing; this conveys additional information beyond that which is offered by a distribution of reaction times alone. Based on these studies, autistic people might exhibit, in comparison to typically-developing individuals, reduced neural multisensory interactions as early as ~90 ms post-stimulus onset (Brandwein et al., 2013).

However, examining MSI in ERPs and RTs together does present some difficulties. When unisensory ERPs are summed together, the electrophysiological correlates of multiple motor responses to stimuli are included and compared to a multimodal ERP that includes the

electrophysiological correlates of only a single motor response. Furthermore, electrophysiological correlates of motor responses might have faster latencies in multimodal conditions. Thus, motor responses and their electrophysiological correlates could confound ERP analyses of MSI at the latencies where they occur. This emphasizes the importance of ensuring that motor RTs are precisely measured so that ERP effects of different latencies can be understood in relation to potential motor confounds.

1.3. Trimodal Integration

Research conducted with general population adults has found evidence that of RT race model violation (e.g., Diederich & Colonius, 2004; Wang et al., 2013) and ERP cross-modal interactions (e.g., Sella et al., 2014) in trimodal audio-visual-somatosensory contexts, indicating that multisensory integration need not be limited to bimodal contexts. Some studies have employed designs aimed to demonstrate when multisensory integration is enhanced by the addition of a third stimulus modality (Diederich & Colonius, 2004), and there appear to be individual differences in trimodal integration: some individuals might benefit more than others from the addition of a third stimulus modality (Hagmann & Russo, 2016).

Prior studies of MSI at the group level in ASD have only examined integration in a bimodal context: typically, they have measured audiovisual integration. Although there may be larger effects in specific paradigms (e.g., McGurk effects, as reviewed by Zhang et al., 2019), overall ASD-TD group differences in audiovisual integration appear to be modest in size (as reviewed by Feldman et al., 2018). While other studies have examined other types of bimodal integration, such as visuo-somatosensory integration (Charbonneau et al., 2020; Greenfield et al., 2015), audio-somatosensory integration (Russo et al., 2010), and visuo-olfactory integration (Stickel et al., 2019), individual studies have not traditionally examined more than one or two forms of bimodal integration. Poole and colleagues (2021) examined effects of shifting attention

among three modalities (visual, auditory, tactile), finding that costs of shifting modalities were generally comparable between autistic and non-autistic adults. However, to the best of our knowledge, trimodal audio-visuo-somatosensory integration itself has not previously been investigated in ASD at the group level, nor for that matter in samples of children from the general population.

1.4. Present Study

The present study used both dense channel array electrophysiological recordings and manual RTs to investigate bimodal and trimodal MSI in cognitively-able autistic and non-autistic adolescents. We sampled participants from the relatively compact age range of 11-14 in order to minimize variance associated with developmental changes, including in the topography and latency of ERPs. ERPs and RTs were recorded from seven stimulus conditions: auditory (A), visual (V), somatosensory (S), audiovisual (AV), audio-somatosensory (AS), visuo-somatosensory (VS), and audiovisual-somatosensory (AVS). We formulated two hypotheses:

1. That unisensory auditory, somatosensory, and visual ERP responses would be attenuated in the ASD group relative to the non-autistic group;
2. That there would be a statistically reliable reduction in the magnitude of bimodal and trimodal multisensory facilitation and interactions in the ASD group compared to the non-autistic group;

2. Methods

2.1. Participants

Study procedures were approved by the UC Davis Institutional Review Board Administration. Participants were recruited through a mixture of community advertising and extant research contact databases, including the UC Davis Health MIND Institute Research Volunteer Registry. 36 autistic (33 male, 3 female) and 19 non-autistic participants (13 male, 6

155 female) provided usable data in the present study (Table 1). Note that one non-autistic and three
156 autistic participants were excluded from ERP analyses due to electrolyte bridging; only their RT
157 data are included in the present study. ERP and RT data were collected from a further three
158 autistic and two non-autistic participants, but excluded from the present study due to an
159 insufficient number of trials, technical problems with recordings, or not meeting eligibility
160 criteria. All participants were required to have Wechsler Intelligence Scale for Children-IV
161 (WISC-IV; Wechsler, 2003) Perceptual Reasoning Index (PRI) scores of at least 65, at-least-
162 typical hearing acuity, and at-least-typical or corrected-to- typical visual acuity. Autistic
163 participants were required to meet autism spectrum criteria per the Autism Diagnostic
164 Observation Schedule (ADOS; Lord et al., 2000) or "pervasive developmental disorder" criteria
165 per DSM-IV. Exclusion criteria included a history of non-febrile seizures or serious head
166 trauma, and use of antipsychotic or barbiturate medications. Exclusion criteria for the non-ASD
167 group included parent reports of a history of developmental, learning, or genetic conditions or
168 neurodivergence; first-degree genetic relatives with known autism spectrum diagnoses; and
169 positive results on autism screening tests.

Table 1. *Characteristics of autistic and non-autistic participants. Mean and standard deviation (SD) are given on each metric, along with minimum and maximum scores. The numbers of participants in each group with available data on each metric are also reported. Where continuous measures were collected from participants in both the ASD and* non-ASD *groups, t-tests are used to compare scores across groups; Cohen's d is reported as an effect size. Fisher's exact test is used to compare groups based on race/ethnic identities; Cramér's V is reported as an effect size.*
All ADI-R scores are based on the diagnostic algorithm. Note that ASD cut-offs are 15 on the SCQ total score, 4 on the ADOS Calibrated Severity Scores (CSS), 10 on the ADI-R Social Interaction score, 8 on the ADI-R Communication score (for verbal participants like those in the present study), and 3 on the ADI-R "Restricted and Repetitive Behaviors" score (Berument et al., 1999; Gotham et al., 2009; Lord et al., 1994). The developers of the ASSQ parent-report form recommend 13 as a sensitive cut-off score and 19 as a specific cut-off score (Ehlers et al., 1999).

	ASD	Non-ASD	*p*	d/V

	Mean (SD)	Range	*n*	Mean (SD)	Range	*n*		
Chronological Age (years)	12.80 (1.19)	11.07 – 14.97	36	13.06 (0.96)	11.57 – 14.73	19	.40	−0.23
WISC Full-Scale IQ (FSIQ)	101.33 (16.42)	65 – 125	36	121.58 (11.52)	91 – 139	19	<.0001	−1.36
WISC Verbal Comprehension Index (VCI)	104.64 (18.22)	61 – 134	36	126.16 (11.46)	99 – 152	19	<.0001	−1.32
WISC Perceptual Reasoning Index (PRI)	108.83 (15.75)	75 – 143	36	119.74 (15.79)	84 – 141	19	.02	−0.69
WISC Working Memory Index (WMI)	97.00 (13.41)	65 – 126	36	109.42 (10.11)	91 – 126	19	.0004	−1.00
WISC Processing Speed Index (PSI)	88.67 (14.50)	62 – 126	36	105.68 (10.60)	91 – 128	19	<.0001	−1.28
SCQ Total	22.06 (5.04)	11 – 31	33	1.16 (1.61)	0 – 5	19	<.0001	5.04
ASSQ Total	29.09 (8.81)	12 – 45	32	1.00 (1.80)	0 – 7	19	<.0001	3.96
ADOS Total CSS	6.29 (1.66)	3 – 10	34	—	—	0	—	—
ADOS Social Affect CSS	5.94 (2.00)	3 – 10	34	—	—	0	—	—
ADOS “Restricted and Repetitive Behaviors” CSS	7.00 (2.35)	1 – 10	34	—	—	0	—	—
ADI-R Social Interaction	20.73 (4.40)	13 – 30	33	—	—	0	—	—
ADI-R Communication	17.64 (4.00)	7 – 25	33	—	—	0	—	—
ADI-R “Restricted and Repetitive Behaviors”	7.73 (2.24)	4 – 12	33	—	—	0	—	—

Modified Edinburgh Inventory	51.46 (63.89)	–100 – +100	35	94.68 (6.17)	+80 – +100	19	.0003	−0.83
Race/Ethnicity	Non-Hispanic White (n=15) Hispanic/Latino (n=7) Multiracial (n=6) Asian (n=2) Black (n=1) Not reported (n=5)			Non-Hispanic White (n=13) Hispanic/Latino (n=1) Multiracial (n=1) Asian (n=1) Not reported (n=3)			.38	0.31

The WISC-IV PRI index was used as an inclusion criterion because it is based on subtests that are relatively independent of perceptuo-motor and timing demands (e.g., two of the three PRI subtests are untimed), which could make it a more valid estimate of fluid cognitive ability in ASD than other WISC-IV indices (Nader et al., 2015, 2016).

For 33 autistic and 18 non-autistic participants, hearing acuity was measured using an Otovation Amplitude T4 clinical audiometer (pure tone average < 20 dB HL in both ears) and visual acuity was assessed with a Titmuss T2S tester (acuity at least 20/40 in both eyes). Although the remaining participants (two non-autistic and three autistic participants) did not complete visual and/or hearing acuity testing, the caregivers reported no hearing or vision loss.

The autism spectrum diagnoses of 33 of 36 autistic participants were verified by clinical judgement and using the Autism Diagnostic Observation Schedule (ADOS) Modules 3 and 4 (Lord et al., 2000); all of these participants met “autism” or “autism spectrum” criteria per the revised algorithms published by Gotham et al. (2007) and Hus and Lord (2014). One further autistic participant did not meet ADOS criteria by a single point, but this participant did meet autism criteria per the ADI-R diagnostic algorithm and clinical judgement suggested that they met DSM-IV diagnostic criteria for a “pervasive developmental disorder.” The remaining two

autistic participants' diagnoses were supported by a recent (<1.25 years) external diagnostic evaluation that included administration of the ADOS.

The parent-report Social Communication Questionnaire (SCQ; Berument et al., 1999) and Autism Spectrum Screening Questionnaire (ASSQ; Ehlers et al., 1999) were used to screen non-autistic participants for autism.

Handedness was assessed using a modified self-report Edinburgh Inventory (Oldfield, 1971). This yields an index ranging from –100 to +100, or complete left- and right-handedness respectively. An inventory was unavailable from one participant, but this participant was reported to be right-handed by caregiver-report.[2] All non-autistic participants with inventories had positive scores (suggesting right-handedness), whereas eight autistic participants had scores of 0 or lower (suggesting ambidextrousness or left-handedness).

2.2. Procedure and Stimuli

Participants completed a speed response time task (responding to all events as quickly as possible) while they were seated in a dimly-lit, electrically shielded, audiometrically quiet testing chamber in front of a custom-built desktop apparatus capable of delivering visual, auditory, and somatosensory stimuli and recording motor button press responses to these stimuli (*Figure 1*). The desktop was designed to maximize spatial proximity between sensory modalities to facilitate multisensory binding. Stimulus intensities were adjusted to be subjectively roughly equivalent across modalities, based on judgement of study personnel and a small number of pilot participants.

[2] In analyses requiring covariation for handedness, this participant's scores were replaced by the average score for participants described as right-handed by their caregivers.

2.2.2. Visual Stimuli

Visual stimuli were 20 ms circular (4.4°) flashes with a luminance of 85 cd/m^2 and a 3:2 contrast ratio; they were generated by LEDs beneath a translucent circular opening in the desktop.

2.2.3. Auditory Stimuli

Auditory stimuli were 20 ms broadband noise bursts with speech-shaped spectra, selected to increase activation of lateral belt areas of the spatial auditory system (Maeder et al., 2001; Rauschecker & Tian, 2004), and delivered at 63 dB SPL intensity at participants' ears. Two loudspeakers (JBL GTO326) used to monophasically present auditory stimuli were positioned on either side of the visual stimulus location, such that auditory stimuli appeared to emanate from the same location as visual stimuli.

2.2.4. Somatosensory Stimuli

Somatosensory stimuli were 8 ms single mechanical taps (120 Hz cosine waves) delivered to participants' right index fingers by a Fosgate Punch car radio speaker enclosed in an acoustically shielded box, driven by a low-distortion audio signal using a Benchmark DAC1 digital-to-analog converter and Hafler Transnova amplifier whose extended low-frequency response eliminated overshoot and rebound (*Figure 2*). As a quiet thump could still be heard accompanying somatosensory stimuli despite the encapsulation of the speaker within a shielded box, a quiet low-frequency noise signal (peak power between 100 and 200 Hz) capable of masking this sound was continuously played in the background during the experiment.

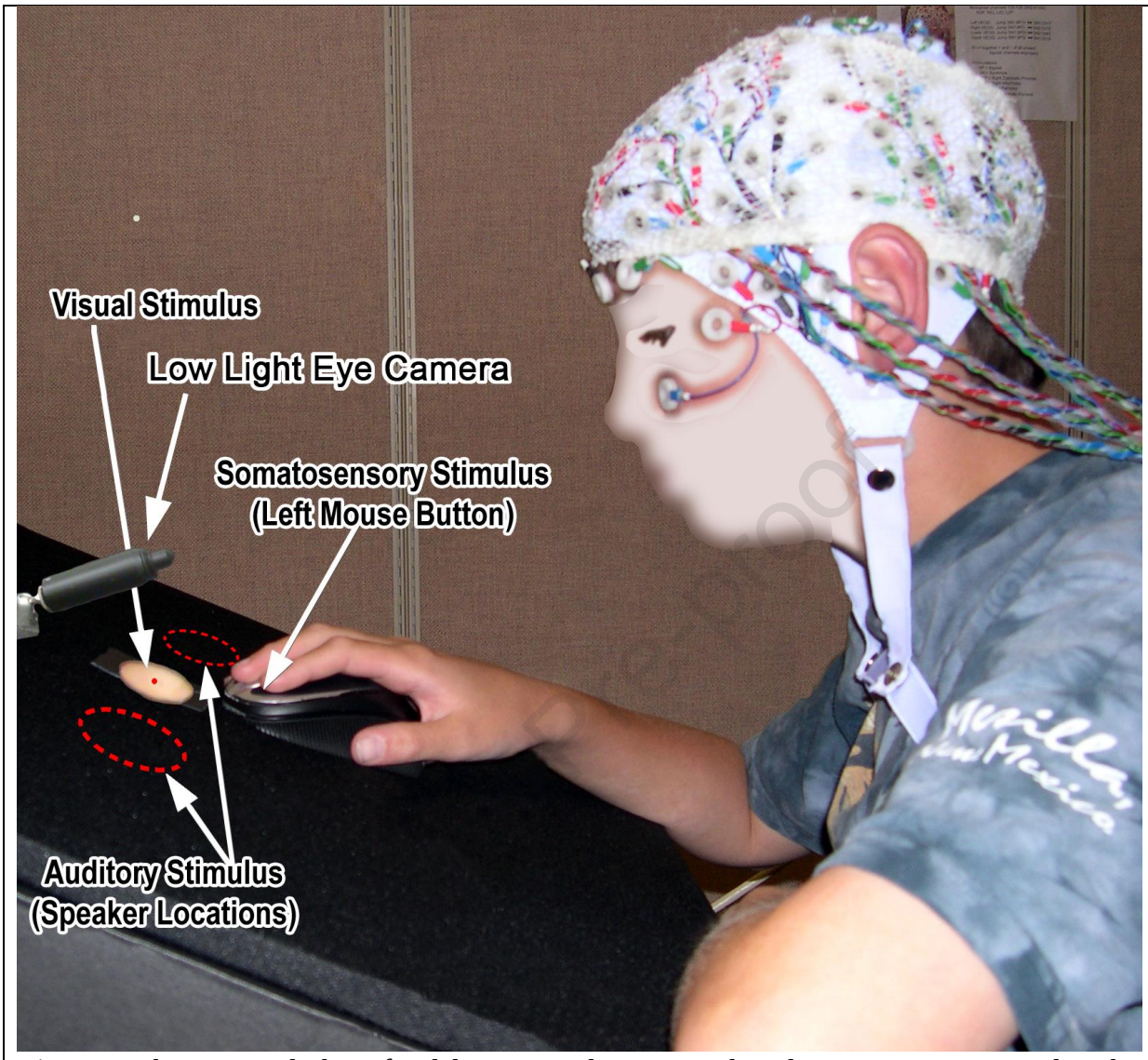

Figure 1. The custom desktop for delivering auditory, visual, and somatosensory stimuli. The apparatus includes a matrix of LED lights, covered by a neutral Plexiglas density filter and diffuser, for delivering visual stimuli. There are also two 8.9 cm monophasic speakers spatially aligned to deliver auditory stimuli in such a manner that they are perceived to originate from the same location as visual stimuli. A third speaker is coupled through a pressure transducer to the left button of a mouse, allowing the speaker to deliver somatosensory stimulation to participants' right index fingers resting on the mouse button. To eliminate any auditory stimulation associated with the operation of the somatosensory stimulator, the somatosensory speaker is housed in a soundproof enclosure and the mouse is filled with epoxy. A low-light camera is oriented towards participants' faces.

227

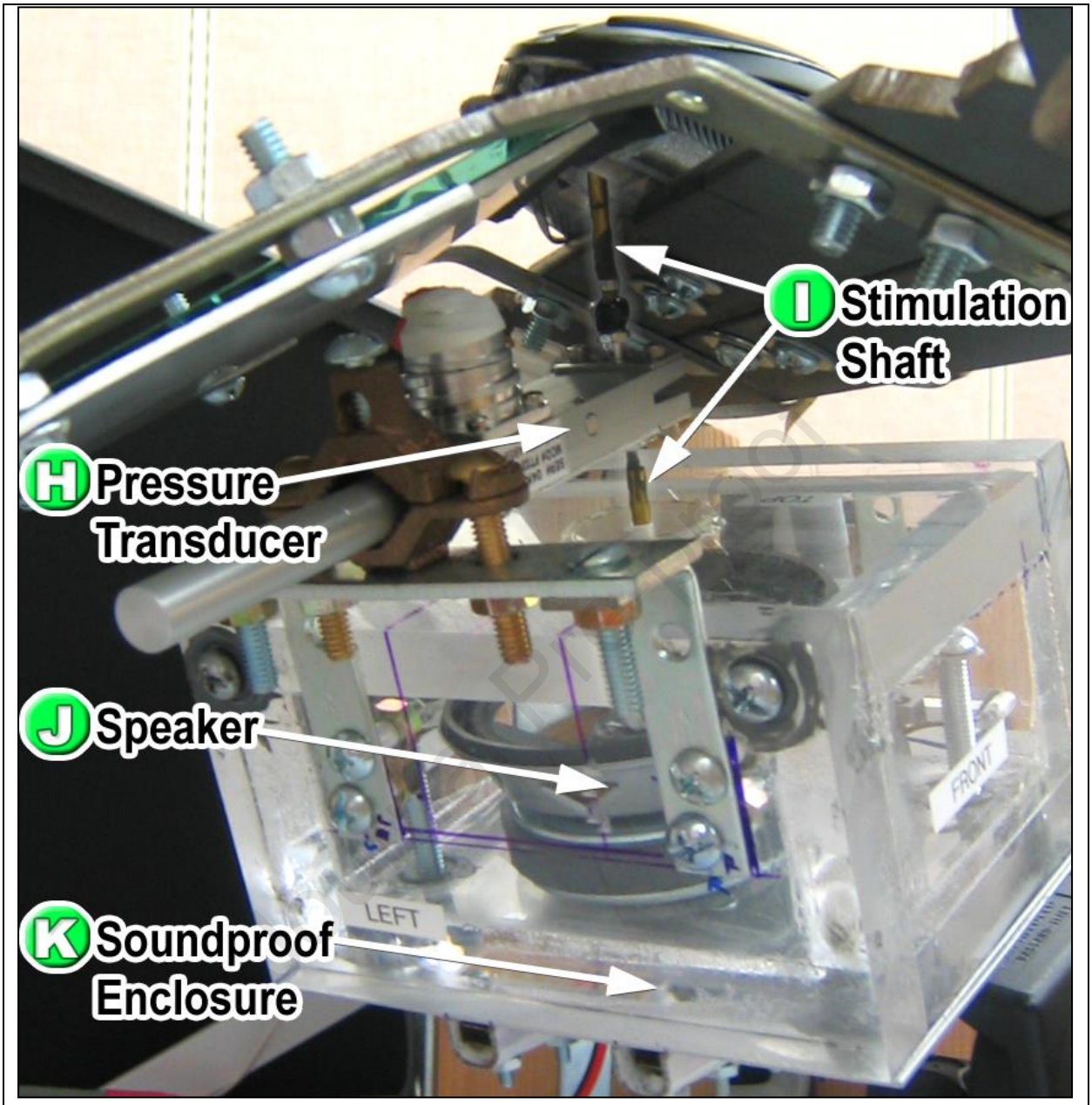

Figure 2. Close-up of the somatosensory stimulator sub-assembly. The speaker enclosed the acoustically shielded box mechanically delivers somatosensory stimuli to participants' right index fingers (positioned on the left button of the immobile mouse). The pressure transducer records participants' motor responses to the stimuli.

228

229 **2.2.5. Procedure**

230 Auditory (A), somatosensory (S), visual (V), audio-somatosensory (AS), audiovisual

231 (AV), visuo-somatosensory (VS), and audiovisual-somatosensory (AVS) were intermixed with a

random interstimulus interval of 1000 – 2250 ms (rectangular distribution). A total of 920 stimuli (~130 per condition) were presented in ten separate blocks; stimuli of all modality types were presented in a randomly intermixed manner within each block. Participants were asked to place their heads on a chin rest and fixate centrally (towards the perceived location of visual and auditory events), where a small red LED was continuously visible in the center of the circular translucent disc that briefly increased brightness with each visual stimulus. Fixation compliance was monitored using a low-light camera focused on the participants eyes. The experimenter in the recording chamber halted the delivery of stimuli when fixation was lost. Participants were instructed to respond to all events by pressing the left mouse button with their right index finger; this is the same button that was used to deliver somatosensory stimuli.

2.3. Reaction Time (RT) Data Acquisition and Processing

2.3.1. Reaction Time (RT) Data Acquisition

RTs in the present study were defined as the onset of motor responses using analog recording of the finger pressure on the left mouse button, rather than the point at which the response button became fully depressed. A Grass FT03 quartz strain-gauge pressure transducer measured the motor force exerted by participants (*Figure 3*). During recordings, the output of the force transducer via a Grass P22 amplifier was fed into a Coulbourn V21-10 window discriminator, which was adjusted for each participant to define a pressure window representing light finger pressure on the mouse button when the participant is resting their finger while waiting for the stimulus. A 20% increase in the output of the pressure transducer was set as the "too high" threshold, which corresponded to a slight increase in finger pressure. Thus, the resting finger pressure was maintained within a narrow window as the perceived somatosensory stimulus amplitude was partly a function of the resting finger pressure. If the participant lifted their finger off the mouse or applied too much pressure to the mouse, the experiment stopped

256 automatically until the resting finger pressure was reinstated. This procedure aimed to reduce
257 the variability of RT and ERP responses related to variations in the perceived amplitude of tactile
258 stimulus. Too light, in-range, and excessive pressure were indicated via a light box visible to the
259 experimenter sitting with the child in enable guidance for achieving in-range finger pressure. The
260 output of the P22 amplifier was digitized at 1kHz along with the EEG and EOG signals.

261 **2.3.2. Reaction Time (RT) Data Processing**

262 The time from stimulus onset to initiation of manual response (right index finger press)
263 was recorded to the nearest ms based on thresholding the output of the pressure transducer.
264 Using BESA 5.3 (www.besa.de) transducer waveform epochs from -200 to +800 ms were
265 baseline corrected from -200 to 0 ms, rectified, differentiated, and a threshold (150 mv) set using
266 the Schmitt trigger function in BESA that reliably created a response event code within ~20 ms
267 of the earliest sign of movement onset (approximately 0.5% of full depression of the button;
268 *Figure 3*). Individual trial RTs were determined from the session event file by calculating to the
269 nearest ms the latency from each stimulus type trigger to the associated response trigger. All
270 generated triggers were then manually inspected and occasional spurious or double triggers were
271 eliminated. To enhance comparability of ERP and RT results, RTs were only extracted from
272 trials with usable ERP data (see Table 2 below). Likewise, single trials with no identifiable
273 behavioural response were removed from the ERP data.

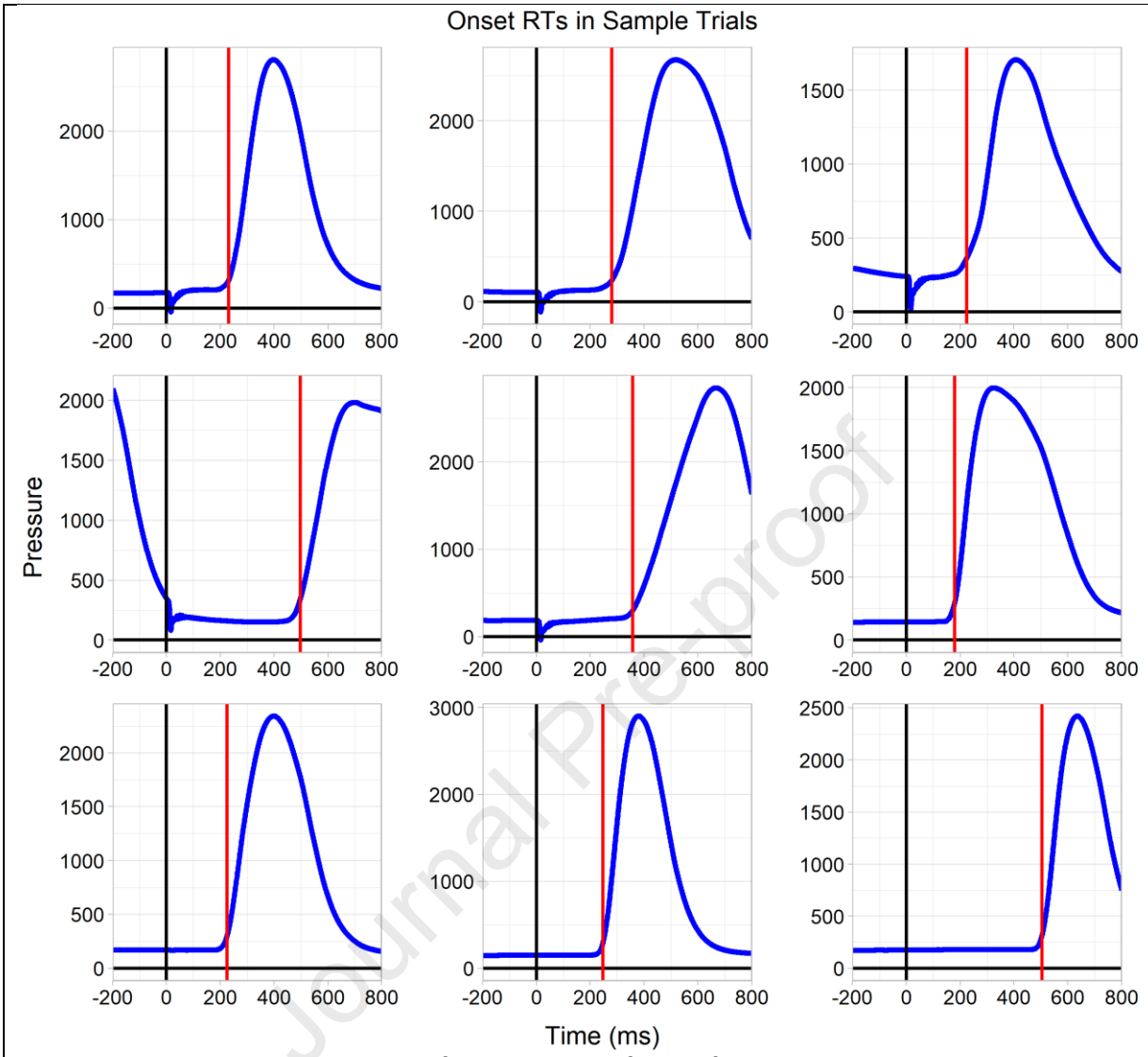

Figure 3. Pressure transducer data from a subset of trials from a single participant. Onset RTs, as measured by the Schmitt trigger generator in BESA 5.3, are indicated by red lines. Note that it is possible in some trials (from the top left, numbers 1-5) to observe a small dip in pressure caused by the delivery of the mechanical somatosensory stimulus to participant's index fingers. Note also that there is some variability in motor acceleration across trials, as well as variability in peak force, such that the difference between onset and peak RTs varies from trial to trial.

2.4. EEG Data Acquisition and Processing

2.4.1. EEG Data Acquisition

Continuous EEG was recorded from 125 Ag/AgCl scalp electrodes in an equidistant montage (www.easycap.de) and digitized at 1000 Hz using a Compumedics Neuroscan Synamp2

acquisition system with Cz as a reference. Three-dimensional electrode locations for each individual participant relative to bony fiducials were obtained using a Polhemus Patriot magnetic field-based 3D digitizer. Eye movements and blinks were monitored using horizontal and vertical EOG.

2.4.2. EEG Data Processing

Data were then imported into BESA Research 5.3, low-cut filtered (0.4 Hz, forward causal, 6 dB/oct roll-off), epoched (-200 ms to +1100 ms), and average-referenced. Trials with extreme amplitudes, trials with EOG events between -200 ms and +400 ms, and trials lacking behavioural responses were removed; bad channels were likewise removed. The remaining data were then entered into a second-order blind source identification (SOBI) independent components analysis using custom MATLAB code (Saggar et al., 2012). On the basis of visualizations described by Saggar et al., as well as channel-by-channel, trial-by-trial time series, components were manually classified as putatively of non-neural or neural origin. Putatively neural components were then reconstructed with epochs spanning -200 to +800 ms. Averages were generated for each condition. The averaged data were exported to CARTOOL (Brunet et al., 2011) and inspected for electrolyte bridging and any further bad channels; all bad channels were interpolated via 3-dimensional spline (Perrin et al., 1987). ERPLAB (Lopez-Calderon & Luck, 2014) was used to apply high-cut filters (50 Hz Butterworth, zero-phase, 24 dB/oct) and to apply a baseline correction using the 100 ms prior to stimulus onset. Finally, in Fieldtrip (Oostenveld et al., 2011), the current source density (CSD) was extracted using a fourth-order spherical spline with lambda (smoothing constant) set to 1.0×10^{-6}.

CSD reflects the continuous rate of change in the rate of change of ERP voltages across electrode sites (see review by Kayser & Tenke, 2015). Because the rate of change or slope of ERP voltages across neighbouring electrode sites would not be affected by the subtraction of a

constant from each site, the CSD is a reference-independent metric; for the same reason, the CSD of a difference of two ERPs is equivalent to the difference between two CSD ERPs. Furthermore, transforming ERP voltages to CSD reduces spatial smearing associated with the passive spread of current through the scalp; CSD scalp topographies are more focal than voltage topographies, allowing for clearer differentiation of different responses. This arguably has a particular value in a multisensory context such as the present study, where responses to multiple stimuli in separate sensory modalities are sometimes simultaneously summating over the scalp.

Counts of usable ERP and RT trials, and of trials eliminated during data processing, are presented by diagnostic group and modality condition in Table 2. There were trends for autistic participants to have fewer retained and more rejected trials than non-autistic participants, and the difference in retained trial counts reached significance in two conditions, while that in rejected trial counts reached significance in one. As signal-to-noise ratio (SNR) increases approximately in proportion to the square root of the number of trials (Luck, 2014), the average counts of usable trials in each group imply that ERP SNR in the ASD group should be approximately ~95% of that in the non-ASD group.

Table 2. *Total counts of retained and rejected trials in both ERPs and RTs by diagnostic group and modality. Mean counts and standard deviations are given, the latter in brackets, along with ranges. T-tests are used to compare totals across groups; Cohen's d is reported as an effect size. Note that the table includes trial counts from the four participants whose ERP data are excluded in the present study due to electrolyte bridging, as their RT data were retained.*

	Retained Trials						Rejected Trials					
	ASD		Non-ASD		*p*	d	ASD		Non-ASD		*p*	d
	Mean (SD)	Range	Mean (SD)	Range			Mean (SD)	Range	Mean (SD)	Mean (SD)		
A	88.22 (21.18)	48 – 132	99.05 (21.14)	49 – 134	.08	−0.51	40.78 (20.98)	5 – 81	32.32 (20.36)	6 – 76	.16	0.41
S	87.83 (21.28)	53 – 128	99.32 (15.07)	71 – 124	.02	−0.59	41.58 (22.41)	10 – 82	30.58 (17.30)	10 – 69	<.05	0.53
V	91.53 (24.60)	49 – 137	104.37 (23.51)	50 – 135	.07	−0.53	37.33 (20.73)	8 – 76	28.21 (16.58)	10 – 68	.08	0.47
AS	89.08 (24.05)	43 – 130	99.63 (20.77)	54 – 126	.10	−0.46	39.44 (22.04)	6 – 91	32.79 (24.10)	8 – 90	.32	0.29
AV	95.22 (22.82)	42 – 144	96.58 (24.89)	42 – 135	.84	−0.06	36.44 (19.56)	10 – 93	30.11 (21.76)	4 – 85	.30	0.31
VS	92.14 (23.08)	51 – 129	104.79 (20.89)	54 – 140	<.05	−0.57	36.89 (19.85)	8 – 72	28.89 (19.39)	10 – 77	.16	0.41
AVS	91.28 (21.50)	50 – 129	103.37 (23.25)	42 – 130	.07	−0.55	37.44 (19.88)	8 – 81	30.47 (21.54)	5 – 86	.25	0.34
Total	635.31 (144.78)	369 – 842	707.11 (136.51)	392 – 848	.08	−0.51	269.92 (136.74)	78 – 551	213.37 (135.76)	72 – 528	.15	0.41

2.5. RT Analyses

2.5.1. Raw RTs.

Among those trials retained for RT analyses, any trials more than four median absolute deviations away from a participant's median RT in each condition were defined as outliers and excluded; these outliers were an average of 6.46% of retained trials in the ASD group and 5.41% in the non-ASD group, percentages which did not significantly differ, t=1.46, p = .15, d=0.38. Median RTs from each participant were then calculated from the cleaned dataset within each modality condition were compared between the ASD and non-ASD groups using *t*-tests. An additional comparison of median RTs across groups was also conducted without outlier removal (Appendix A, Table A.1).

2.5.2. Within-Group Race Model Analyses.

Reaction time analyses were conducted to determine whether race model violation occurred in each group and to determine whether the magnitude of RT facilitation differed between groups.

To test the race model inequality within groups, we adapted the R script for one-tailed permutation paired t-tests published by Gondan and Minakata (2016). These race models involve comparing the summed probability distributions of RTs (that is, the summed cumulative proportions of RTs falling within or below consecutive quantile bins) in response to unimodal stimuli to the cumulative probability distribution for multimodal stimuli. If the probability distribution for multimodal stimuli significantly exceeds the sum of the cumulative unimodal distributions at any point, it is possible to conclude that multisensory facilitation of RTs occurred. That is, it would indicate that the speeding of multisensory RTs was greater than could be expected simply from having two redundant but independent signals (one of which might be slightly faster from chance alone). This is frequently expressed using bimodal (1, 2, 3) and

trimodal (4) equations of the following form, with $F_X(t)$ denoting the cumulative probability distribution of modality X:

(1) $F_{AS}(t) \leq F_A(t) + F_S(t)$

(2) $F_{AV}(t) \leq F_A(t) + F_V(t)$

(3) $F_{VS}(t) \leq F_V(t) + F_S(t)$

(4) $F_{AVS}(t) \leq F_A(t) + F_S(t) + F_V(t)$

In the permutation tests used to test these four race models, we examined the cumulative probability distributions in the first eight of twenty quantiles (i.e., 5% through 40%). The *maximum* t-statistic from any of these quantiles (not the *sum* statistic) was compared to a permutation distribution of 10001 maximum t-statistics.

2.5.3. Between-Group RT Facilitation Comparisons.

The magnitude of RT facilitation was compared between the ASD and non-ASD groups, separately for each of the four race models presented above, by taking the difference between the multimodal and sum probability distributions (representing the extent of race model violation). The R permutation test script published by Gondan and Minakata (2016) was adapted to compare the magnitude of these differences between groups using two-tailed independent-samples t-tests. In the first eight of twenty quantiles (i.e., 5% through 40%), the maximum absolute value of the t-statistic was compared to a permutation distribution created by randomly re-allocating participants to groups 10001 times.

In addition, due to group differences in WISC scores and handedness (see Table 1), a variant of the same permutation test using ANCOVA to covary for Perceptual Reasoning Index (PRI) scores and Edinburgh Handedness Inventory scores was also employed. The single participant lacking Edinburgh Inventory scores – who was described as right-handed by

caregiver-report – was assigned the average Edinburgh Inventory score of right-handed participants, in order to provide complete data.

2.5.4. Additional Exploratory Analyses.

In order to contextualize ANCOVA analyses by describing any associations between multisensory facilitation of RTs and WISC PRI, permutation tests using ordinal and linear correlation coefficients were conducted in supplementary materials (see Appendix A, Table A.2).

Additionally, we examined whether the magnitude of multisensory RT facilitation between any given combination of modalities was associated with the magnitude of RT facilitation in other combinations of modalities (Appendix A, Tables A.3-A.4).

2.6. ERP Analyses

2.6.1. Unisensory Responses.

To compare unisensory ERPs across groups, we used cluster-based permutation independent-samples *t*-tests (see Maris & Oostenveld, 2007). The cluster-based permutation test differs from the maximum-based permutation tests employed with our RT data in that it uses a summed cluster statistic, rather than the maximum statistic. Specifically, parametric tests were used to initially establish whether effects at any channel or time-point (in our analysis, between 40 – 200 ms) attained initial statistical significance at a given alpha level (in our analyses, .05, two-tailed). If an initially-significant channel was spatially and temporally adjacent to a given number of (in our analyses, two) other initially-significant channels, these channels were grouped together to form a "cluster." The *t*-tests from all the spatiotemporally contiguous data points falling within a cluster were then summed, and these sums were compared to a distribution of summed cluster statistics based on a given number of (in our analyses, 10,000) permutations to determine the final statistical significance of effects.

The 40 – 200 ms analysis time window was chosen due to its relevance to multisensory interactions: prior research using ERPs suggest the earliest multisensory interactions in non-ASD adults can begin around or shortly after 40 ms (reviewed by De Meo et al., 2015), while apparent multisensory interactions that in reality most likely reflect motor responses can be observed in the present study data following 200 ms (see *Figure 8* below).

Note that the exact spatial and temporal boundaries of cluster-based permutation effects cannot be strongly interpreted (Maris & Oostenveld, 2007; Sassenhagen & Draschkow). The tests are subject to threshold effects, and it is (for example) possible that a true effect outside the cluster boundaries failed to attain the initial significance needed for cluster inclusion, or that a fluke extended the boundaries of the cluster beyond the boundaries of the true effect.

2.6.2. Multisensory Interactions and Integration.

For within-groups analyses to determine whether significant multisensory interactions occurred between 40 – 200 ms, we used dependent-samples cluster-based permutation t-tests with 10,000 permutations each. Similarly to the approach taken in the RT equations, bimodal and trimodal CSD waveforms were compared to corresponding sums of unimodal CSD waveforms. Statistical differences between summed unimodal and multimodal responses would suggest that the stimuli are processed differently when they are presented together, or that the sensory modalities interact.

For between-group comparisons, difference waves between these multimodal CSD waveforms and the corresponding sums and differences of unimodal and/or bimodal CSD waveforms were obtained in each group for the 40 – 200 ms postimulus period:

(5) $AS - (A + S)$

(6) $AV - (A + V)$

(7) $VS - (V + S)$

(8) $AVS - (A + S + V)$

These difference waves were then compared across groups using independent-samples permutation *t*-tests with 10,000 permutations each.

Furthermore, we conducted group comparisons using ANCOVA to covary for WISC PRI scores, for Edinburgh Inventory scores, and for RTs. Averages of each participant's median RTs from each experimental condition included in a given difference wave (e.g., for AV integration, raw median RTs from the A, V, and AV conditions are averaged together) were used as the RT metric. Due to computational limitations, only 1,000 permutations were used in ANCOVA analyses.

2.6.3. Additional Exploratory Analyses.

To contextualize ANCOVA analyses by describing any associations between ERP multisensory interactions and WISC PRI scores, permutation tests using ordinal Spearman's ρ and linear Pearson's *r* correlation coefficients were conducted in supplementary materials (see Appendix A, Table A.5). Similar analyses were also carried out for Edinburgh Handedness Inventory scores (Appendix A, Table A.6) and raw RTs (Appendix A, Table A.7).

As a further control for handedness, ERP analyses of multisensory integration within groups and comparing the extent of multisensory interactions across groups were repeated only among right-handed participants (Appendix A, Table A.8).

Finally, we used cluster-based permutation ordinal Spearman's ρ and linear Pearson's *r* tests to examine the correlations between multisensory ERP difference waves in each group and the extent of RT facilitation. This analysis is presented in Appendix A (Table A.9).

3. Results

3.1. Raw RTs.

Summary statistics related to the median onset RTs of participants in each group are displayed in Table 3. RTs onsets were strikingly fast, with some participants displaying median RT onsets as low as ~140-150 ms in some conditions. Results of inferential tests comparing RTs between the two groups, after outlier removal, did not approach significance. This pattern of results was strikingly similar to that obtained without removing outliers (Appendix A, Table A.1).

Table 3. *Means, standard deviations, and ranges of median RTs (in ms) from participants in each group and modality condition, along with results of* t*-tests comparing them. Cohen's d is reported as an effect size.*

	ASD		Non-ASD		*p*	d
	Mean (SD)	Range	Mean (SD)	Range		
A	242.65 (56.75)	153.00 – 360.00	230.92 (44.07)	174.00 – 325.50	.40	0.22
S	286.24 (70.73)	191.50 – 408.50	257.68 (52.56)	178.50 – 373.50	.10	0.44
V	290.01 (57.85)	189.00 – 404.00	275.32 (48.74)	210.50 – 382.00	.33	0.27
AS	223.36 (62.52)	152.50 – 374.00	205.42 (43.66)	152.00 – 311.50	.22	0.32
AV	230.61 (56.61)	151.00 – 361.00	211.97 (44.81)	155.00 – 306.00	.19	0.35
VS	245.72 (59.02)	171.00 – 359.00	229.55 (44.02)	172.00 – 318.50	.26	0.30
AVS	215.97 (58.69)	148.00 – 358.50	194.74 (40.45)	137.50 – 283.00	.12	0.40

3.2. RT Facilitation.

3.2.1. Within-Group Analyses.

Using maximum-based permutation paired *t*-tests, clear evidence of race model violation was observed in each group (Table 4). Specifically, in non-autistic participants, there was evidence of significant audio-somatosensory, $p = .03$, and trimodal, $p = .006$, RT facilitation relative to unimodal conditions. In the ASD group, there was significant evidence of visuo-somatosensory and trimodal facilitation, both $p = .03$. There were also strong but nonsignificant trends towards audio-somatosensory facilitation in ASD, $p = .06$, and towards audiovisual facilitation in non-ASD participants, $p = .09$.

Table 4. *Results of permutation tests examining whether race model violation occurred in each group, along with results of permutation tests comparing the magnitude of RT facilitation across groups. P-values are given in the left column within each modality combination, while the maximum effect sizes (partial η^2 or absolute values of Cohen's d, as applicable) observed in any of the examined RT quantiles (i.e., 5% through 40%) are provided to the right within each modality combination.*

Analysis		Modalities							
		AS		AV		VS		AVS	
		p	d/η_p^2	*p*	d/η_p^2	*p*	d/η_p^2	*p*	d/η_p^2
ASD	Race model violation (permutation paired *t*-test one-tailed *p*-values, along with maximum positive value of Cohen's d effect size)	.06	0.36	.22	0.24	.03*	0.44	.03*	0.42
Non-ASD	Race model violation (permutation paired *t*-test one-tailed *p*-values, along with maximum positive value of Cohen's d effect size)	.03*	0.64	.09	0.46	.16	0.40	.006**	0.84
Group Comparison	Permutation independent samples *t*-test two-tailed *p*-values, along with maximum absolute value of Cohen's d effect size	.83	0.20	.07	0.63	.67	0.28	.07	0.59
	Permutation ANCOVA *p*-values, covarying for WISC PRI (cognitive ability) and Edinburgh Inventory (handedness), along with maximum partial eta squared effect size	.92	.007	.18	.069	.58	.027	.19	.064

Single asterisk (*) indicates $p < .05$ and double asterisks (**) indicates $p < .01$, uncorrected.

3.2.2. Between-Group Analyses.

There was no significant evidence of group differences in multisensory RT facilitation. Per maximum-based permutation *t*-tests, the extent of audiovisual facilitation trended towards being greater in the non-ASD group than ASD, $p = .07$ (*Figures 4B, 5B*; see also Appendix A, *Figures A.1B-A.4B*), even though audiovisual race model violation did not attain significance in either group. Similarly, there was a trend towards group differences in trimodal facilitation, $p = .07$ (*Figures 4D, 5D*; see also Appendix A, *Figures A.1D-A.4D)*. However, after using maximum-based permutation ANCOVA to covary for cognitive ability and handedness, neither effect approached significance, audiovisual $p = .18$, trimodal $p = .19$. Neither linear nor ordinal permutation associations between the magnitude of race model violation and either covariate attained significance, although there were some slight trends involving cognitive ability in ASD (Appendix A, Table A.2).

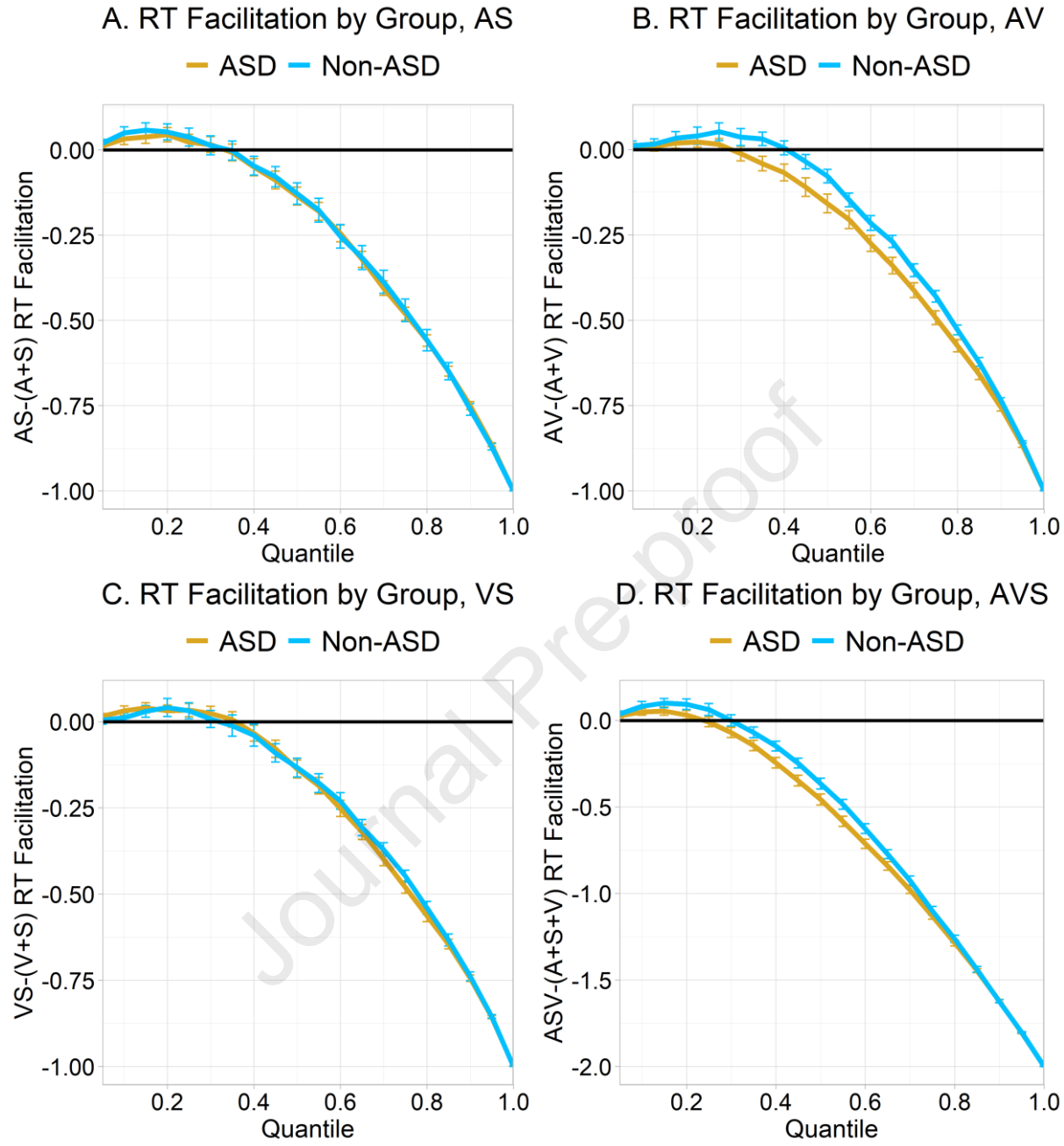

Figure 4. Differences between probability distributions for multimodal stimuli and summed unimodal stimuli, with positive values representing RT facilitation, in the ASD and non-ASD groups. The first eight quantiles, up to a probability of 0.4, were examined in permutation *t*-tests comparing groups (see Table 4). Error bars are standard errors.
A (top left panel). Audio-somatosensory RT facilitation.
B (top right panel). Audiovisual RT facilitation.
C (bottom left panel). Visuo-somatosensory RT facilitation.
D (bottom right panel). Trimodal RT facilitation.

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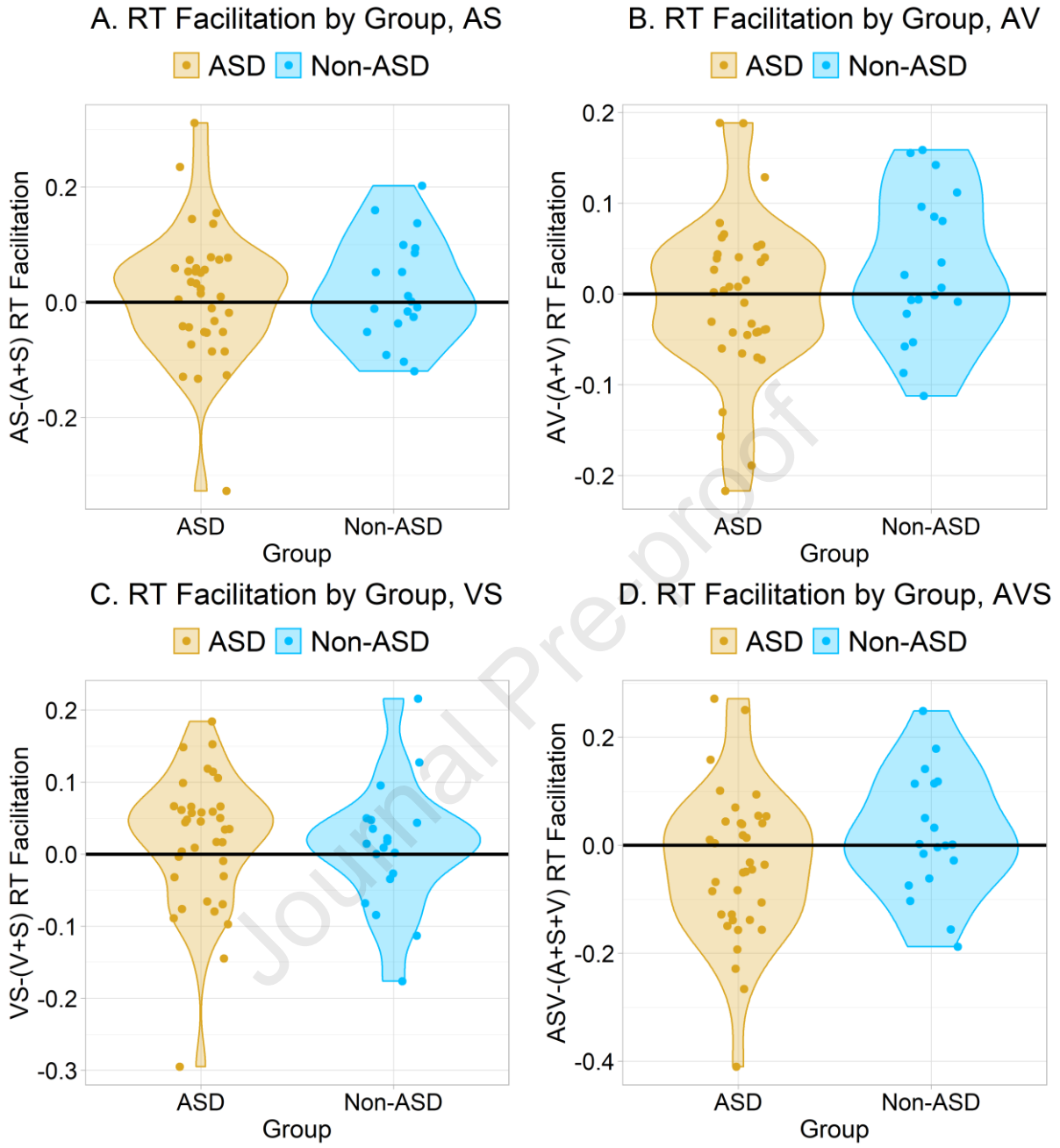

Figure 5. Differences between probability distributions for multimodal stimuli and summed unimodal stimuli, with positive values representing RT facilitation, in the ASD and non-ASD groups, as averaged across quantiles 0.05 to 0.40. Note that these values are **not** those examined in the statistical test comparing groups; the permutation test is based on the *maximum* group difference in *any* examined quantile, not the *average* group difference across *all* examined quantiles.

A (top left panel). Audio-somatosensory RT facilitation.

B (top right panel). Audiovisual RT facilitation.

C (bottom left panel). Visuo-somatosensory RT facilitation.

D (bottom right panel). Trimodal RT facilitation.

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3.3. Unisensory ERPs

Per cluster-based permutation *t*-tests, between-group differences in auditory (lowest p = .29; *Figure 6A*) and somatosensory (lowest p = .56; *Figure 6B*) conditions did not attain statistical significance per cluster-based permutation independent-samples *t*-tests test during the 40 – 200 ms time window. However, more negative visual CSD amplitudes were observed in the non-ASD group than the ASD group, p = .001, over a cluster of central sites spanning 92 – 188 ms (*Figure 6C*).

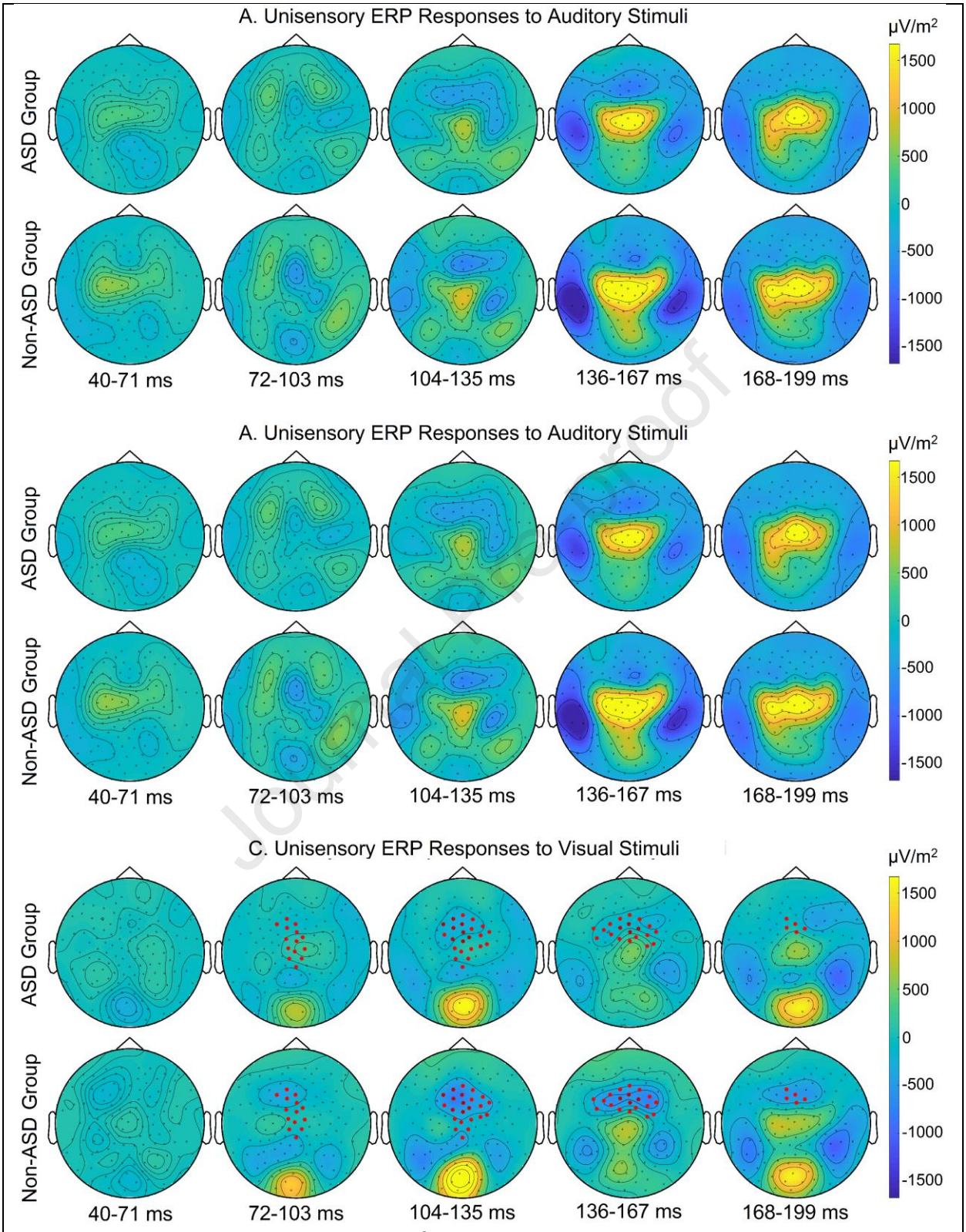

Figure 6. Unisensory CSD topographies from each diagnostic group in the auditory (panel *A*), somatosensory (panel *B*), and visual (panel *C*) conditions averaged across five different time windows. Channels at which significant group differences were observed in cluster-based

permutation tests are marked in red. Significant between-group differences were found in the visual condition (panel *C*), with amplitudes over central channels appearing more negative in the non-ASD group than ASD.

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476 **3.4. Multisensory ERPs**

477 **3.4.1. Within-Group Analyses.**

478 Dependent-samples cluster-based permutation *t*-tests found significant multisensory

479 interactions in several conditions (Table 5).

Table 5. *Lowest* p-*values obtained in dependent-samples cluster-based permutation tests examining whether multisensory ERPs differed from summed/difference unisensory waveforms in each group (which would indicate the presence of multisensory interactions) across all channels during a 40 – 200 ms time window, along with lowest* p-*values obtained in independent-samples tests using difference waves between multisensory and summed/difference unisensory waveforms to compare the magnitude of multisensory interactions across groups in the same 40 – 200 ms window.*

	Dependent-samples cluster-based permutation t-tests in ASD group	Dependent-samples cluster-based permutation t-tests in non-ASD group	Group Comparisons	
			Independent-samples cluster-based permutation t-tests	Permutation ANCOVAs covarying for WISC PRI, raw RTs, and Edinburgh Inventory
Comparing AS & (A + S)	.03*	.008**	.23	.52
Comparing AV & (A + V)	.04*	<.001***	.03*	.01*
Comparing VS & (V + S)	.31	.04*	.14	.42
Comparing AVS & (A + V + S)	.002**	<.001***	.13	.27

Single asterisk (*) indicates $p < .05$, double asterisks (**) indicates $p < .01$, and triple (***) indicates $p < .001$, uncorrected.

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Audiovisual. Per cluster-based permutation paired *t*-tests, a cluster of audiovisual interactions over right-fronto-central channels between 150 – 200 ms attained significance in the ASD group, $p = .04$ (*Figure 7A, Figure 8A*). Multisensory AV CSD values over these sites were more positive than the sums of unisensory A + V CSD values. There were also significant audiovisual interactions in the non-ASD group, $p < .001$, with multisensory AV CSD being more positive than the sums of unisensory A + V CSD in a cluster over fronto-central channels spanning 79 – 200 ms (*Figure 7B, Figure 8B*), substantially earlier than in the ASD group, which is interesting to note in light of the audiovisual between-group differences discussed below.

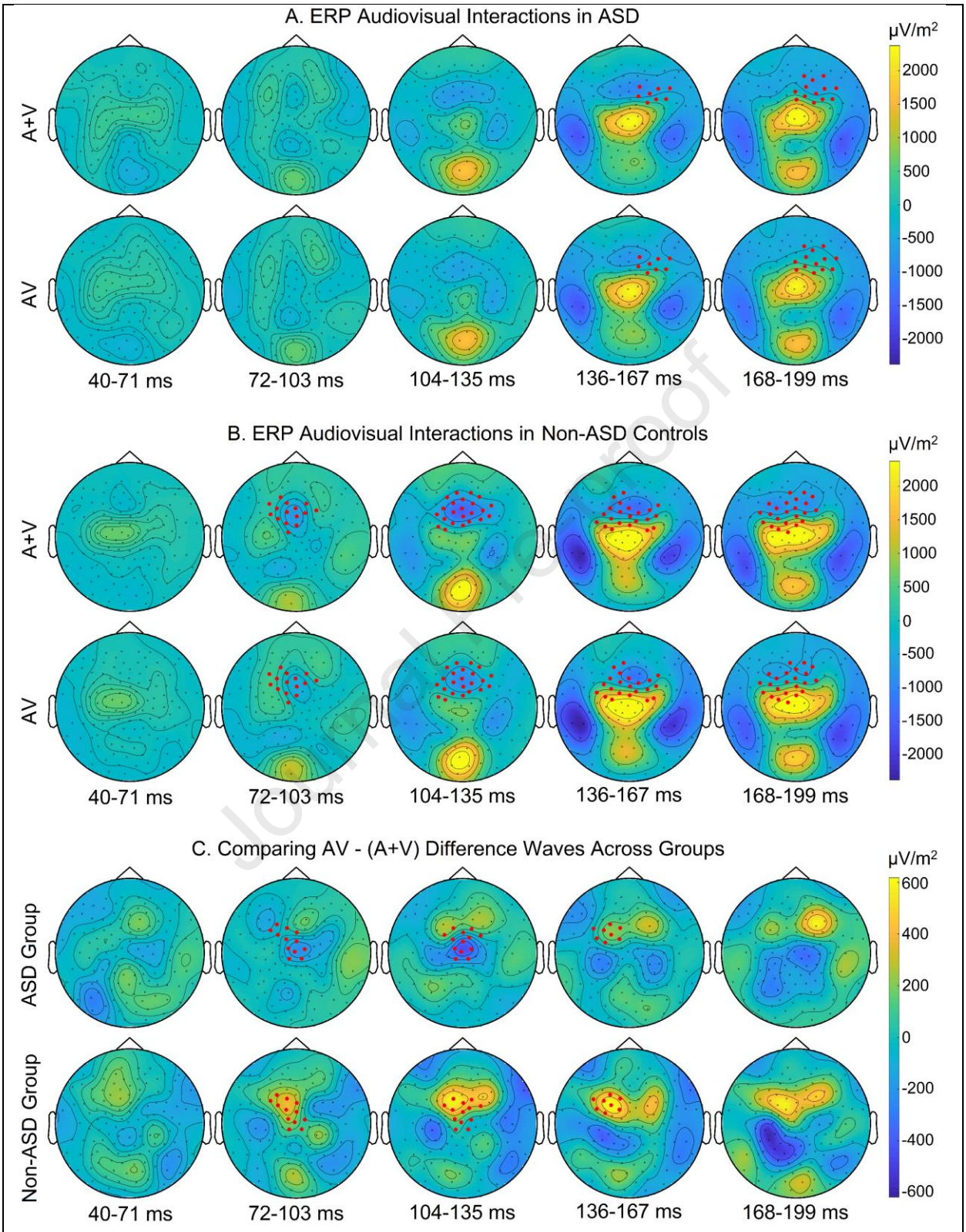

Figure 7. Panels *A&B*. In the ASD group, summed unimodal (A+V, top row) and multimodal (AV) CSD topographies in the ASD group (Panel A) and non-ASD group (Panel B). Channels

over which dependent-samples cluster-based permutation tests comparing sum and multimodal responses attained significance are marked in red.
Panel *C*. Topographies of AV – (A + V) CSD difference waves, reflecting audiovisual multisensory interactions, in each group. Channels over which independent-samples cluster-based permutation tests comparing groups attained significance are marked in red.

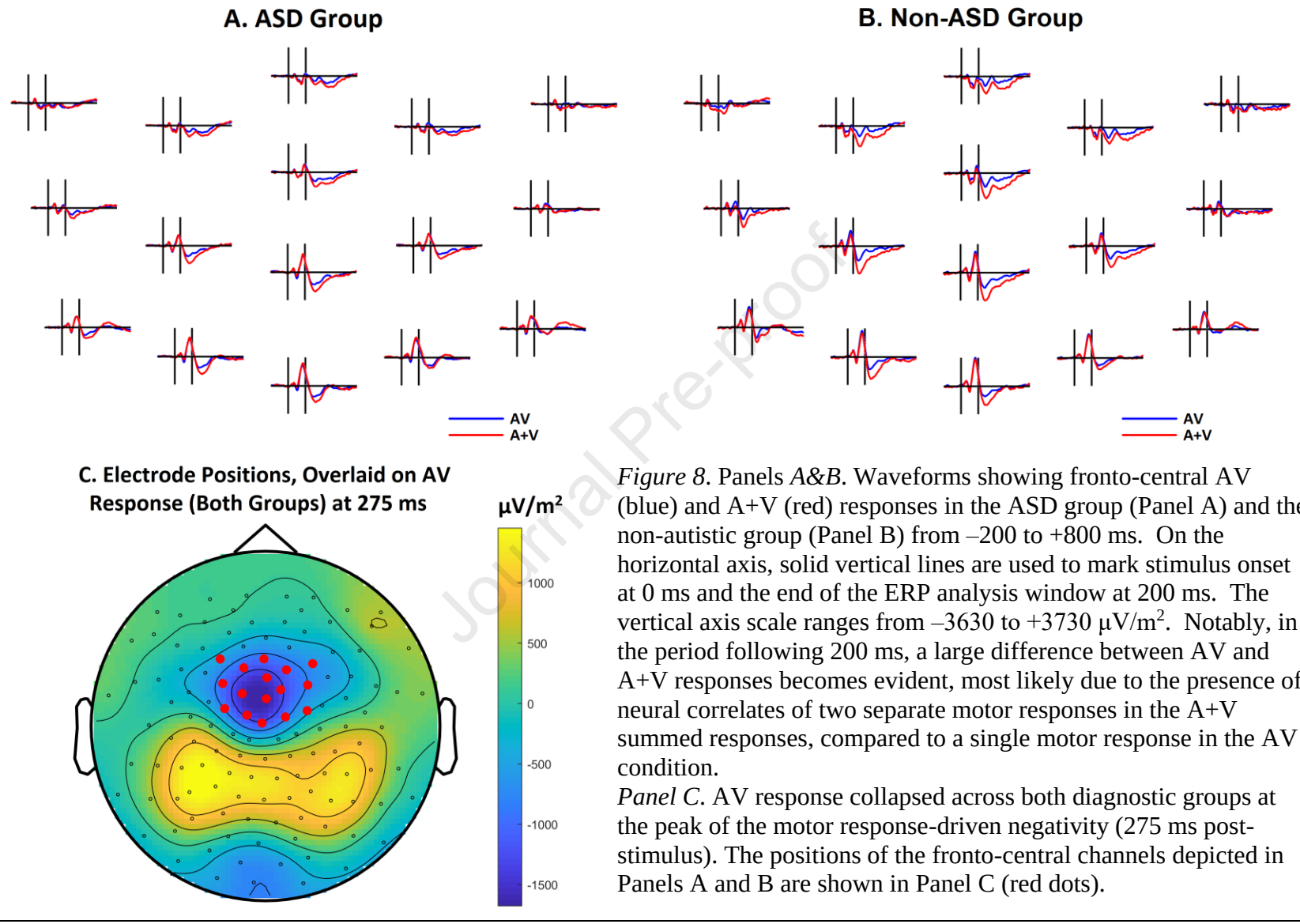

Figure 8. Panels *A&B*. Waveforms showing fronto-central AV (blue) and A+V (red) responses in the ASD group (Panel A) and the non-autistic group (Panel B) from –200 to +800 ms. On the horizontal axis, solid vertical lines are used to mark stimulus onset at 0 ms and the end of the ERP analysis window at 200 ms. The vertical axis scale ranges from –3630 to +3730 µV/m^2. Notably, in the period following 200 ms, a large difference between AV and A+V responses becomes evident, most likely due to the presence of neural correlates of two separate motor responses in the A+V summed responses, compared to a single motor response in the AV condition.

Panel C. AV response collapsed across both diagnostic groups at the peak of the motor response-driven negativity (275 ms post-stimulus). The positions of the fronto-central channels depicted in Panels A and B are shown in Panel C (red dots).

Audio-somatosensory. Per cluster-based permutation paired *t*-tests in the ASD group, there were significantly more positive multisensory audio-somatosensory CSD amplitudes than summed unisensory auditory and somatosensory amplitudes in two clusters: one over posterior channels between 45 – 106 ms, $p = .03$, and another over right-fronto-temporal channels between 139 – 200 ms, $p = .05$ (*Figure 9A*). In contrast, in the non-ASD group, there were significantly more negative audio-somatosensory amplitudes than summed unisensory amplitudes, $p = .008$, over a cluster of centro-parietal channels spanning 134 – 200 ms. While these significant ASD and non-autistic effects are opposite in direction, visual inspection of *Figure 9A* suggests some negatively-trending differences in ASD and positively-trending in non-autistic may simply not have attained statistical significance.

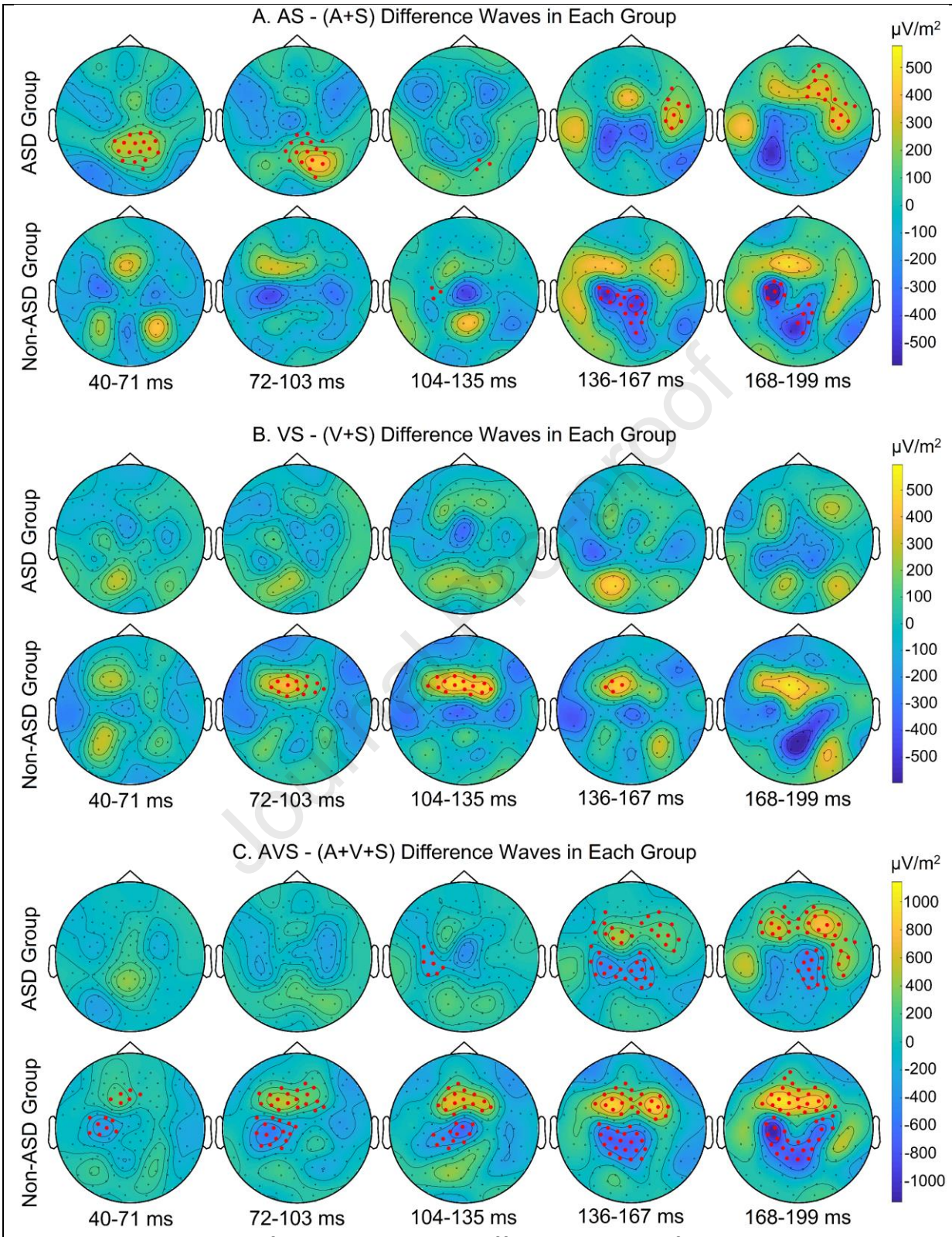

Figure 9. Topographies of AS – (A + S) CSD difference waves, reflecting audio-somatosensory multisensory interactions (Panel A), VS – (V + S) CSD difference waves, reflecting visuo-somatosensory multisensory interactions (Panel B), and AVS – (A + V + S)

CSD difference waves, reflecting audio-visuo-somatosensory multisensory interactions (Panel C), in each group. Channels over which dependent-samples cluster-based permutation tests comparing sum and multimodal responses in each group attained significance are marked in red.

Visuo-somatosensory. In the non-autistic group, per cluster-based permutation paired *t*-tests, there were significantly more positive multisensory visuo-somatosensory CSD amplitudes than summed unisensory visual and somatosensory amplitudes over a cluster of fronto-central channels spanning 86 – 147 ms, $p = .04$ (*Figure 9B*). No visuo-somatosensory interaction effects attained significance in ASD, lowest $p = .31$.

Audio-visuo-somatosensory. In the ASD group, per cluster-based permutation paired *t*-tests, there were significantly more positive multisensory audio-visuo-somatosensory than summed unisensory auditory, visual, and somatosensory CSD amplitudes, $p = .002$, over a cluster of frontocentral and right-temporal channels spanning 142 – 200 ms (*Figure 9C*). Furthermore, in the ASD group, there were significantly more negative multisensory than summed unisensory amplitudes, $p = .02$, over a cluster of centro-parietal channels spanning 130 – 200 ms. In the non-autistic group, there were significantly more positive multisensory than summed unisensory amplitudes, $p < .001$, over a cluster of fronto-central channels spanning 64 – 200 ms, and there were significantly more negative multisensory than summed unisensory amplitudes, $p < .001$, over a cluster of centro-parietal channels spanning 61 – 200 ms. This pattern suggests more sustained evidence for MSI in the AVS condition for the non-autistic vs. ASD groups.

3.4.2. Between-Group Analyses.

When difference waves between multisensory CSD and sums/differences of non-multisensory CSD were compared across groups using cluster-based independent samples *t*-tests, no significant differences were found in most conditions. However, non-autistic and ASD

groups appeared to differ in the neural correlates of audiovisual integration. AV–(A+V) difference waves were more positive in amplitude in the non-autistic group than the ASD group over a cluster of central sites spanning 84 – 153 ms, $p = .03$ (*Figure 7C*). This effect proved robust to covarying for handedness, cognitive ability, and raw RTs (Table 5) using cluster-based permutation ANCOVA, $p = .014$; it also proved robust when examined only among right-handed participants (Appendix A, Table A.8).

4. Discussion

The present study examined three types of bimodal sensory integration (audio-somatosensory, audiovisual, visuo-somatosensory) in autistic and non-autistic adolescents using both RTs and ERPs. In addition, it examined trimodal audiovisual-somatosensory integration. Within-group analyses suggested that significant multisensory interactions in ERP and RT facilitation did occur, although the present study found no significant ASD-nonASD group differences in multisensory RT facilitation. However, our results suggest that autistic and non-autistic participants might have differed in the extent to which they showed audiovisual ERP multisensory interactions. No other group difference in multisensory RT facilitation or ERP interactions reached significance; however, given the rigorous cluster-based permutation correction applied to our ERP data, and our use of a null hypothesis significance testing rather than Bayesian framework, this should not be taken as definitive evidence of a lack of group differences.

4.1. Reaction Times

In the present study, RTs were measured as the onsets of motor responses, rather than the point at which the response button became fully depressed. These onset RTs were often rapid, with ~200 to ~300 ms being typical in different conditions; some participants displayed median onset RTs as low as ~150 ms. The speed of these responses suggests that there is a significant

risk that ERP correlates of motor preparation could contaminate ERP analyses of multisensory interactions (either due to a difference in the number of motor responses included in multisensory and summed unisensory waveforms, or due to a difference in RTs across conditions). While covarying for RTs did not eliminate group differences in ERP multisensory interactions in the present study, and responses in *Figure 8* suggest that major motor-related ERP responses occurred after 200 ms, future multisensory ERP studies should also take care to monitor and control for, or eliminate, this potential confound.

We did observe significant violation of the RT race model in both the non-autistic and autistic groups, indicating that multisensory RT facilitation did occur. Specifically, in non-autistic participants, RT facilitation was observed due to audio-somatosensory and trimodal interactions. In ASD, the race model was significantly violated for visuo-somatosensory and trimodal interactions. Admittedly, evidence of RT facilitation is somewhat modest compared to some prior developmental studies, and surprisingly, we observed no significant audiovisual facilitation in either group. While it is unclear whether some prior studies corrected for multiple comparisons across quantiles (e.g., Brandwein et al., 2013; Yang et al., 2020), but robust audiovisual race model violation is observed by Molholm and colleagues (2020), who do apply Bonferroni corrections to correct for multiple comparisons, suggesting that our permutation correction is unlikely to account for group differences. However, the non-autistic comparison sample in the present study sample is smaller than that in Molholm et al. (2020), which may contribute to our failure to observe effects. That said, these studies do use very different methods. For example, the present study uses less intense sounds than Molholm et al., and a moderately bright flash rather than a red disk as a visual stimulus. The present study also used a pressure transducer to record motor response onsets, so RTs in the present study are themselves

not strictly comparable to RTs as recorded in prior research. Any of these methodological differences might account for discrepancies in study results.

The present study did not find significant ASD-nonASD group differences in RT facilitation. Nonsignificant trends for audiovisual and trimodal facilitation to be attenuated in the ASD group no longer approached significance after covarying for cognitive ability and handedness.

4.2. Event-Related Potentials

4.2.1. Unisensory ERPs.

Unexpectedly, we did not observe significant group differences in somatosensory and auditory ERPs, while the significant group differences in visual ERP amplitudes were observed over central channels, considerably anterior to the large visual ERPs canonically observed over occipital channels. These results may reflect the statistical approach used in the present study: the cluster-based permutation test has more power to detect widely distributed effects than more focal effects (such as those involving visual occipital responses), limiting the present study's comparability to prior literature. It should be noted that trends towards smaller canonical ERP amplitudes in the autism group can be observed in all three unisensory conditions through visual inspection of *Figure 6*.

4.2.2. Within-Group Effects.

As with RTs, we found significant evidence of multisensory interactions in ERP CSD in each diagnostic group. Specifically, we observed audio-somatosensory, audio-visual, and trimodal audio-visuo-somatosensory interactions in each group. Significant evidence of visuo-somatosensory interactions was only observed in the non-autistic group.

Notably, in the ASD group, a cluster of audio-somatosensory interactions reached significance as early as 45 ms post-stimulus, while in non-ASD participants, clusters of trimodal

592 interactions began around 60-65 ms. Although it is important to recognize that the cluster-based
593 permutation test does not test the significance of cluster boundaries, this finding nevertheless
594 appears consistent with prior research suggesting that neural correlates of MSI can be observed
595 at early latencies (i.e., <100 ms; see De Meo et al., 2015), including in non-autistic
596 developmental populations (Brandwein et al., 2013).

597 Interestingly, the present study's detection of early audio-somatosensory MSI effects in
598 autistic participants does appear to differ from prior studies which observe audio-somatosensory
599 interactions in autistic children only at later latencies (Russo et al., 2010), although this study
600 only detects significant audiovisual interactions at later latencies in autism, comparable to prior
601 research (Brandwein et al., 2013; Molholm et al., 2020). Furthermore, the specific onset time of
602 audio-somatosensory interactions around ~45 ms observed in the ASD group appears to be
603 somewhat earlier than the effect latencies observed in prior ERP studies of audio-somatosensory
604 interactions in developmental populations (Brett-Green et al., 2008; Russo et al., 2010). The
605 speed of the audio-somatosensory interactions in this study could reflect factors such as the
606 inclusion of younger participants in prior studies or between-study differences in the extent to
607 which auditory and somatosensory stimuli were presented in a spatially-aligned manner. It
608 seems unlikely to have reflected ASD-nonASD differences, as visual inspection of *Figure 9A*
609 shows similar but nonsignificant patterns in the non-autistic group.

610 **4.2.3. Between-Group Effects.**

611 There was some exploratory evidence of differences in ERP multisensory interactions
612 between the autistic and non-autistic groups. A group difference in audiovisual interactions was
613 observed over a cluster of central sites between ~84 and ~153 ms. Specifically, non-autistic
614 participants exhibited less negative/more positive multisensory AV CSD values than unisensory
615 summed CSD values over these sites, whereas autistic participants appeared to exhibit mostly

neutral or negative difference values. Notably, this between-group difference appeared to spatiotemporally overlap with a significant within-group non-autistic cluster effect reflecting audiovisual interactions, perhaps indicating the between-group difference was driven by greater multisensory interactions in the non-autistic group. Such interactions might have been driven by multisensory diminution of the canonical central auditory N1 response in non-ASD participants. However, the N1 is difficult to discern in CSD averages from *Figure 6A*. Auditory ERPs over fronto-central scalp undergo a major shift around 9-14 years of age, or approximately coinciding with the age range of the present study: the child frontocentral P1-N2 complex evolves into the central P1-N1-P2-N2 complex seen in adults (Albrecht, Suchodoletz, & Uwer, 2000; Gilley et al., 2005; Ponton et al., 2002; Sharma et al., 1997). Thus, the suggestion that the N1 is differentially impacted by multisensory stimuli across groups should be taken with caution. Furthermore, negative visually-evoked CSD amplitudes over central sites are apparent in *Figure 6C*, and it seems possible that audiovisual interactions affected these.

Interestingly, the scalp location and timing of the audiovisual interaction group difference observed in the present study initially appears to overlap with fronto-central ASD-TD group differences in ERP audiovisual interactions observed around ~100-120 ms by Brandwein and colleagues (2013), but with a crucial difference in effect directionality. Specifically, in Brandwein et al. (2013), non-autistic participants exhibited more negative audiovisual ERPs than summed ERPs, whereas in the present study, non-autistic participants exhibited more negative summed ERPs than audiovisual ERPs. We are uncertain why these two studies find effects in essentially opposing directions.

4.4. Limitations

In the present study, there are various possible factors that could contribute towards group differences in ERPs. There was a large difference in measured cognitive ability between

640 autistic and non-autistic participants, and some left-handed participants were included in the
641 ASD group, which we explored by using these variables as covariates as well as by running
642 analyses examining only right-handed participants. Although data regarding family background
643 (such as income or parental education levels) were not collected in the present study, there were
644 apparent tendencies (per Table 1) for autistic participants to be recruited from more diverse
645 racial/ethnic backgrounds than non-autistic participants. Race/ethnicity did not statistically
646 differ between diagnostic groups, but this could reflect the relatively small sample of the present
647 study. A likely explanation for potential demographic differences between diagnostic groups is
648 that non-autistic participants were recruited disproportionately from the city of Davis, where
649 educational attainment levels are substantially higher than those for California as a whole
650 (United States Census Bureau). In contrast, autistic participants were recruited from various
651 communities, including Sacramento County. As a result, it would not be unreasonable to
652 imagine that groups could differ in levels of parental education. This would be consistent with
653 the very high WISC scores obtained from the non-autistic group (see Table 1). It is unclear
654 whether and how this might affect MSI.

655 The present study also adopted an exploratory approach. We did not feel that prior
656 literature provided clear enough evidence regarding the probable locations of effects to focus our
657 analyses on particular RT quantiles or ERP channels/time points, and we therefore analyzed a
658 broad range of RT quantiles, a broad range of ERP time-points, and all scalp electrodes. While
659 we used cluster- and maximum-statistic-based permutation tests to correct for comparisons
660 across RT quantiles, ERP latencies, and ERP channels, the conservatism of these corrections –
661 particularly in relation to ERP analyses – likely puts us at risk of Type II error. On the other
662 hand, we did not correct for multiple comparisons based on the four combinations of sensory

modalities (audiovisual, audio-somatosensory, visuo-somatosensory, and trimodal interactions) investigated in the present study, because we regard them as uniquely interesting dependent variables. This might increase our risk of Type I error.

Finally, the present study was drawn from a relatively limited range of the autistic population. The lack of autistic people with intellectual disabilities may be a particularly serious issue. Many prior studies of MSI in ASD also exclude participants with intellectual disabilities (Feldman et al., 2018), which reflects the exclusion and under-representation of these individuals in autism research generally (Russell et al., 2019). Given that audiovisual MSI is likely involved in language learning (Mason et al., 2019), and that reduced communication abilities might impact IQ scores, future research should therefore prioritize developing and using more passive paradigms (e.g., Bahrick et al., 2018; Kissine et al., 2021) that can be feasibly employed to study MSI in autistic people with intellectual disabilities, along with nonspeaking and minimally-verbal autistic people.

4.5. Summary

The present study found apparent evidence of MSI in both autistic and non-autistic adolescents. Both groups showed multisensory facilitation of RTs and multisensory interactions in ERPs. Significant ERP multisensory interaction clusters began as early as ~45 ms, and while the present study's statistical approach was not intended to test the latencies of MSI, this finding is consistent with the idea that early MSI effects can be observed at latencies <100 ms, even in adolescent populations. We also observed generally rapid onsets of motor responses, often commencing at ~200 or even ~150 ms. While controlling for RTs did not eliminate the group differences in ERP audiovisual interactions observed in the present study, the speed of these RT responses does emphasize the need for caution in future studies using both RTs and ERPs to examine MSI.

We found no evidence of ASD-nonASD group differences in MSI RT facilitation. Trends towards group differences in audiovisual and trimodal RT facilitation disappeared after covarying for cognitive ability and handedness. Autistic and non-autistic participants did appear to differ in audiovisual ERP multisensory interactions, and this exploratory effect proved robust to covarying for cognitive ability, handedness, and raw RTs, as well as to examination in only right-handed participants. A reduction in audiovisual MSI in autistic participants would be consistent with prior research, and such a difference could have some practical significance. Audiovisual MSI contributes to language learning, audiovisual MSI and lip-reading could facilitate everyday conversations, and the ability to integrate numerous simultaneous visual and auditory signals might help individuals make sense of complex sensory environments and avoid being overwhelmed by them. Future research may benefit from exploring audiovisual MSI in under-studied populations such as autistic people with intellectual disabilities, who are nonspeaking, or who are minimally-verbal.

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Declarations of Interest

The authors have no relevant conflicts of interest to declare.

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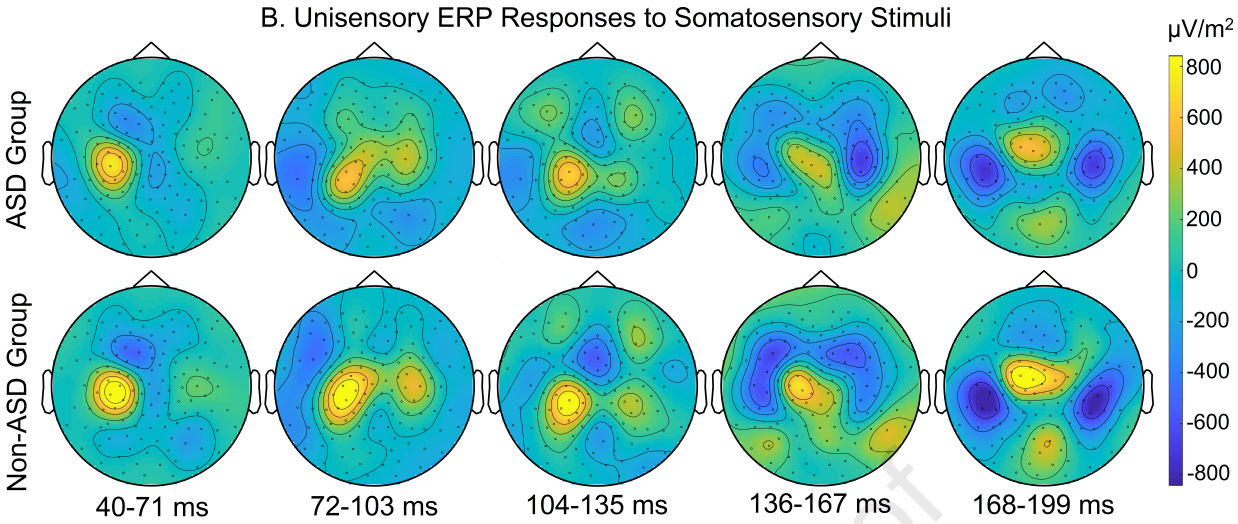

Highlights

- Both autistic and non-autistic adolescents exhibit multisensory facilitation of reaction times
- Both autistic and non-autistic adolescents exhibit multisensory interactions in ERPs
- Multisensory facilitation of reaction times does not significantly differ between groups
- Audiovisual interactions in ERPs significantly differ between autism and typical development