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Semantic and Structural Processing of Visual Narratives in Individuals with Autism Spectrum Disorder

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SEMANTIC AND STRUCTURAL PROCESSING OF VISUAL NARRATIVES IN INDIVIDUALS WITH AUTISM SPECTRUM DISORDER

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ABSTRACT

Understanding a story ("narrative comprehension") is often difficult for individuals with Autism Spectrum Disorder (ASD), regardless of whether stories are told through language ("linguistic narratives") or pictures ("visual narratives"). Narrative comprehension across modalities requires understanding meaning ("semantics") and understanding grammar ("structure"). While it is well-established that individuals with ASD have difficulties with semantic processing, little is known about whether difficulties with structural processing contribute to impaired narrative comprehension. This study tested, via measurements of neural activity, our prediction of whether structural processing is impaired during visual narrative comprehension in individuals with ASD compared to typically developing (TD) individuals. Our results on semantic processing in ASD replicated what has been found in prior language studies, with the TD group showing an increased sensitivity to semantic relatedness in early time windows and the ASD group showing an increased sensitivity at later time windows. Importantly, we also observed differences in structural processing for ASD groups compared to TD groups, such that individuals with ASD showed reduced sensitivity to the presence of narrative grammar. These novel results indicate potential narrative comprehension difficulties in individuals with ASD.

INTRODUCTION

Introducing ASD

ASD is a neurodevelopmental condition that can lead to social and behavioral differences (CDC, 2020). This is a wide spectrum condition with a range of symptomatic presentations depending on the individual. The prevalence of children with ASD has been identified to be about 1 in 54 (1.85%) in the United States as of 2016 (CDC, 2020). Statistical tracking by the Autism and Developmental Disabilities Monitoring Network has demonstrated an upward trend in these estimations, with 1 in 150 children reported to be diagnosed in 2000. The monitoring network identified similar reports of ASD regardless of racial and ethnic groups in 8-year-olds, but a more drastic difference depending on gender (Maenner et al., 2020). ASD is reported to be 4.3 times more likely in boys of this age (CDC, 2020). Gender differences may be due to different symptomatic presentation or social standards between genders. Developmental assessment is used as a diagnostic tool, focusing on aspects of children's behavior such as: avoidance of eye contact, reduced social interaction, decreased display of language, and desire for routine. Necessary symptoms to diagnose ASD include decreased functioning in social communication, decreased social interaction and the presence of repetitive and restrictive behaviors (APA, 2021).

An integral aspect of research on ASD addresses the potential challenges in language processing and comprehension among some individuals with ASD compared to typically developing peers. Although not necessary for diagnosis according to the DSM-5, language comprehension has been implicated as an area of difficulty for some individuals with autism (Tager-Flusberg et al., 2005). Research shows that individuals with autism can demonstrate semantic, syntactic, and pragmatic challenges (Groen et al., 2008), which are key components in language comprehension. Before delving into studies and reviews that exist on language processing in individuals with ASD, it is important to note there is a wide range of language abilities in the population. Individuals with ASD can have fully functioning language skills, or be completely non-verbal (Tager-Flusberg et al., 2005).

Language Processing

Language is overarchingly viewed as containing key components including morphology, syntax, semantics, and pragmatics (Hoque, 2015). The current study focuses on the necessity of semantics and syntax to a narrative sequence. *Semantics* refers to the actual meaning of language stimuli. *Syntax*, or grammar, refers to the structural component of language. Importantly, semantics and syntax are present at the level of both sentences and *narratives*, or stories. A narrative would be considered semantically meaningful if the events are linked in meaning and considered syntactically meaningful if the story follows a narrative arc that creates a structure for narrative events.

Psycholinguistic studies have identified certain brain responses that are associated with semantic and syntactic processing of language. These studies primarily examine event-related potentials (ERPs), which represent the neural responses of cognitive processes in response to presented stimuli (Sur & Sinha, 2009) and are derived from electroencephalography (EEG) recordings, which measure the electrical activity of the brain via electrodes that are placed on the scalp. Prior ERP studies have suggested that the N400 component of the ERP – a negativity occurring at approximately 400 milliseconds (ms) – is implicated in semantic processing, while later components, such as the P600 (a positivity occurring at approximately 600 ms), is implicated in syntactic processing (Gonda et al., 2020). The N300 is an ERP component related to semantic features of narrative like the N400 and has been shown in response to nonlinguistic (picture) stimuli (Cohn et al., 2012). In the current study, we will use EEG techniques to determine participants' neural responses to semantic and syntactic components of narratives.

It is common to default to thinking about semantics and syntax in the context of verbal language, since this is the modality that much of the research has focused on. However, this thesis will argue that *visual narratives* (i.e., stories told through sequential images, such as a comic strip) represent a visual form of language that is reliant on similar cognitive and neural processing mechanisms as *linguistic narratives* (i.e., stories told through written or spoken language). This theory is primarily based on theoretical and empirical research from Cohn that demonstrates that "all languages obey similar principles" regardless of whether they are "spoken, signed or drawn" (Cohn, 2022, Visual Language Lab Home Page).

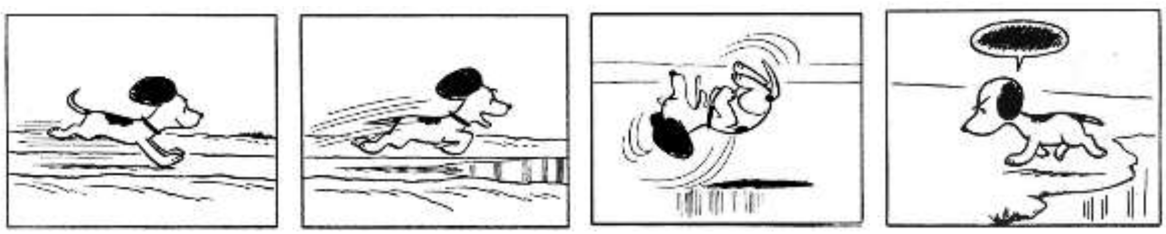
Visual Narratives

Visual and linguistic narratives, although relying on separate input modalities, use similar cognitive and neural processing mechanisms. Just as spoken and written narratives contain grammatical and semantic components that are necessary for comprehension, visual narratives contain both grammatical and semantic components (Cohn et al., 2012). Cohn's "Visual Narrative Grammar" proposes that visual narratives contain both event and narrative structures. Event structure in visual narratives is analogous to semantics: the invocation of meaning in images (Cohn, 2013). Although it may be intuitive to how visual narratives, such as comics, rely on readers applying meaning to the images, a review by Cohn (2014) references multiple studies that have demonstrated the evidence of reliance on semantics to comprehend visual narratives. Just as in linguistic narratives, in visual narratives readers must consistently understand characters, events, relationships, and environments that change over time. Indeed, empirical research has shown that the semantic processing of visual narratives elicits similar effects at the N400 ERP component as the semantic processing of linguistic stimuli (West & Holcomb, 2002; Cohn et al., 2012; Coderre et al., 2020).

Narrative syntax is the structural component of the narrative that describes how images are ordered. According to this theory, there are necessary structural components in a narrative sequence and each panel plays a role in the overall narrative structure. Depending on their position and role within the sequence, panels can be categorized as: Establishers, Initials, Peaks, and Releases. These components make up a complete canonical narrative arc (Cohn, 2014). The structure of a visual narrative begins with an Establisher, which conveys the relationships between the characters in a passive manner (as compared to events in an active manner). In Figure 1, the Establisher panel sets up the scene of Snoopy running. At this point there is no narrative action occurring. The Initials are the beginning of actions/events in the narrative. The panel in Figure 1 that demonstrates this is Snoopy jumping onto a frozen pond. The Peak of a visual narrative is analogous to its climax, the culmination of events. In Figure 1, the Peak panel shows Snoopy slipping on the ice. The Releases of a sequence are the resolution of the events that have occurred in the narrative. Figure 1 ends with a Release panel, Snoopy angry and leaving the frozen pond (Cohn, 2014).

Importantly, these components do not need to be strictly linear in sequence; for instance, there could be an Establisher later in the sequence, used for the purpose of introducing additional relationships (Cohn, 2014). Instead, these components can, and typically do, appear in more complex narrative structures that contain both linear and grouped formats. However, all visual narratives will follow a general narrative structure. For instance, although an Establisher may appear multiple times in a sequence, there will always be an Establisher preceding an Initial to allow the reader to comprehend the narrative more easily. Cohn's theory of Narrative Grammar argues that these are necessary components to the structure of visual narratives, and that this structure is analogous to the syntax of linguistic narratives (Cohn, 2014).

Figure 1: A Peanuts comic strip demonstrating the structural categories of panels in a visual narrative: Establisher, Initial, Peak, and Release



In a seminal ERP study on visual narrative grammar, Cohn et al. (2012; Experiment 2) provided evidence of the essentiality of structural and semantic components to visual narrative comprehension, as well as of the similarity between visual and linguistic narrative processing. In this study, comic sequences were manipulated to contain both semantics and structure (“Normal” sequences); narrative structure but no semantic relatedness between panels (“Structural Only” sequences); semantic relatedness but no narrative structure (“Semantic Only” sequences); or neither semantics nor structure (“Scrambled” sequences; see Figure 2).

The results of Cohn et al. (2012) provided evidence that the structural component of a visual narrative sequence is separate from the semantic component. As expected, the Normal sequences elicited the smallest N300/N400 effect, since the presence of both the structural and semantic components allowed for integrated narrative processing. Semantic Only sequences had reduced N300/N400 amplitudes compared to the Structural Only and Scrambled conditions because the available semantic context allowing readers to link the events in meaning. These effects of semantic relatedness were seen only at the N400 component, just as in linguistic narratives (Kutas & Federmeier, 2011). In contrast, effects of structural processing were smaller and were identified as a different ERP component: a left anterior negativity (LAN) which was smaller for Structural Only compared to Scrambled sequences. This LAN effect is similar to that seen in response to syntactic facilitation in linguistic narratives (Cohn, 2014; Friederici, 2002; Neville et al., 1991). This study demonstrated that not only are semantic and structural components beneficial to processing of visual narratives, but these components also have neural processing mechanisms comparable to the semantic and structural components of linguistic narratives.

In this thesis we will replicate the methods from the Cohn et al. (2012) study, with the inclusion of a group of individuals with ASD. While the aim of the Cohn et al. (2012) study was to analyze structural processing of visual narratives for fluent comic readers, our aim is to analyze the differences of structural processing of visual narratives within an ASD population as compared to a TD population.

Language Processing in ASD

Overarchingly, studies on language comprehension in ASD have relied on linguistic stimuli, as opposed to visual stimuli.

Semantic Processing of Linguistic Stimuli in ASD

Reviews of prior literature indicate challenges in semantic processing of narratives specific to ASD. For example, Tager-Flusberg et al. (2005) review results in which sentence processing strategies for individuals with ASD were identical to those of TD individuals, but individuals with ASD were less able to understand the context within a story. In another comparison of reported story details (e.g., central ideas and characters) for a narrative by TD children and children with ASD (Kenan et al., 2019), higher levels of autistic traits were associated with a reduced ability to interpret the meaning of individual words (semantics) and meaning based on surrounding context (pragmatics). This may suggest that an increase in autistic traits is linked to a decrease in correctly analyzing the context of a linguistic narrative. Coderre et al. (2018) also refers to multiple studies that have identified linguistic narrative comprehension challenges in ASD populations, with results that point to a struggle in creating inferences, understanding themes, and establishing a connection between story elements (Jolliffe & Baron-Cohen, 2000; Vermeulen, 2015). These abilities are essential to the correct integration of semantic relatedness within a narrative. Overall, prior literature seems to conclude that there are differences in semantic comprehension in individuals with ASD at the level of narratives.

Syntactic Processing of Linguistic Stimuli in ASD

Multiple studies have noted difficulties for children with ASD when presented with past tense grammar (Tager-Flusberg et al., 2005). Overall, Tager-Flusberg et al. (2005) concludes that "syntactic development in children with autism is more similar than dissimilar to normal development" (p. 345), although impairments still exist. A review of the current literature on syntax in individuals with ASD sums up the discrepancies between different findings. There have been multiple studies demonstrating difficulties with syntactic processing, as well as some studies with no such difference found (Friedman & Sterling, 2019). Because of the extremely diverse profile of ASD, with the spectrum of autistic traits being so large, there is little conclusive evidence that ASD is correlated with syntactic deficits, although there may be a potential link between level of autistic traits and their effects on syntax comprehension, as noted by the studies mentioned above.

Brynskov et al. (2017) raises awareness of the discrepancies between the various studies hoping to identify if there really are differences in structural processing within the ASD population. The critique is raised that some of the earlier studies have limitations based on what is considered to demonstrate language level (matching ASD and TD groups by vocabulary skills), as well as differences in measures, such as using standardized language tests compared to depending on spontaneity of produced language. Within a population of children, Byrnskov et al. (2017) assessed syntax and morphology skills with the Clinical Evaluation of Language Fundamentals (CELF), requiring the recall of syntactically complex sentences and the production of sentences. The ASD group had statistically significant syntax impairments compared to the TD group, even among individuals with ASD who did not have any significant early language delay. This study aimed to show that contradictory results from earlier studies may have been because of the limitations of these studies, and that evidence points toward challenges with structure for ASD groups.

A more recent study analyzed the structural production of narratives told by ASD individuals and TD individuals (Lee et al., 2018). The narratives were created by the participants themselves based on image stimuli from the Thematic Apperception Test. The researchers analyzed both the differences in structural production and semantic comprehension. Results showed that ASD participants had decreased syntactic complexity within created narratives compared to TD participants (Lee et al., 2018). Although this study analyzed the production of narrative structure by participants, it still represents how structural processing may differ, since accurate narrative production requires accurate narrative comprehension (Coderre et al., 2018).

Nonlinguistic Processing in ASD

Given the documented evidence of difficulties with various aspects of language processing among individuals with ASD, including semantic and syntactic processing, many clinical assessments and interventions use visual stimuli in an effort to bypass linguistic processing demands. There is a prevalent "Visual Ease Assumption" within educational and clinical settings that propagates the notion that visual stimuli reduce difficulties in comprehension in some conditions with linguistic complications like ASD (Coderre, 2020). However, there is a lack of evidence for the "Visual Ease Assumption" in studies addressing ASD, among other clinical conditions (Coderre, 2020). In fact, as reviewed above, there is now abundant evidence that visual and linguistic narratives, despite relying on separate input modalities, use similar cognitive and neural processing mechanisms. These common processing mechanisms would suggest that non-linguistic narratives may *not* be easier to process than linguistic narratives simply because they use visual stimuli (Coderre, 2020).

Semantic Processing of Visual Narratives in ASD

There is indeed evidence that narrative comprehension is impaired in ASD for both visual and linguistic modalities. In addition to the semantic processing difficulties of linguistic narratives, there are similar semantic processing difficulties for visual narratives in ASD groups. Coderre et al. (2018) collected ERP data as participants read written sentences (linguistic narratives) and viewed comic strips (visual narratives). Both types of narratives were manipulated to contain a semantically congruent or incongruent end to the sequence (i.e., final word in sentence or final image in comic strip). In both the linguistic and non-linguistic narratives, the ASD group demonstrated reduced N400 effects as compared to the TD group, suggesting challenges with semantic processing. In another study, Manfredi et al. (2020) found that N400 effects were again reduced when children with ASD were presented with both a compatible and incompatible final panel in a visual narrative, as well as a compatible and incompatible sentence in a linguistic narrative, compared to a TD group. These studies point to difficulties in semantic comprehension for non-linguistic narratives as well as linguistic narratives.

Structural Processing of Visual Narratives in ASD

As described above, understanding the syntax or structure of a narrative is important for accurate comprehension. However, there are few studies examining how structural comprehension is affected in visual narratives for individuals with ASD. Adornetti et al. (2020) used a picture arrangement task and found that children with ASD demonstrated a lower ability to correctly arrange visual stimuli into a coherent narrative than TD groups. Although the picture arrangement task has been utilized in other studies to examine visual narrative processing in ASD, as noted in a review by Coderre (2020), this task addresses general visual narrative comprehension and does not isolate structural processing. Additionally, a possible limitation of this task is that it takes a subjective approach to naming a “correct” sequence, when this could contain a neurotypical bias. To our knowledge, there are no studies explicitly testing structural processing of visual narratives in ASD individuals. The current study aims to address this gap in the literature by examining the independent contributions of semantics and structure in comprehending visual narratives in individuals with ASD.

Current Study

Because visual and linguistic narrative comprehension rely on similar cognitive processes, there is a further need for studying the non-linguistic comprehension of visual narratives to ensure that the "Visual Ease Assumption" does not inadequately support the learning of individuals with ASD. ASD sometimes affects an individual's verbal language comprehension, but the "Visual Ease Assumption" implies that comprehension difficulties can be mitigated with visual narratives. This may lead to a bias in the tools that are used in education systems. This project aims to address the lack of research into grammatical processing for visual narratives in individuals with ASD. If we observe grammatical processing impairments in visual narratives in ASD individuals, it may dismantle the assumption that visual narratives are easier to understand. It would be essential for clinicians and educators to be aware of this, in terms of assessments and interventions. Gaining knowledge on differences in processing, with extension into visual narratives, is very important because findings can be used to develop learning interventions and identify adjustments societally to allow accessibility.

METHODOLOGY

Stimuli Construction

This study replicates the methodology from the Cohn et al. (2012) study on visual narratives. The stimuli used were constructed by Charles Schulz in the *Complete Peanuts* volumes 1-6 (1950-1962). The consistent panel setup, consistent themes and repetitive characters, recognizability, and large amounts of content are the main reasons *Peanuts* comics were chosen. Cohn et al. (2012) ensured the selected visual narratives would not lead to episodic memory effects by selecting novel six-panel sequences that had been tested for familiarity. No text was included in the stimuli, to avoid linguistic narrative inference.

Four sequence types were created to isolate semantic and structural processing of visual narratives. The comic strips below provide examples of each of the four conditions. The first condition (Figure 2a) was the Normal sequence, containing both semantic relatedness and narrative structure. This sequence is linked both meaningfully and in a comprehensible grammatical order (e.g., the panels depict a baseball game in canonical narrative arc). The second condition (Figure 2b) was the Semantic Only sequence. It has a semantic context (e.g., each panel is linked to a baseball game) but no narrative structure because there is no canonical narrative arc. The third condition (Figure 2c) was a Structural Only sequence. This strip has a global narrative structure with core elements like an Establisher, Initial, Peak and Release categories, but there is no meaningful semantic relatedness between the panels. The last condition (Figure 2d) was a Scrambled sequence that does not contain a semantic relationship or narrative structure (e.g., panels do not have the same semantic theme and are not ordered in a canonical narrative arc.

Figure 2: Examples of the four conditions, including an overview of the presence or absence of either semantic relatedness or narrative structure in each condition and examples of each type of sequence.

Condition Type	**Semantic Relatedness**	**Narrative Structure**	**Example Sequence**
Normal	+	+	
Semantic Only	+	–	
Structural Only	–	+	
Scrambled	–	–	

Participants

The participants recruited as part of the ASD group for this study were 20 adolescents and adults with ASD (12 male, 7 female, 1 trans male) from the University of Vermont campus and additional areas of Burlington, Vermont. All participants in the ASD group either had a diagnosis of autism or were self-diagnosed. All participants in this group were administered the Autism Diagnostic Observation Schedule version 2 (ADOS-2; Lord et al., 2012). Two of the participants did not meet the cutoff for ASD according to the ADOS SA+RBB or CSS scores but scored high on the Autism Quotient (AQ), a self-report measure of autistic traits. Twenty TD subjects (7 male, 12 female, 1 trans male) were included as a control group. See Table 1 for full demographic information.

Procedure

Written consent was obtained from all participants, which included written assent from individuals who were not their own legal guardians and additional consent from said legal guardians. After consenting, participants completed a series of cognitive and language assessments. The Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4) was used as a measure of receptive vocabulary (Dunn & Dunn, 2007). The Kaufman Brief Intelligence Test (KBIT) was used as a cognitive assessment of both verbal and nonverbal intelligence (Kaufman & Kaufman, 2004). The Visual Language Fluency Index (VLFI) was administered to participants and is a measure of expertise in comprehending non-linguistic narratives that was used by Cohn et al. (2012) and has since been used in a multitude of additional studies (Cohn, 2020). Both the forward and backward digit span tasks measure working memory (Baddeley, 2003). The Autism Quotient (AQ) was administered to measure characteristics of ASD in the general public. This self-report questionnaire assesses social skills, communication, attention switching, attention to detail, and imagination (Baron-Cohen et al., 2001). Participants in the ASD group were also administered the ADOS-2 (Lord et al., 2012), a diagnostic measure of ASD.

Demographic information of participants is reported in Table 1. The ASD group was slightly older than the TD group ($t(23.81) = -2.56$, $p < 0.05$) and had a slightly higher VLFI score ($t(23.67) = -1.82$, $p = 0.08$). The ASD group had lower working memory scores on both the forward and backward digit span (all *p*'s < 0.05). As expected, the ASD group had a higher AQ score than the TD group ($t(35.4) = -7.24$, $p < 0.01$). The groups did not differ on receptive language ability ($p = 0.69$) or verbal or non-verbal IQ (all *p*'s > 0.42).

Table 1: Demographic information of the participants included in the study. Means and ranges are reported for each variable, as well as group differences as assessed with independent-samples *t*-tests. Asterisks indicate statistical significance (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). All participants maintained verbal and nonverbal KBIT scores above 70, which is within 2 standard deviations of the standardized mean. SA+RBB: Social Affect and Restricted and Repetitive Behaviors. CSS: Calibrated Severity Score.

Variable	**TD group (n=20)**	**ASD group (n=20)**	**Group difference**
Age	22.4 (17-32)	29.9 (16-63)	0.02 *
PPVT	113.6 (98-136)	111.9 (93-132)	0.69
KBIT: Verbal	115.3 (91-141)	111.4 (89-135)	0.42
KBIT: Non-verbal	105.1 (74-130)	105.5 (79-134)	0.99
KBIT: Combo	112 (89-137)	109.4 (82-132)	0.55
VLFI	7.5 (2-15.1)	11.9 (1.5-33.25)	0.08 §
Digit Span: Forward	12.2 (7-16)	10.2 (7-15)	0.01 *
Digit Span: Backward	9.5 (5-14)	8.0 (5-12)	0.04 *
Autism Quotient	15.9 (8-25)	30.5 (17-41)	< 0.0001 ***
ADOS: SA+RBB	N/A	11.9 (5-21)	N/A
ADOS: CSS	N/A	6.4 (2-10)	N/A

Before the experiment began, we measured participants' head circumference to determine the appropriate size EEG net. A wax pencil was used to mark a reference point at the midpoint of lines between the nasion and inion and preauricular points. Prior to placement, an electrolyte solution of water, potassium chloride and baby shampoo was used to soak the net. The net was placed on the participant's head and experimenters ensured each electrode was contacting the scalp. Impedances were kept under 50 kΩ as much as possible. Impedances were continuously checked, and electrodes were re-wetted approximately every twenty minutes.

Participants were separated from the experimenters except for a joint open door connecting the rooms. Lights were left on. The experiment used E-Prime 2.0.10.356 for stimuli presentation. NetStation 5 was used to record the EEG data.

Instructions were presented to each participant to inform them that they will watch short stories based on the Peanuts comics and these stories consisted of several comic panels. The participants were informed that they would first see a "Ready?" screen at the start of each story and they could press any button on the screen to start. They were informed they would then see each panel one at a time and should try to remain still, try to not more their eyes, and try to only blink when there are blank screens in between the panels. The instructions also notified the participants that after each story they would be asked to judge if the story made sense or not. To convey their answer, there would be a question mark after each final panel as a prompt, and they should Press 1 if the story did make sense and Press 2 if not. After some trials there would be a comprehension question and the participants were informed to Press 1 for YES and Press 2 for NO. They were then informed on screen they could press any button in order to start the practice trials.

The instructions were also read out loud by the experimenter, so participants were able to ask any questions. There were ten practice trials presented to the participants to allow for familiarity with formatting. The experimental trials began after the practice trials.

There were six blocks of 40 trials each. This totals 240 trials, with 60 trials per condition. In total, the experiment ranged from 50-75 minutes in length. To prevent repeated panels from appearing in different strips or conditions, there were four sets of stimuli created to ensure no repetition. To start every trial, participants responded to the word "READY?" in white font against a black background via button press. They then viewed a white fixation cross for 500 ms. There were then six panels for each sequence. The panels were black and white against an all-black background. Each panel was on the screen for 1350 ms with a 300 ms inter-stimulus interval (ISI). At the end of each sequence, there was a red question mark to prompt them to answer if the story made sense. The participants responded with a button press to initiate the next trial. Participants were asked a comprehension question after some sequences to assess overall comprehension. "Did Snoopy catch the leaf?", would be an example of this for a particular sequence.

EEG Preprocessing

Data was preprocessed with EEGLab (version 14.1.1b) and Matlab (version 2019a). The data was first filtered using a 0.1-50 Hz bandpass filter. Bad channels were identified as those exceeding +/-30 μV; these channels were replaced via interpolation. The continuous EEG data was then segmented into epochs time-locked to the onset of each panel in the sequence, extending 100 ms before and 1500 ms after panel onset. Eye movement artifacts were identified and then later removed from the data with independent component analysis (ICA). Before running ICA, the mean of each trial was removed (Groppe et al., 2009) and the data were reduced to 32 dimensions. After ICA decomposition, eye movements, blinks, muscle artifacts, and other noise components were identified visually and removed from the data manually. The data was then baseline-corrected using the first 100 ms of each segment and was re-referenced to the average of the mastoids.

Statistical Analysis

We performed two analyses on the behavioral data. First, we evaluated whether participants' ratings of coherence differed between sequence type, taken from their responses of whether each sequence "made sense" or not. Second, we analyzed accuracy on comprehension questions, which were presented after a subset of trials. Both analyses were performed using a group by condition repeated-measures ANOVA and follow-up *t*-tests. Age and digit span forward were included as covariates.

ERP amplitude was evaluated with R version 4.0.3 and topographic plots were created with Matlab version R2021a. We analyzed ERP data from nine electrode clusters across the scalp, centered around left frontal (F3), midline frontal (Fz), right frontal (F4), left central (C3), midline central (Cz), right central (C4), left parietal (P3), midline parietal (Pz), and right parietal (P4) regions.

Repeated-measures ANOVAs were run on the average ERP amplitude in three different time windows: 200-350, 400-600, and 600-900 ms. These time windows are similar to those used in Cohn et al. (2012) and were designed to examine the N300, N400, and late components, respectively. We first examined overall effects by including group (TD, ASD) as a between-subjects factor and condition (Normal, Semantic Only, Structural Only, Scrambled), site (frontal, central, parietal), and laterality (left, midline, right) as within-subjects factors. Age and digit span forward values were included as covariates. For these analyses, only significant interactions of group and condition were followed up using simplified ANOVAs. Paired-samples *t*-tests were used to identify significant differences between all conditions within each group.

We also examined the data by comparing difference waves. Because of the number of conditions (four sequence types) and the differences in effect size between conditions (Cohn et al., 2012), the overall ANOVAs discussed above may not reveal subtle differences, particularly between the scrambled and structural conditions. Difference waves were computed by subtracting the amplitude of condition 2 from that of condition 1 at each timepoint. Difference wave amplitudes were then averaged over each time window of interest for each participant and electrode cluster. To identify main effects and interactions, repeated-measures ANOVAs were run on the difference wave amplitudes in each time window. Group was included as a between-subjects factor and site (frontal, central, parietal) and laterality (left, midline, right) were included as within-subject effects. Age and digit span forward values were included as covariates. Only significant main effects of, or interactions with, group were followed up. Independent-samples *t*-tests were used to identify significant group differences.

RESULTS

Behavioral Analyses

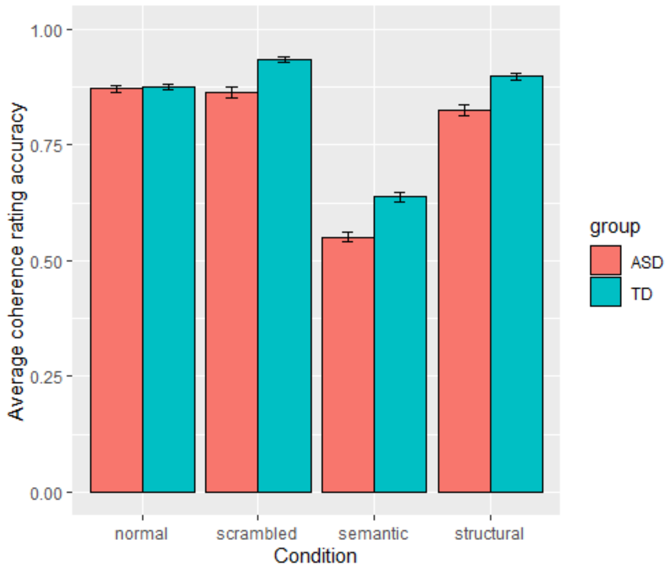
Coherence Ratings

The group by condition repeated-measures ANOVA with age and digit span forward values included as covariates showed no interaction between group and condition (Table 2). However, there was a main effect of condition ($F(3,114) = 45.05$, $p < 0.0001$). Follow-up paired-sample t-tests indicated that, over both groups, participants were significantly less accurate at judging the coherence of the semantic condition ($M = 0.59$, $SD = 0.21$) compared to all other conditions (all *p*'s < 0.0001; Figure 3). Accuracy was also significantly lower for the structural condition (M = 0.86, SD = 0.19) compared to the scrambled condition (*M* = 0.90, *SD* = 0.19; $p < 0.01$). There were no differences between the normal (*M* = 0.87, *SD* = 0.13) and structural conditions ($p = 0.70$), or between the normal and scrambled conditions ($p = 0.41$).

Table 2: *F*-values for the repeated-measures ANOVA on the behavioral coherence ratings, with a between-subjects factor of group (TD, ASD) and within-subjects factor of condition (normal, semantic only, structural only, scrambled). Age and digit span were included as covariates. Asterisks indicate statistically significant results **(**§ = $p < 0.10$; ***** = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	***F*-value**
Age	0.22
Digit span	4.98 *
Group	1.35
Condition	45.05 ***
Group:condition	0.77

Figure 3: Average accuracy for the behavioral coherence ratings in each group and condition. Error bars show the standard error of the mean.



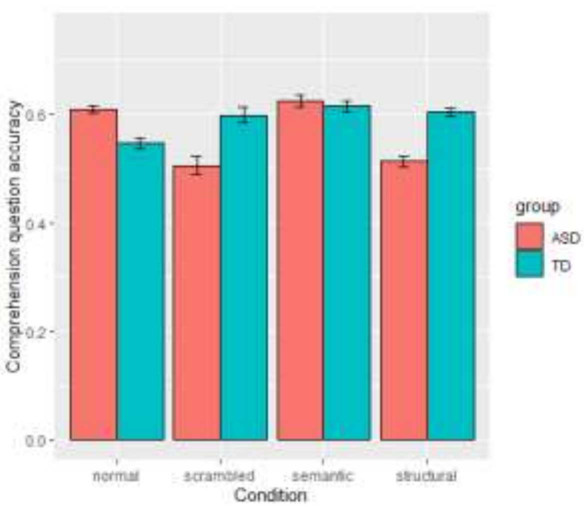
Comprehension Questions

The group by condition repeated-measures ANOVA with age and digit span forward as covariates showed no main effect of group or condition, and no interaction between group and condition (see Table 3 and Figure 4).

Table 3: *F*-values for the repeated-measures ANOVA on the behavioral accuracy on the comprehension questions, with a between-subjects factor of group (TD, ASD) and within-subjects factor of condition (Normal, Semantic Only, Structural Only, Scrambled). Age and digit span were included as covariates. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	***F*-value**
Age	0.09
Digit span	0.61
Group	0.40
Condition	0.71
Group:condition	1.16

Figure 4: Average accuracy for the behavioral comprehension questions in each group and condition. Error bars show the standard error of the mean.



ERP Results

The ERPs for all four conditions in each group are plotted in Figure 5 for the TD group and Figure 6 for the ASD group.

<u>Figure 5</u>: ERP waveforms for the four conditions in the TD group at nine electrode clusters across the scalp. Negativity is plotted upwards

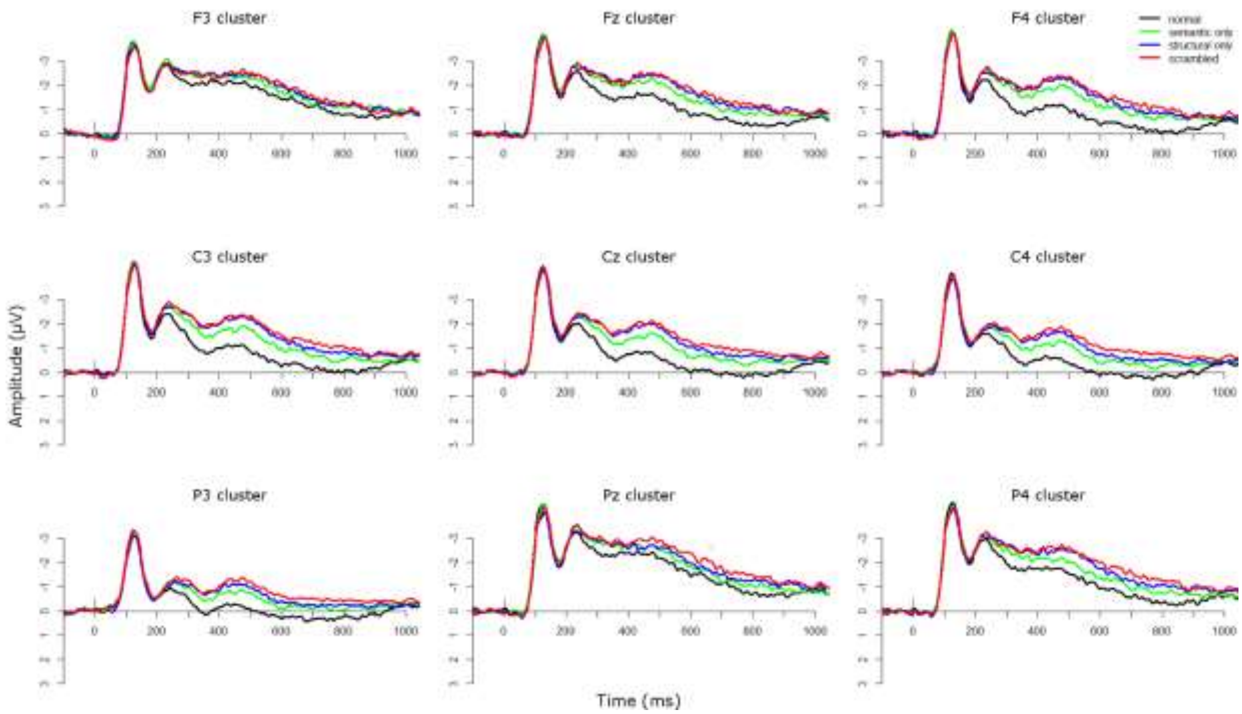
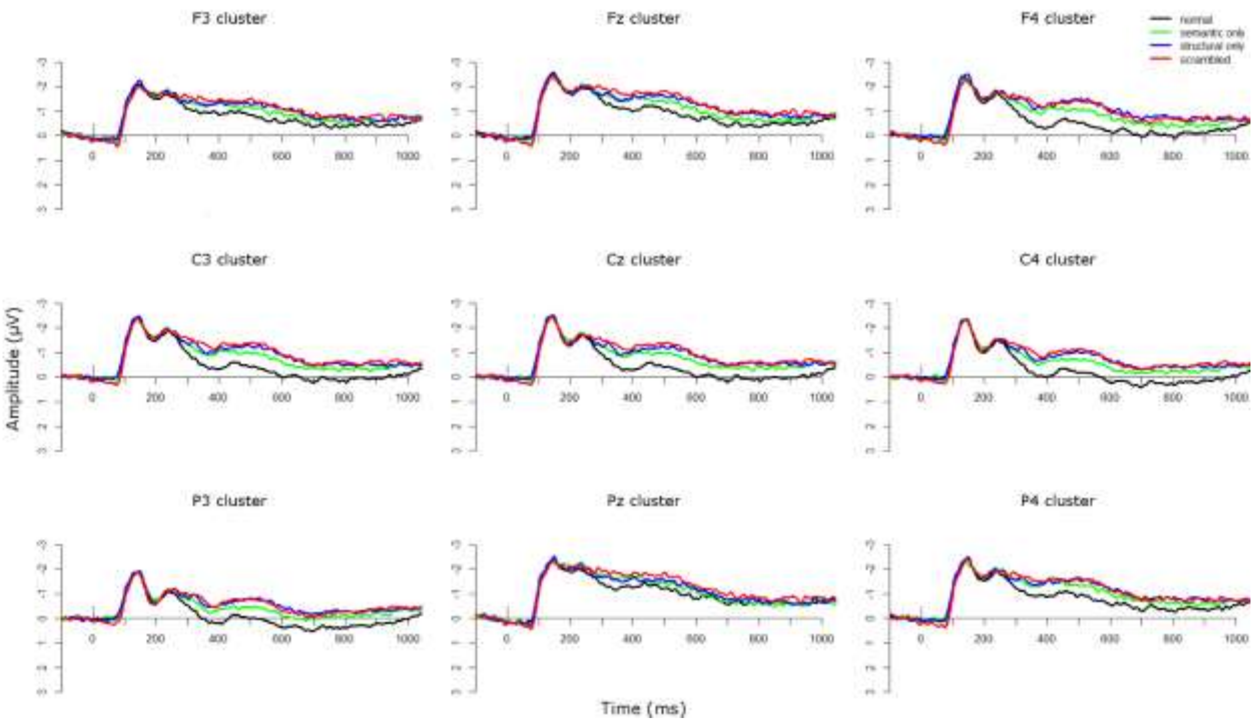


Figure 6: ERP waveforms for the four conditions in the ASD group at nine electrode clusters across the scalp. Negativity is plotted upwards.



We first explored effects of condition and group using group (TD, ASD) by condition (Normal, Semantic Only, Structural Only, Scrambled) by site (frontal, central, parietal) by laterality (left, midline, right) repeated-measures ANOVAs in three different time windows: 200-350 ms, 400-600 ms, and 600-900 ms. Age and digit span values were included as covariates. The full results are shown in Table 4; only interactions of group and condition are discussed in the text.

Table 4: *F*-values for the repeated-measures ANOVAs on the ERP amplitude in each analysis window, with a between-subjects factor of group (TD, ASD) and within-subjects factors of condition (Normal, Semantic Only, Structural Only, Scrambled), site (frontal, central, parietal), and laterality (left, midline, right). Age and digit span were included as covariates. Interactions of group and condition are highlighted in bold. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	Time window 1 (200-350 ms)	Time window 2 (400-600 ms)	Time window 3 (600-900 ms)
Age	0.68	0.03	0.11
Digit span	0.47	0.68	1.19
Group	0.07	0.10	0.05
Condition	9.03***	31.74 ***	18.50 ***
Group:condition	0.32	0.20	0.45
Site	75.21 ***	65.09 ***	37.05 ***
Group:site	3.97 *	3.84*	1.91
Laterality	14.69 ***	15.90 ***	6.99 **
Group:laterality	0.08	0.32	0.21
Condition:site	12.62 ***	30.20 ***	19.08 ***
Group:condition:site	**2.51 ***	**3.90 *****	**3.50 ****
Condition:laterality	1.60	1.20	0.56
Group:condition:laterality	0.66	0.93	0.88
Condition:site:laterality	0.83	2.92***	2.85 ***
Group:condition:site:laterality	0.33	0.71	1.49

200-350ms. A significant negative deflection occurred from 200-350 ms, representing the N300 ERP component. Results from the repeated-measures ANOVA (Table 4) showed a significant interaction of group, condition, and site ($F(6,228) = 2.51$, $p < 0.05$). Follow-up ANOVAs breaking up by site showed no interactions of group and condition at any site (all *p*'s > 0.32). However, when breaking up by group, there were significant interactions of condition and site in both the TD group ($F(6,114) = 8.76$, $p < 0.0001$) and the ASD group ($F(6,114) = 5.08$, $p < 0.001$). In both groups, there was a significant main effect of condition at frontal sites and central sites (all *p*'s < 0.05), but not at parietal sites (all *p*'s < 0.14).

Follow-up paired-samples *t*-tests (at frontal and central sites in each group) indicated that, for both groups, Normal sequences elicited the least negative deflection compared to the Semantic Only, Structural Only and Scrambled sequences, respectively, with the comparison of Normal sequences to all three other sequence types being significant (all p's < 0.001). No group showed a significant difference in the comparison of the Semantic only and Structural Only sequence (although this was a statistical trend for the TD group at frontal sites: $p = 0.08$). Comparisons of the Semantic Only and Scrambled sequences demonstrated significant differences for the ASD group at both frontal and central sites (all p's < 0.05) but not for the TD group (all p's > 0.15). Comparisons of the Structural Only and Scrambled sequences demonstrated significant differences for the ASD group at frontal sites ($p < 0.05$) but not central sites ($p = 0.13$), but no differences at either site for the TD group (all p's > 0.33).

Thus, overall, the groups showed similar patterns of amplitude modulation by condition, although there were some subtle differences such that the ASD group showed larger differences between the Scrambled condition and other conditions compared to the TD group. This can also be seen in Figure 5 and Figure 6, in which the ASD group shows some divergence of the Scrambled condition with other conditions between 200-350 ms, whereas for the TD group the Scrambled and Structural Only conditions appear very similar.

400-600ms. A significant negative deflection occurred from 400-600 ms, representing the N400 ERP component. Results from the overall ANOVA (Table 4) showed a significant interaction of group, condition, and site ($F(6,228) = 3.94$, $p < 0.001$). Follow-up ANOVAs breaking up by site showed no interactions of group and condition at any site (all p's > 0.33). However, when breaking up by group, there were significant interactions of condition and site in both the TD group ($F(6,114) = 21.68$, $p < 0.001$) and the ASD group ($F(6,114) = 10.44$, $p <$

0.0001). In the TD group, there was a significant main effect of condition at both frontal and central sites (all *p*'s < 0.0001). In the ASD group, there was a main effect of condition at frontal, central, and parietal sites (all *p*'s < 0.0001).

Follow-up paired-samples *t*-tests indicated that, at both frontal and central sites for both groups, Normal sequences elicited the least negative deflection compared to the Semantic Only, Structural Only and Scrambled sequences, respectively, with the comparison of Normal sequences to all three other sequence types being significant (all *p*'s < 0.001). The exception to this pattern was at parietal sites in the ASD group, in which the Structural Only condition had the most negative amplitude, followed by the Scrambled, Semantic Only, and Normal conditions, respectively. Once again, the Normal condition showed significant differences compared to all other conditions (all *p*'s < 0.001).

Both groups showed significant differences in the comparisons of the Semantic Only and Structural Only sequences (all *p*'s < 0.001) and of the Semantic Only and Scrambled sequences (all *p*'s < 0.0001) at all sites of interest (frontal and central sites in the TD group; frontal, central, and parietal sites in the ASD group).

When comparing the Structural Only versus Scrambled conditions, the TD group showed a significant difference only at central sites ($p < 0.05$), whereas the ASD group showed significant differences only at frontal and parietal sites (all *p*'s < 0.05). This may suggest a difference in topographic distribution of structural processing in ASD and TD groups, potentially suggesting different processing mechanisms.

600-900ms. The 600-900 ms time window was chosen to examine sustained negativity effects. Results from the overall ANOVA (Table 4) showed a significant interaction of group, condition, and site ($F(6,228) = 3.50$, $p < 0.01$). There was a trend of an interaction of group and condition at parietal sites ($F(3,114) = 2.22$, $p = 0.09$), which arose from a significant main effect of condition in the ASD group ($F(3,57) = 8.49$, $p < 0.0001$) but not in the TD group ($p = 0.45$). At parietal sites, the ASD group showed the least negative amplitudes for the Normal condition, followed by the Semantic Only, Scrambled, and Structural conditions, respectively. Paired-sample t-tests showed significant differences between all conditions (all *p*'s < 0.05). In contrast, at parietal sites, the TD group showed the least negative amplitudes for the Normal condition, followed by the Structural Only, Semantic Only, and Scrambled conditions, respectively. In this group there were differences between the Normal and Semantic Only conditions ($p < 0.05$), and between the Normal and Scrambled conditions ($p < 0.05$), but all other comparisons were non-significant (all *p*'s > 0.17). Overall, this suggests that the difference between conditions at this late time window extends into parietal sites for the ASD group, but not for the TD group.

Difference waves: Scrambled – Structural Only to Isolate Structural Processing

Because including condition as a four-level factor in the ANOVAs may overlook smaller differences between conditions, we also explored using difference waves to directly compare conditions. In particular, we were interested in the comparison of Scrambled and Structural Only conditions in this study, which will isolate structural processing of visual narratives. However, as was found in Cohn et al. (2012), the difference between these two conditions was much smaller than the differences between other conditions. This may result in these smaller effects being overshadowed in the overall ANOVA. Therefore, we calculated difference waves by subtracting the Structural Only amplitudes from the Scrambled amplitudes at each time point and electrode cluster. The ERP waveforms can be seen in Figure 7; topographic plots of this difference are shown in Figure 8a. We then ran group (TD, ASD) by site (frontal, central, parietal) by laterality (left, midline, right) repeated-measures ANOVA in the same time windows as before. Age and digit span forward values were again included as covariates. The full results are presented in Table 5. Only significant main effects of, or interactions with, group are discussed in the text.

<u>Figure 7</u>: Difference waves for the Scrambled – Structural Only comparison for each group at each of the nine electrode clusters across the scalp. Negativity is plotted upwards.

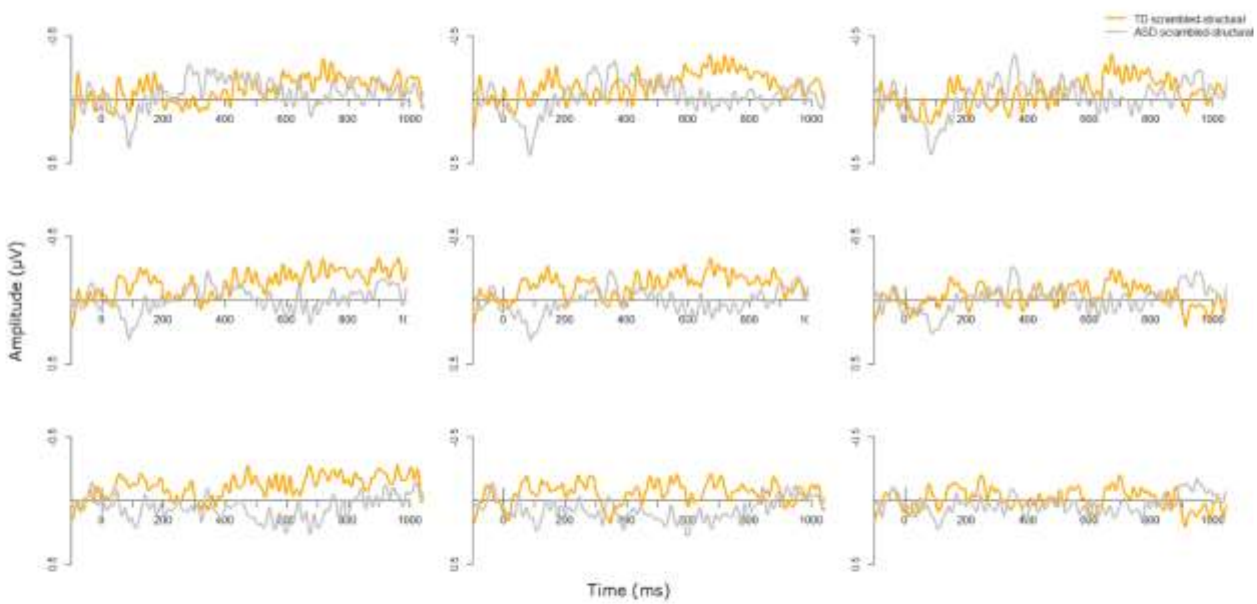


Figure 8: Topographic plots of the difference waves in each time window for the contrasts of interest: a) Scrambled – Structural Only; b) Semantic Only – Normal; c) Scrambled – Semantic Only; d) Structural Only – Normal.

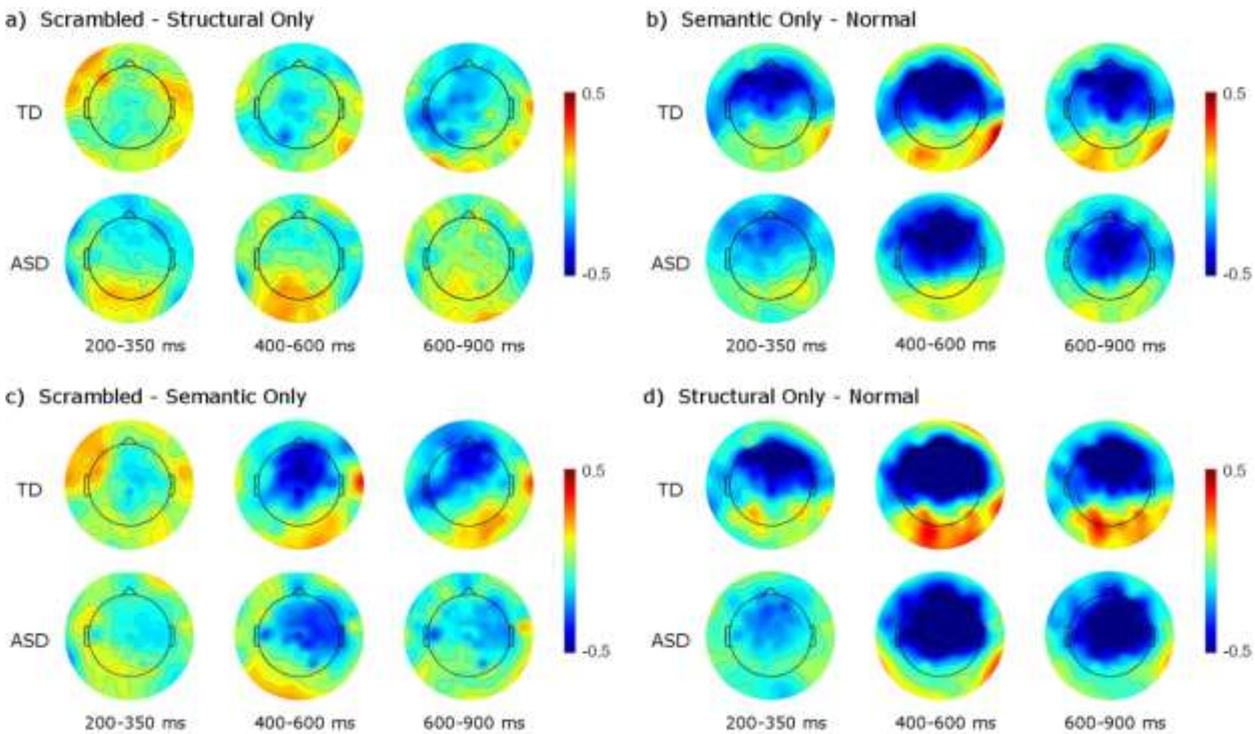


Table 5: *F*-values for the repeated-measures ANOVAs on the Scrambled – Structural Only difference waves in each analysis window, with a between-subjects factor of group (TD, ASD) and within-subjects factors of site (frontal, central, parietal) and laterality (left, midline, right). Age and digit span were included as covariates. Main effects of or interactions with group are highlighted in bold. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.0001$).

Main effect or interaction	Time window 1 (200-350 ms)	Time window 2 (400-600 ms)	Time window 3 (600-900 ms)
Age	4.61 *	0.50	0.15
Digit span	0.08	0.08	0.08
Group	0.59	2.18	2.71
Site	1.13	4.09 *	3.55 *
Group:Site	**2.86 §**	**2.87 §**	0.01
Laterality	0.21	0.61	0.77
Group:laterality	0.39	1.38	1.08
Site:laterality	0.68	0.41	0.68
Group:site:laterality	0.17	1.51	1.61

200-350 ms. The overall ANOVA (Table 5) showed a trend of an interaction of group and site from 200-350 ms ($F(2,76) = 2.86$, $p = 0.06$), which arose from a significant main effect of group at parietal sites ($F(1,116) = 6.21$, $p < 0.05$) such that the TD group had a larger negative amplitude ($M = -0.04$, $SD = 0.30$) compared to the ASD group ($M = 0.05$, $SD = 0.23$). This indicates that the TD group had a significantly larger difference wave, i.e., a greater difference between Scrambled and Structural Only conditions during this early time window compared to the ASD group.

400-600 ms. The overall ANOVA (Table 5) showed a trend of an interaction of group and site from 400-600 ms ($F(2,76) = 2.87$, $p = 0.06$). There was a significant main effect of group at central sites ($F(1,116) = 7.30$, p < 0.01), with the TD group having a larger negative amplitude, i.e., a larger difference wave ($M = -0.12$, $SD = 0.39$) compared to the ASD group ($M = -0.018$, *SD* = 0.28). There was also a statistically significant effect of group at parietal sites ($F(1,116) = 9.22$, $p < 0.01$), with the TD group having a larger negative amplitude (*M* = -0.08, *SD* = 0.383) compared to the ASD group (*M* = 0.096, *SD* = 0.27). The data indicates that the TD group had a significantly increased difference wave centroparietally during the 400-600 ms window compared to the ASD group.

600-900 ms. There were no significant main effects of group or interactions with group in this time window.

Difference waves: Semantic Only – Normal to Isolate Structural Processing

Through the subtraction of Normal sequences (semantics and structure) from Semantic Only sequences (just semantics), we can isolate the neural activity and increased negativity of structural processing. Therefore, we calculated difference waves by subtracting the Normal amplitudes from the Semantic Only amplitudes at each time point and electrode cluster (see Figure 8b and Figure 9). We then ran group (TD, ASD) by site (frontal, central, parietal) by laterality (left, midline, right) repeated-measures ANOVA in the same time windows as before. Age and digit span forward values were again included as covariates. The full results are presented in Table 6. Only significant main effects of, or interactions with, group are discussed in the text.

The overall ANOVA (Table 6) showed no statistically significant interactions during any of the three-time windows. This suggests that there were no differences between groups in structural processing as measured by this contrast.

Figure 9: Difference waves for the Semantic Only – Normal comparison for each group at each of the nine electrode clusters across the scalp. Negativity is plotted upwards.

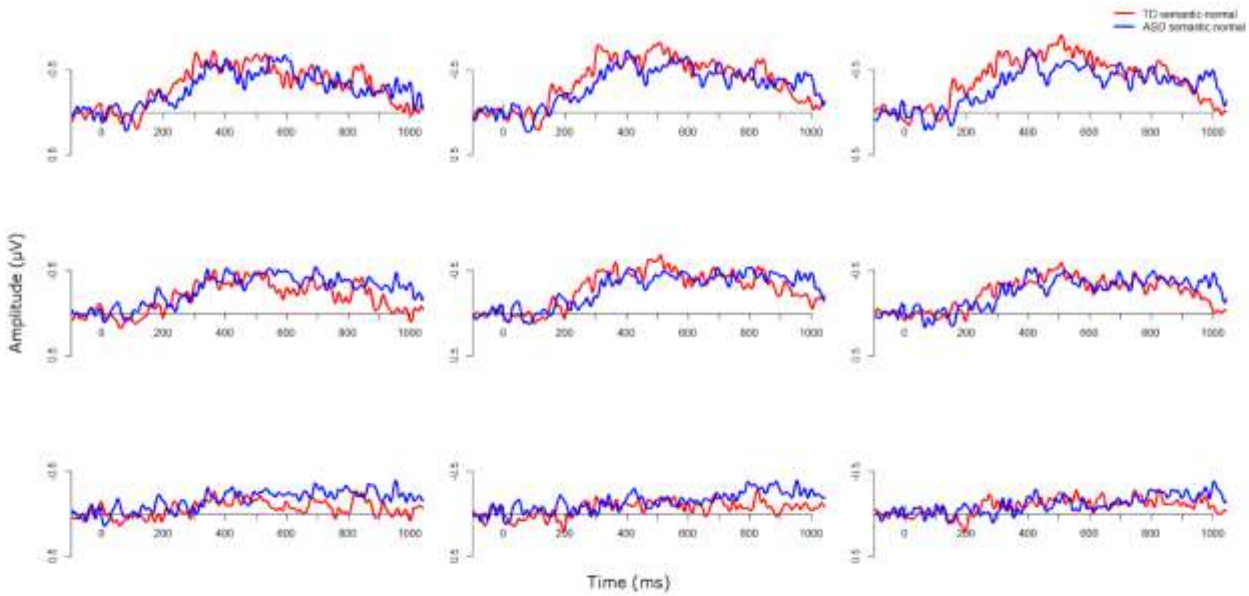


Table 6: *F*-values for the repeated-measures ANOVAs on the Semantic Only – Normal difference waves in each analysis window, with a between-subjects factor of group (TD, ASD) and within-subjects factors of site (frontal, central, parietal) and laterality (left, midline, right). Age and digit span were included as covariates. Main effects of or interactions with group are highlighted in bold. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	Time window 1 (200-350 ms)	Time window 2 (400-600 ms)	Time window 3 (600-900 ms)
Age	0.59	0.64	1.17
Digit span	0.13	0.21	0.86
Group	0.13	0.21	0.01
Site	17.48 ***	30.76 ***	12.10 ***
Group:site	1.88	0.86	1.25
Laterality	0.37	0.37	1.22
Group:laterality	0.47	1.32	0.75
Site:laterality	0.96	3.98 **	2.55 *
Group:site:laterality	0.60	0.53	0.75

Difference waves: Scrambled – Semantic Only to Isolate Semantic Processing

Through the subtraction of Semantic Only sequences (only semantics) from Scrambled sequences (neither structure nor semantics), we can isolate the neural activity related to semantic processing. Therefore, we calculated difference waves by subtracting the Semantic Only amplitudes from the Scrambled amplitudes at each time point and electrode cluster (see Figure 8c and Figure 10). We then ran group (TD, ASD) by site (frontal, central, parietal) by laterality (left, midline, right) repeated-measures ANOVA in the same time windows as before. Age and digit span forward values were again included as covariates. The full results are presented in Table 7. Only significant main effects of, or interactions with, group are discussed in the text.

Figure 10: Difference waves for the Scrambled – Semantic Only comparison for each group at each of the nine electrode clusters across the scalp. Negativity is plotted upwards.

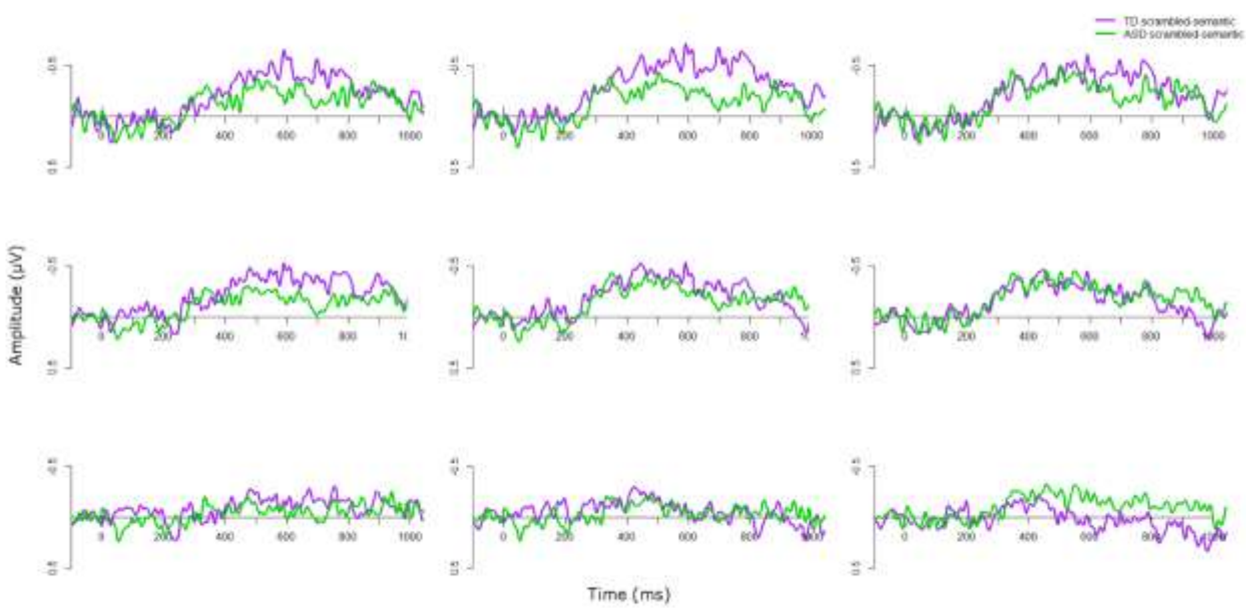


Table 7: *F*-values for the repeated-measures ANOVA on the Scrambled – Semantic Only difference waves in each analysis window, with a between-subjects factor of group (TD, ASD) and within-subjects factors of site (frontal, central, parietal) and laterality (left, midline, right). Age and digit span were included as covariates. Main effects of or interactions with group are highlighted in bold. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	Time window 1 (200-350 ms)	Time window 2 (400-600 ms)	Time window 3 (600-900 ms)
Age	5.49 *	2.44	4.54 *
Digit span	0.03	0.00	0.01
Group	0.91	2.12	2.90
Site	2.19	11.43 ***	12.82 ***
Group:site	<0.01	1.44	**2.83 §**
Laterality	2.90 §	0.64	0.29
Group:laterality	0.74	2.07	**2.46 §**
Site:laterality	0.10	0.53	2.01
Group:site:laterality	0.34	0.98	**3.33 ***

200-350 ms. There were no main effects of or interactions with group in this time window.

400-600 ms. There were no main effects of or interactions with group in this time window.

600-900 ms. The overall ANOVA (Table 7) showed a significant interaction between group, hemisphere, and site from 600-900 ms ($F(4,152) = 3.33$, $p < 0.05$), which arose from a significant interaction of group and site at the midline ($F(2,76) = 3.15$, $p < 0.05$) and in the right hemisphere ($F(2,76) = 4.52$, $p < 0.05$).

At the midline, there was a main effect of group at frontal sites ($F(1,36) = 5.02$, $p < 0.05$), and a trend at central sites ($F(1,36) = 3.24$, $p = 0.08$), but a non-significant effect at parietal sites

(p = 0.61). At both frontal and central sites, the TD group had a more negative difference wave compared to the ASD group.

In the right hemisphere, there was a main effect of group at frontal sites ($F(1,36) = 4.60$, $p < 0.05$), and a trend at central sites ($F(1,36) = 2.92$, $p = 0.10$), but a non-significant effect at parietal sites ($p = 0.87$). At frontal sites, the TD group had a more negative difference wave (M = -0.37, SD = 0.69) compared to the ASD group (M = -0.23, SD = 0.54), while at central sites the ASD group had a more negative difference wave (M = -0.22, SD = 0.47) than the TD group (M = -0.19, SD = 0.48).

Difference waves: Structural Only – Normal to Isolate Semantic Processing

Through the subtraction of Normal sequences (structure and semantics) from Structural Only sequences (structure), we can isolate the neural activity of semantic processing. Therefore, we calculated difference waves by subtracting the Normal amplitudes from the Structural Only amplitudes at each time point and electrode cluster (see Figure 8d and Figure 11). We then ran group (TD, ASD) by site (frontal, central, parietal) by laterality (left, midline, right) repeated-measures ANOVA in the same time windows as before. Age and digit span forward values were again included as covariates. The full results are presented in Table 8. Only significant main effects of, or interactions with, group are discussed in the text.

Figure 11: Difference waves for the Structural Only – Normal comparison for each group at each of the nine electrode clusters across the scalp. Negativity is plotted upwards.

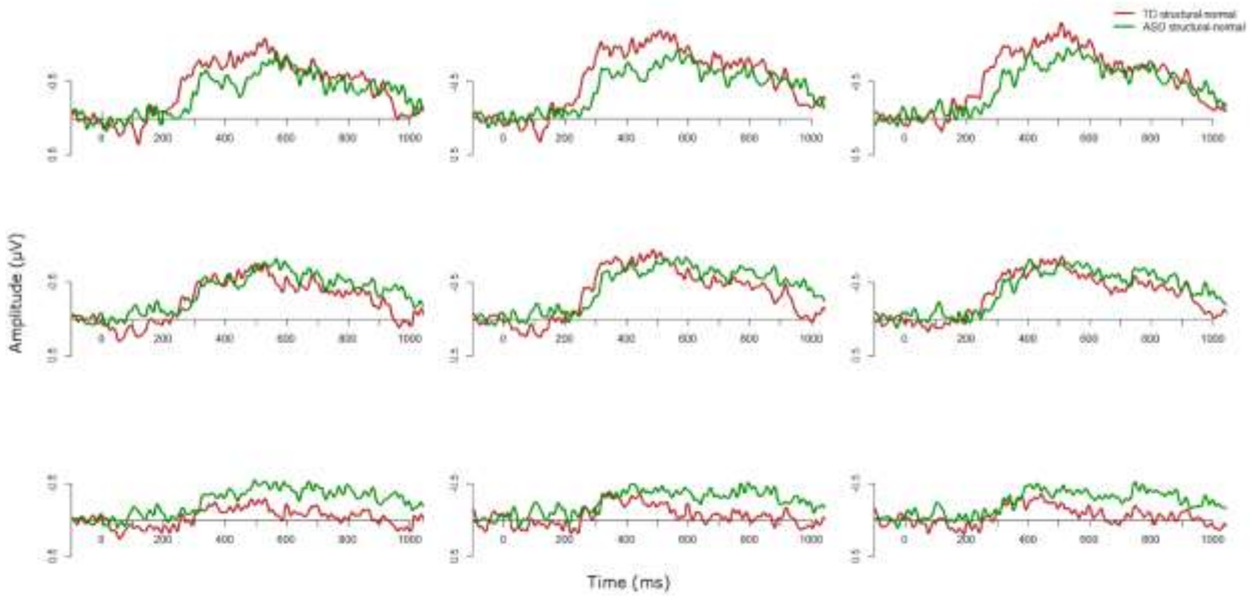


Table 8: *F*-values for the repeated-measures ANOVAs on the Structural Only – Normal difference waves in each analysis window, with a between-subjects factor of group (TD, ASD) and within-subjects factors of site (frontal, central, parietal) and laterality (left, midline, right). Age and digit span were included as covariates. Main effects of or interactions with group are highlighted in bold. Asterisks indicate statistically significant results (§ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

Main effect or interaction	Time window 1 (200-350 ms)	Time window 2 (400-600 ms)	Time window 3 (600-900 ms)
Age	<0.01	1.23	3.87 §
Digit span	0.12	0.22	0.76
Group	0.60	0.18	0.03
Site	18.74 ***	43.39 ***	26.95 ***
Group:site	**6.15 ****	**8.20 *****	**5.71 ****
Laterality	1.54	1.83	0.87
Group:laterality	0.62	0.20	<0.01
Site:laterality	1.26	4.78 **	4.02 **
Group:site:laterality	0.20	0.11	0.35

200-350 ms. The overall ANOVA (Table 8) showed a statistically significant interaction of group and site for the 200-350 ms time window ($F(2,76) = 6.15$, $p < 0.01$). There was a significant main effect of group at frontal sites ($F(1,116) = 7.62$, $p < 0.01$), with the TD group having a larger negative deflection ($M = -0.58$, $SD = 0.59$), i.e., a larger difference wave, compared to the ASD group ($M = -0.28$, $SD = 0.46$).

400-600 ms. The overall ANOVA showed a statistically significant interaction of group and site for the 400-600 ms time window ($F(2,76) = 8.20$, $p < 0.001$). There was a significant main effect of group at frontal sites ($F(1,116) = 5.60$, $p < 0.05$). with the TD group having a larger negative deflection ($M = -1.00$, $SD = 0.78$), i.e., a larger difference wave, compared to the ASD group ($M = -0.73$, $SD = 0.79$).

600-900 ms. The overall ANOVA showed a statistically significant interaction of group and site for the 600-900 ms time window ($F(2,76) = 5.71$, $p < 0.01$). There was significant main effect of group at parietal sites ($F(1,116) = 6.01$, $p < 0.05$), with the ASD group having a larger negative deflection ($M = -0.37$, $SD = 0.48$), i.e., a larger difference wave, compared to the TD group ($M = -0.05$, $SD = 0.48$).

To summarize, the TD group had larger difference waves during the first two time windows at frontal sites (200-350 ms, 400-600 ms) and at ASD group had a larger difference wave at parietal sites from 600-900 ms.

DISCUSSION

This study aimed to observe differences between ASD and TD groups regarding the processing of both narrative structure and semantic relatedness in visual narratives. ERP data was used to identify temporally specific neural activity in participants during the presentation of visual narratives. Replicating a prior study by Cohn et al. (2012) exploring the role of grammatical structure in visual narrative processing, this study utilized four types of visual narrative sequences in order to isolate both structure and semantic relatedness within visual sequences. The purpose of this study was to determine if participants with ASD had challenges with narrative structure and/or semantic relatedness in the context of visual narratives as compared to TD participants.

Overall ERP Data

Based on the results from Cohn et al. (2012), we expected that Normal sequences would elicit the smallest negative amplitudes, followed by Semantic Only, Structural Only, and Scrambled sequences, respectively. Similar to the methods employed by Cohn et al. (2012), we compared ERP amplitudes in three different time windows designed to target the N300 ERP component (200-350 ms), the N400 ERP component (400-600 ms), and later ERP components (600-900 ms).

In the TD group, our results largely replicated the findings of Cohn et al. (2012). At both the N300 and N400 time windows, the Normal sequence elicited the least negative amplitude, followed by the Semantic Only, the Structural Only, and the Scrambled sequences. There were no significant effects of condition in the last time window, which contradicts Cohn et al. (2012) who found that the patterns of negativity were sustained into this late time window. One potential difference between our TD sample and that of Cohn et al. (2012) was that Cohn and colleagues specifically recruited comic readers, whereas we did not require any prior levels of visual language fluency. Indeed, the TD sample from Cohn et al. had a mean VLFI score of 17, whereas our TD group had a mean of 7.5. It is possible that these individual differences in visual language fluency may have led to our less fluent readers showing earlier effects, whereas the more fluent readers of Cohn et al. (2012) showed more sustained effects. This is in line with recent work from our group showing that individuals who begin reading comics earlier show larger late positivity effects, whereas individuals who begin reading comics at a later age show larger early negativity effects (Coderre & Cohn, under review). While Cohn et al. (2012) do not provide a summary of the age at which their participants began reading comics, it remains a possibility that these individual differences in comic reading experience could be modulating neural responses to semantic and grammatical processing in the current study. This will be an important avenue for future analyses for this project and future research in this area.

The ASD group in our study showed similar patterns of amplitude modulation compared to the TD group during the first time window exploring the N300 component. The Normal sequence elicited the least negative amplitude, followed by the Semantic Only, the Structural Only, and the Scrambled sequences. Of note, the ASD group had a larger difference between the Scrambled sequence and other sequences as compared to the TD group, potentially demonstrating a difference in the Scrambled sequences and other sequences shown in the ASD group that are not seen in the TD group.

In the N400 time window, both groups had the least negative deflection in the Normal sequences, followed by Semantic Only, Structural Only and Scrambled sequences at frontal and central sites. The ASD group also showed a trend reversal, with the Structural Only sequences having a larger amplitude than the Scrambled sequences parietally.

Finally, in the last time window, whereas there were no effects of condition for the TD group, the ASD group did show sustained amplitude differences: the Normal condition had the least negative deflection, followed by the Semantic Only, Scrambled, and Structural Only conditions at parietal sites. Again, individual differences in comic reading fluency may underlie these group differences, since the ASD group had higher VLFI scores than the TD group (with a mean of 12). Future analyses will explore these individual differences by investigating correlations of the ERP amplitudes with VLFI scores.

Isolation of Structural Processing

Based on the components of each sequence, we can contrast specific conditions to isolate structural processing specifically (see Figure 2). Comparing Scrambled sequences (which contain neither semantic relatedness nor structure) to Structural Only sequences (which contain narrative structure but no semantics) will isolate grammatical processing in the absence of semantics. Comparing Semantic Only sequences (which contain semantic relatedness but no narrative structure) to Normal sequences (which contain both semantic relatedness and narrative structure) will isolate grammatical processing in the presence of semantics. Therefore, semantic relatedness is being held constant in the conditions that are contrasted (either both have or both lack semantic relatedness). Since only narrative structure differs between the conditions of each contrast, that is the manipulated variable that is being isolated. If individuals with ASD have difficulties processing narrative structure, then we would expect the ASD group to have smaller differences for both of these contrasts compared to the TD group, suggesting a reduced sensitivity to narrative structure.

Scrambled – Structural Only Sequences

At the first two time windows (200-350 ms, corresponding to the N300 component, and 400-600 ms, corresponding to the N400 component), the TD group shows a greater difference between Scrambled and Structural Only conditions as compared to ASD groups at parietal sites, with a significant trend at central sites in the N400 time window. There were no differences in the late time window (600-900 ms). This increased centroparietal difference wave for the TD group at the N300/N400 component may indicate that the TD group is more sensitive to the presence of narrative structure in a sequence in comparison to the ASD group. These are surprising early effects of structural processing based on prior studies in language (e.g., Van Petten & Kutas, 1991); however, they are in line with the findings of Cohn et al. (2012), who found small but significant attenuations in amplitude for Structural Only narratives compared to Scrambled sequences in all of the time windows identified. This effect was left-lateralized and occurred over frontal scalp, which led Cohn et al. (2012) to refer to this as potentially being a separate component, like a LAN during the same time window as the N300/N400 component, as we would not expect the sequence with only structure to affect the N300/N400 time component without semantic relatedness. In our data, the topography of the Scrambled – Structural Only difference does not appear to have a left anterior distribution until the latest time window (600-900 ms; see Figure 8a). Nevertheless, the fact that the TD group showed larger differences between these conditions than the ASD group demonstrates a sensitivity to narrative structure among TD individuals that was not seen in individuals with ASD.

Semantic Only – Normal Sequences

For the Semantic Only – Normal sequences, the results showed no statistically significant effects of group in any time window, suggesting similar levels of sensitivity to the presence of narrative structure between the TD group and the ASD group. This contradicts the results of the above contrast of Scrambled – Structural Only sequences, which suggested differences in grammatical processing between groups. The large amplitude differences in both groups between Semantic Only and Normal sequences may have mitigated smaller group differences; in contrast, the smaller amplitude differences between the Scrambled and Structural Only sequences may allow for more subtle differences to be identified between groups. Alternatively, these two contrasts may not be identical because of the presence of the Normal sequence in the latter comparison, which is not comprised of narrative structure and semantic relatedness independently. While the Scrambled – Structural Only contrast isolates structural processing in the *absence* of semantics, the Semantic Only – Normal contrast isolates structural processing in the *presence* of semantics. These contrasts are therefore not equal. There may be something important about the combination of structure and semantics together that makes overall narrative processing different than the sum of its parts. Thus, it could be that the interactions between narrative structure and semantic relatedness in the Normal sequence do not allow for independent isolation of either component once combined. We propose that one of these above reasons is why the results from this contrast do not match the above contrast.

In light of these differences between the two types of contrasts, it is interesting to consider the group differences we observed. In the *presence* of semantic relatedness (the Semantic Only – Normal contrast), the ASD group did not show any differences in processing structural information. But in the *absence* of semantic relatedness (the Scrambled – Structural Only contrast), the ASD group showed a reduced sensitivity to the presence of narrative grammar. This may suggest that individuals with ASD do have difficulties with structural processing, but that the facilitation from the presence of semantics can overcome any structural processing difficulties in Normal sequences.

Isolation of Semantic Processing

Based on the components of each sequence, we can also contrast specific conditions to isolate for semantic processing specifically (see Figure 2). Comparing Scrambled sequences (which contain neither semantic relatedness nor narrative structure) to Semantic Only sequences (which contain semantic relatedness but no narrative structure) will isolate semantic processing in the *absence* of narrative structure. Comparing Structural Only sequences (which contain narrative structure but no semantics) with Normal sequences (which contain both narrative structure and semantic relatedness) will isolate semantic processing in the *presence* of narrative structure. If individuals with ASD have difficulties processing semantic relatedness, we would expect the ASD group to show smaller differences for both contrasts compared to the TD group, suggesting a decreased sensitivity to semantic relatedness.

Scrambled – Semantic Only Sequences

There were no significant differences between groups during the first two time windows. This suggests that the ASD and TD groups have similar semantic processing mechanisms during the early semantic processing of visual narrative stimuli. During the later time window from 600-900 ms, there was a statistically significant difference between groups, with the TD group showing a larger fronto-central negativity than the ASD group (see Figure 8c). These results suggest a more sustained effect of semantic relatedness for the TD group, which has resolved by the N400 component for the ASD group.

Structural Only – Normal Sequences

This contrast identified significant differences between the TD group and the ASD group for all time windows. The TD group had a larger frontal and central negativity from 200-350 ms

(Figure 8d), along with a larger frontal negativity during 400-600 ms, compared to the ASD group. This suggests that the TD group may be more sensitive to semantic relatedness in visual narrative stimuli than ASD groups at these earlier time windows reflecting the N300 and N400 ERP components. However, this group difference was flipped in the later time window, with the ASD group showing a larger parietal negativity from 600-900 ms (Figure 11). Together, these results may indicate the TD group is more sensitive to initial semantic relatedness whereas the ASD group is more sensitive to semantic relatedness during later time windows. This is in line with the finding of a prior study which reported that individuals with ASD show smaller N400 responses to semantic processing compared to TD individuals, but larger effects at later components (Pijnacker et al., 2010). This finding was interpreted as reflecting initial difficulties with semantic processing in individuals with ASD (leading to smaller N400 effects) which are compensated for during later semantic re-analysis and integration processes (leading to larger effects at later components).

Again, the results of this latter contrast do not match the results of the first contrast isolating semantic processing. In the *absence* of structural information (Scrambled – Semantic Only), there were similar effects of semantic processing between groups for the N300/N400 but a more sustained semantic effect in the TD group. In the *presence* of structural information (Structural Only - Normal), individuals with ASD showed a reduced N300/N400 but a later sensitivity to semantic relatedness compared to TD individuals. Once again, these results suggest that the interactions between semantic relatedness and narrative structure in the Normal sequence do not allow for independent interaction. These differential effects of semantic and structural processing, and how they interact with each other when both are present, will be an interesting avenue for future research investigating narrative comprehension in individuals with ASD.

Limitations

Some potential limitations for this study revolve around the effects of individual differences. As mentioned in the Introduction, autism is a broad-spectrum condition, and studies on language processing of individuals with ASD have had mixed results. Although all participants in the ASD group in our study had received a diagnosis or been self-diagnosed with ASD, the level of autistic traits was not accounted for in the statistical analyses. One benefit of the AQ measure that we used in this study is that it can be given to all participants, regardless of which diagnostic group they fall into. Indeed, as can be seen in Table 1, there was some overlap in the range of AQ scores between participants in the TD group (range 8-25) and the ASD group (range 17-41). Because of the potential for mixed results due to differences in levels of autistic traits, it would be important to include AQ scores as a predictor in the statistical models to examine the influence of diversity in ASD on the results. We are currently exploring this in secondary analyses.

There also may be a difference in individual experience with reading comics. Cohn (2020) has argued that visual language fluency is important for narrative comprehension but is not a universal trait. Rather, readers must acquire a fluency with visual language sequences, much like they must acquire a fluency with reading written language. The Visual Language Fluency Index (VLFI) is designed to assess participants' fluency in reading visual narratives. Scores on this measure have shown interesting modulations of neural responses to visual narrative sequences (Coderre & Cohn, under review). In the current study, the processing of semantic relatedness and/or narrative structure may differ based on a participant's experience with reading visual narratives. Therefore, examining the influence of VLFI scores on the results will be an important step for future research, and one that we are actively pursuing in secondary analyses.

Conclusions

After using ERP results to examine visual narrative processing in both ASD and TD groups, we have determined that there are existing differences in how individuals with ASD process visual narrative structure and semantic relatedness. Our results on semantic relatedness replicate those of prior studies (e.g., Pijnacker et al., 2010), suggesting that TD groups have a higher sensitivity to semantic relatedness early on, while ASD groups have a higher sensitivity in later time points of processing. The results on structural processing demonstrated the TD group as more sensitive to narrative structure than the ASD group, particularly at early time windows. As this is the first study to examine structural processing of visual narratives in individuals with ASD, these results offer important insight into narrative processing in ASD. Our study suggests that difficulties understanding narrative structure may underlie some of the documented difficulties with narrative comprehension that many individuals with ASD face. The results of this study indicate a further need to study visual narratives in ASD populations, as well as the importance of considering individual differences.

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