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SEMANTIC PROCESSING IN INDIVIDUALS WITH INTELLECTUAL DISABILITIES

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by

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ABSTRACT

Enhancing the effectiveness of clinical materials used for communication support in populations with communication disorders is an important priority for public health. Success requires insights about how clearly these materials convey semantic information to users—information that is largely absent from the existing literature. This current study focused on characterizing neural activity associated with semantic processing in individuals with Down syndrome (DS) in the context of exposure to Augmentative and Alternative Communication (AAC) symbols and speech. Using knowledge and tools from developmental disability research, communication intervention, and brain imaging, the study explored the event-related potential (ERP) components related to linguistic processes. ERPs were recorded while participants viewed Mayer-Johnson Picture symbols that varied in animacy and heard a matching (semantically congruent) or mismatching (semantically incongruent) auditory stimulus. Consistent with previous semantic processing ERP studies in typically developing populations, semantically incongruent trials yielded larger negative amplitude responses than semantically congruent trials. While mean amplitudes did not differ significantly by animacy or post-stimulus presentation epoch, brain responses did vary by channel with electrode site C3 displaying the largest negative magnitude compared to other channels. Response latencies were within the range of the N400 observed in typically developing adults. In contrast to previous N400 findings, however, the DS sample showed a more frontally distributed response to semantically incongruent information similar to what has been observed in adults in a picture-only viewing task. Overall, the results indicate that individuals with DS process AAC symbols in a manner akin to the ways typically developing individuals process semantic information.
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Introduction

Language and interpersonal communication are a vital part of daily living (Rayner & Clifton, 2009). In typically developing individuals, communication tends to be rapid, easy, and multi-modal. It has even been argued that humans have an innate ability to process grammar and speech and identify structure within strings of symbols (Kapetanios, Tatar, & Sacarea, 2013). While communication seems to be simple, it is actually very complex. In fact, there are many elements in language that are important for communication (Akmajian, Demer, Farmer, & Harnish, 2001). These components include phonetic information (sound patterns), lexical structure information (word structure), syntactic information (sentence structure), semantic information (word meanings), and pragmatic information (word usage in discourse) (Akmajian et al., 2001).

Given the complexity of linguistic communication, linking concepts and words and formulating phrases can be especially challenging for individuals with communication difficulties (Kapatenios et al., 2013; Lázaro, Garayzábal, & Moraleda, 2013). Millions of individuals in the United States struggle to cope with severe communication disorders (Beukelman & Mirenda, 2013; Downey & Hurtig, 2003) due to developmental or acquired deficits. Many individuals with these communicative challenges interact with others by means of an intervention called augmentative and alternative communication (AAC). As described below, AAC often involves the use of visual symbols representing words commonly needed in daily discourse. In the U.S. population, roughly 8-12 individuals per 1,000 utilize AAC (Beukelman & Ansel, 1995) techniques.

The current study focuses on Down Syndrome (DS), a developmental disorder in which communication deficits are common, and about which relatively little is known concerning the
mechanisms of visual or auditory language processing. The study sought to quantify neural responses to AAC symbols in a DS sample using an event-related potential (ERP) technique, thus addressing a gap in the literature concerning the extent to which AAC symbols evoke semantic processing functions analogous to those found in participants showing typical patterns of development. In the review that follows, I first describe AAC, its devices and the populations that use it, including individuals with DS. Next, I discuss nonverbal measures of language processing and evidence about this processing in typically and atypically developing populations. Finally, I discuss why the current study about semantic processing in a DS sample is needed. The goal is to determine to what extent young adults with DS process the semantics of visual symbols commonly used in AAC in ways similar to typically developing individuals. Since DS so often involves expressive language deficits, nonverbal response measures such as event-related potentials must be used to address these questions. Understanding whether individuals with communication disorders can semantically process line drawings used in aided AAC can provide insight into the effectiveness of these tools. Findings from the current study may ultimately promote improvement in the design of AAC devices.

**Augmentative and Alternative Communication Techniques and Devices**

AAC comprises a set of nonverbal communication techniques that enhance an individual’s spoken language and/or writing (Lloyd, Fuller, & Arvidson, 1997), in many cases by means of visual symbols. AAC has two categories: aided and unaided (Smith, 2005; Wilkinson & Hennig, 2007; Wilkinson, Light, & Drager, 2012). For unaided AAC, individuals depend on their own bodies to communicate without equipment and it includes hand movements, facial expressions, body postures, eye gaze, and sign language. (Downey & Hurtig, 2003; Sigafoos, 2010; Smith, 2005). In aided AAC, people utilize equipment for communication such as picture
boards and devices that produce speech output (see Figure 1). Aided AAC can be divided into two categories: light or low-technology and high-technology (Downey & Hurtig, 2003; Wilkinson & Hennig, 2007). In the low-technology mode, eye gaze boards, alphabet boards, communication books, notebooks and/ or boards are used during social interactions. For the high-technology mode of AAC, individuals use voice output devices, including computers and other electronic devices, to communicate (Downey & Hurtig, 2003; Fager, Bardach, Russell, & Higginbotham, 2012; Rassool, 1999; Wilkinson & Hennig, 2007). There are multiple forms of AAC, however despite its widespread use, the design of AAC tools is largely ad hoc and not especially well-informed by cognitive or visual neuroscience. The tools and techniques utilized in these disciplines could prove useful in uncovering whether AAC devices are effective, under what conditions, and how their effectiveness might be improved.

The population of AAC users varies among many dimensions, including the duration of use. For example, a patient with an intubation is considered a temporary user. Individuals with Amyotrophic Lateral Sclerosis, Autism Spectrum Disorder, Cerebral Palsy, and Down syndrome tend to be a part of the permanent user population (Light & McNaughton, 2012). The AAC user population has increased over the past several years due to the inclusion of individuals with speech delays and unintelligible speech as well as earlier intervention (Light & McNaughton, 2012). Based on the growth of the AAC population, one might assume that the intervention is working, but how effective is it?

A study with young children showed that only augmented communication intervention (input and output), not spoken communication intervention, led to substantial speech and vocabulary improvements (Romski, Sevcik, Adamson, Cheslock, Smith, Barker, & Bakeman, 2010). In a case study involving a toddler with delayed expressive communication, a sign
language and picture symbol intervention led to the acquisition of speech (Leech & Cress, 2011). Additionally, a meta-analysis of 23 studies from 1975-2003 showed that 89% of AAC users showed improvements in speech (Millar, Light, & Schlosser, 2006). On the other hand, although AAC devices are prevalent among individuals who need communication supports, some users frequently abandon them (Phillips & Zhao, 1993). Limited understanding of the benefits of the technology, poor support, lack of training, system characteristics, and the user’s involvement in device selection are some of the factors related to continued or discontinued use of devices (Johnson, Inglebret, Jones, & Ray, 2006; Riemer-Reiss & Wacker, 2000). These findings suggest that although AAC interventions have led to gains in speech and language, the devices need improvement.

These AAC supports often have visual symbols. Thus, it is critically important to understand how the processing of these symbols compares to speech processing that AAC is intended to replace. Since different forms of language impairment present different profiles (Singer Harris, Bellugi, Bates, Jones, & Rossen, 1997), it is also crucial to study specific populations of AAC users. There is also much variability in the communication technologies available to AAC users. Therefore, it is important to identify which technologies are most useful to individuals who use AAC as well as the user’s device preference (Light, Roberts, Dimarco, & Greiner, 1998; van der Meer, Sigafoos, O’Reily, & Lancioni, 2011). Understanding specific users’ communication limitations can promote careful and strategic design of devices that fit well with users’ needs. This in turn could reduce challenges encountered with previous devices and thereby decrease abandonment of AAC devices.
**Down Syndrome Communication Profile**

DS is a common genetic neurodevelopmental disorder that occurs as a result of an extra chromosome 21 (Korenberg, Kawashima, Pulst, Ikeuchi, Ogasawara, Yamamoto, Schonberg, West, Allen, Magenis, Ikawa, Taniguchi, & Epstein, 1990). Deficits in speech and language production as well as difficulty with expressive and receptive communication are common in DS (Chapman, 1997; Chapman, 2003; Chapman & Hesketh, 2000). Chapman also suggests that speech production and speech perception develop slowly in people with DS, which is linked to poor speech comprehension and production (Chapman, 2003). Slow development of speech production and perception in this population is linked to atypical oral-motor structure, low muscle tone, and hearing loss (Abbeduto, Warren, & Connors, 2007). Studies have shown that individuals with DS have deficits in language (Chapman, 1997; Chapman, Hesketh, & Kistler, 2002; Chapman, Schwartz, & Kay-Raining Bird, 1991; Dykens, Hodapp, & Evans, 1994; Rosin, Swift, Bless, & Kluppel Vetter, 1988; Zampini & D’Odorico, 2011) including weaker expressive language than receptive language, poorer expressive syntax than both vocabulary and syntax comprehension, poor morphosyntactic abilities, as well as communication skills that are delayed compared to daily living and socialization skills. This population also has difficulties with language that are related to hearing and oral-motor structure and function (Roberts, Price, & Malkin, 2007). Because of these language difficulties, many individuals with Down syndrome use AAC as a primary mode of communication (Niemeijer, Donnellan, & Robledo, 2012).

There is some evidence that information processed via the visual stream may be optimal for the DS population. Participants with DS performed better on a visual-spatial short-term memory task (Corsi block test) than a verbal short-term memory task (Digit Span) (Wang & Bellugi, 1994). In the same study, individuals with Williams syndrome who are reported to have
strong linguistic skills (Singer Harris et al., 1997) showed the reverse pattern of performance
with better outcomes on the Digit Span task (Wang & Bellugi, 1994). This finding illustrates that
limitations in one modality may not be present or as severe in another modality, thus exploring
language processing in multiple modalities in the DS population is essential to understanding
how communication supports function. Variation in task performance among individuals who
have similar cognitive abilities also highlights the importance of studying specific populations
for understanding behavioral outcomes. More evidence of the advantage of visual information
comes from a study exploring generalizability of language and cognitive skills in DS to other
populations with language impairment. In a story narration task, adolescents with DS showed
reduced expressive language deficits when they had a chance to preview the story with picture
supports (Chapman, 2006). This provided evidence that visual aids can enhance communication
(Stancliffe, Larson, Auerbach, Engler, Taub, & Lakin, 2010). There is also evidence that visual
context provides support for communication (Tanenhaus, Spivey-Knowlton, Eberhard, &
Sedivy, 1995). So, while existing evidence suggests that individuals with DS may be well-
equipped to benefit from visually-based communication aids, how well the aids function and
whether they tap the same language processing systems as spoken language is not known. Other
measures of language processing are needed to answer these questions.

**Nonverbal Measures of Language Processing**

Nonverbal measures are crucial to understand language processing in Down syndrome
because they allow researchers to acquire rich data from samples without challenging task
demands (e.g., speech production in samples with language difficulties). I discuss
electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) in turn,
focusing first on evidence from these methods in typically developing adults and children before
discussing the evidence from adults and children with atypical developmental profiles.

**EEG in Typically Developing Populations**

EEG remains a powerful method for exploring the time course of brain function (Stern, Ray, & Quigley, 2000) across behavioral domains. Event-related potential recordings (ERPs) in particular have been important for studying language and its underlying neural circuitry (Lau, Phillips, & Poeppel, 2008). In fact, several language processing waveforms, called *components*, have been quantified via ERP studies including the P600, LAN/ELAN (left anterior negativity) for syntactic processing, and the N400 and N300 components for semantic processing.

ERP components vary in amplitude, cortical areas of activity, latency (time following a stimulus onset or change), and polarity (negative or positive voltage). Several studies indicate that ERP is a reliable method for studying linguistic processing (Benau, Morris, & Couperus, 2011; Besson & Macar, 1987; Coch, Maron, Wolf, & Holcomb, 2002; Friedrich & Friederici, 2004; Kutas & Hillyard, 1980). For example, the P600 component is a positive potential that peaks approximately 500-900 milliseconds after a stimulus is presented and is typically most prominent at centro-parietal electrodes. In one ERP study, adults were presented with sentences they had to judge as acceptable (semantically and grammatically correct) or unacceptable. Words that did not fit with the expected syntactic structure elicited a P600 (Osterhout & Holcomb, 1992). Hagoort and colleagues (1993) also found that a P600 was produced following syntactic agreement and word order violations (Hagoort, Brown, & Groothusen, 1993). These and other ERP studies provide evidence that the P600 is associated with syntactic processing. Another ERP component that has been linked to syntactic processing is the (early) left anterior negativity (LAN/ELAN). The LAN/ELAN component is a negative going potential with a post stimulus
peak of 100-200ms or 300-500ms and prominent activity over left anterior electrodes. Several ERP studies with adults show evidence that the LAN/ELAN component is also linked to syntactic processing (Coulson, King, & Kutas, 1998; Friederici, Pfeifer, & Hahne, 1993; Kutas & Hillyard, 1983).

Semantic processing is also an important part of language. Previous ERP studies have shown that verbal (e.g., spoken words) and nonverbal stimuli (e.g., pictures) produce ERP components that are linked to semantic processing (West & Holcomb, 2002; Willems, Özyürek, & Hagoort, 2008). The N400 ERP component has been identified as one marker of semantic processing. This ERP response is a negative deflection peaking approximately 400 milliseconds after a stimulus is presented. It typically has a central and parietal scalp distribution (Besson & Macar, 1987; Kutas & Hillyard, 1980). Adults showed the largest N400 amplitudes when semantically incongruent information (e.g., *He took a sip from the transmitter*) was present in visually displayed sentences (Kutas & Hillyard, 1980). In a similar semantic priming paradigm, adults’ N400 responses attenuated when primed with semantically related words (Rossell, Price, & Nobre, 2003).

Most studies exploring semantic processing have used words as stimuli however; other stimulus types have also been employed. One experiment focused on semantic processing of pictures. Adults’ ERPs were recorded as they judged whether sequentially displayed picture pairs were semantically related (Barrett & Rugg, 1990). Results showed that ERPs to pictures that were not semantically associated (e.g., a picture of a teacup and a leaf) were more negative than semantically linked pairs (e.g., a picture of a wrench and a nut). This study identified the N300 as an additional ERP component that is elicited when semantic incongruity among images is present, thus suggesting that there are distinct neural semantic processing systems for words and
pictures. Combinations of stimuli have also been used to understand the mechanisms underlying semantic processing. Hamm and colleagues (2002) presented adults with a visual word of an object then a semantically mismatching or matching object. Both the N300 and N400 were elicited (Hamm, Johnson, & Kirk, 2002). The results showed that the N400 effect was present for all semantic incongruities while the N300 effect was only found for between-category mismatches. This led authors to conclude that the N300 component reflects categorization of items and has a frontal distribution, while the N400 is strongly linked to semantic incongruity.

Semantic processing ERP components have also been studied in developmental populations. In an ERP study with adults and 10-year-old children, participants were presented with sentences that were semantically congruent, moderately incongruent, or strongly incongruent (Benau et al., 2011). Adults showed the largest N400s for the strongly incongruent sentences while children showed equally large N400s to the moderately and strongly incongruent sentences. These findings suggest that semantic processing may be different in developmental populations. A similar study with 19-month-olds also provided evidence for developmental differences in semantic processing (Friedrich & Friederici, 2004). Participants were simultaneously presented with pictures and auditorily presented semantically incongruent or congruent words. The children showed an analogue to the adult N400 with a later onset, longer lasting effect, and different spatial distribution (robust frontal and left parietal electrode site activity).

fMRI Evidence from Typically Developing Individuals

Functional magnetic resonance imaging (fMRI) is another neuroimaging technique that is useful for unveiling the mechanisms of language processing. In fact, many brain areas reported to be involved in language processing, including but not limited to the inferior frontal gyrus,
superior temporal gyrus, and middle temporal gyrus (Friederici, 2011; Hickok & Poeppel, 2007; Joanisse & Gati, 2003; Ketteler, Kastrau, Vohn & Huber, 2008; Kuperberg et al., 2000; Vigneau et al., 2006), have been identified via fMRI studies. Neuroimaging data from developmental samples suggest that identical or similar brain regions are recruited when children are processing language as well. For instance, in an fMRI semantic verbal fluency task, children (7-14-year-old) and adults silently produced words belonging to a category (Gaillard et al., 2003). The left inferior frontal gyrus and left middle frontal gyrus were regions found to be active for adults and children alike. Additionally, no differences in laterality were shown between children and adults. Another fMRI experiment with children also demonstrates that specific brain regions are a part of language processing early on in development. In this study, 11-13-year-old children passively listened to some stories and actively responded to other stories. During these tasks, the left inferior frontal gyrus, bilateral superior temporal gyrus, and primary auditory cortex showed robust activity (Vannest et al., 2009). Different aspects of language processing, such as syntactic processing, have been explored with this method. Ben-Shachar and colleagues (2004) identified neural correlates related to syntactic processing in two fMRI studies. In a sentence comprehension task, adults heard sentences and answered related comprehension questions. Results showed that activation in the left inferior frontal gyrus, left ventral precentral sulcus, and bilateral posterior superior temporal sulcus was consistent for all stimuli (Ben-Shachar, Palti, & Grodzinsky, 2004). In a similar paradigm, the bilateral planum polare and left frontal operculum also showed activity exclusively related to syntactic processing (Friederici, Meyer, & von Cramon, 2000).

Brain regions specifically involved in semantic processing have been identified as well. In one fMRI experiment, adults heard nouns (objects) and decided whether they belonged in a
certain environment. Participants had responses in the medial temporal lobes (hippocampal formation) and the inferior temporal lobes (fusiform and lingual gyrus), regions not consistently reported in other imaging studies as involved in phonetic or syntactic processing (Bartha et al., 2003). Additionally, a large number of functional neuroimaging studies have identified several brain regions reliably activated during semantic processing: the posterior inferior parietal lobe, middle temporal gyrus, fusiform and parahippocampal gyri, dorsomedial prefrontal cortex, inferior frontal gyrus, ventromedial prefrontal cortex, and posterior cingulate gyrus (Binder, Desai, Graves, & Conant, 2009).

Although there are a number of brain regions involved in semantic processing, some evidence suggests that areas of activity vary by the modality in which stimuli are presented. For example, a meta-analysis of functional neuroimaging literature found that verbal (spoken words or sentences) and nonverbal (pictures written words) stimuli elicited activation in the anterior temporal lobes during semantic processing (Visser, Jeffries, & Ralph, 2010). However, responses to pictures tended to more inferior in this brain region than those for other stimuli. Neural activation for semantic processing may also differ by stimulus category. In an event-related fMRI study, adults were visually presented with nouns that they had to classify as living or non-living (Leube, Erb, Grodd, Bartels, & Kircher, 2001). Findings indicated that the inferior occipital gyri, left inferior frontal gyrus, and left inferior parietal lobule activation did not vary by stimulus classification. However, distinct regions were only activated for living nouns including the right inferior frontal gyrus, middle temporal gyrus, and fusiform gyrus indicating variable processing for stimulus category type.
EEG Studies in Atypically Developing Populations

The literature on neural activity to language-related stimuli in populations with developmental disorders is diverse, reflecting the fact that disorders with seemingly similar communication profiles may in fact represent quite different alterations in the language processing circuitry. For example, individuals with Williams syndrome (WS) and Autism Spectrum Disorder (ASD) have often been reported to have difficulty with language and communication (Fishman, Yam, Bellugi, Lincoln, & Mills, 2010). Recent evidence from an ERP study (Fishman et al., 2010) has revealed that individuals with WS and ASD have different brain responses to semantic information despite both groups encountering challenges with language. In this semantic processing study, adults with WS, ASD, and typically developing adults listened to sentences and indicated whether the sentences made sense with a button press. Results showed that the N400 effect was much larger for the WS group than the other groups. Conversely, the N400 effect for the ASD group was significantly smaller (nearly non-existent) than the other groups (Fishman et al., 2010). In a similar ERP study with children and adults with WS, results indicated that individuals with WS had more positive P600 responses than their typically developing counterparts (Pinheiro, Galdo-Alvarez, Sampaio, Niznikiewicz, Goncalves, 2010).

A semantic processing ERP study with learning disabled adults (LD) has also provided evidence that neural measures of language processing vary within atypically developing populations (Plante, Van Petten, & Senkfor, 2000). In this experiment, LD adults and controls viewed and heard semantically matching or mismatching nonverbal stimuli (e.g., picture of an ambulance and siren sound) and verbal stimuli (e.g., word “dog” visually and spoken word “dog”). Each trial was followed by a probe recognition stimulus that participants provided yes
(stimulus present) or no (stimulus not present) answers to. The controls showed a typical N400 effect in both the verbal and nonverbal conditions with mismatches eliciting larger N400 responses. LD adults did not show an N400 effect for the verbal condition, however this group had a robust and typical N400 effect for the nonverbal condition suggesting that difficulties with associations may only exist in the verbal domain (Plante et al., 2000).

Evidence from an ERP study with children also suggests that semantic processing is different in individuals with specific language impairment (SLI) relative to those who are typically developing. In this study, children with SLI and typically developing controls heard sentences with correct semantic information and sentences with violations (Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2006). Though both groups of children did well identifying semantic violations in a behavioral task, the ERP data revealed differences in semantic processing. The controls had a typical N400 effect with incorrect sentences eliciting the largest negative amplitudes while the SLI group did not show an N400 effect instead having equally large negative amplitudes to correct and incorrect sentences. These EEG experiments are not the only method used to study language processing in atypically developing individuals. In fact, neuroimaging studies (e.g., fMRI experiments) have emerged as a useful method for studying this population as well.

Generalizations about semantic processing in DS are difficult to make from data about typically developing individuals and individuals with other developmental disorders. For example, people with Williams syndrome appear not to have the same verbal deficits that have been shown in individuals with DS (Karmiloff-Smith, Grant, Berthoud, Davies, Howlin, & Udwin, 1997). In several semantic processing ERP studies, researchers also found that participants with WS had different temporal region activity than typically developing controls
(Neville, Holcomb, & Mills, 1989; Neville, Mills, & Bellugi, 1994). These findings indicate that semantic processing varies between these groups possibly due to differences in typical and atypical brain development.

fMRI Studies with Atypically Developing Populations

A recent fMRI study provided evidence that individuals with DS may process speech differently than typically developing individuals (Losin, River, O’Hare, Sowell, & Pinter, 2009). In this study, participants passively listened to a story. Results showed that the participants with DS had less activation in brain areas (superior temporal gyrus and middle temporal gyrus) linked to receptive language than their age matched counterparts. However, these individuals showed greater activation in the precuneus, cingulate gyrus, as well as the superior and inferior parietal lobules, than the typically developing controls. Additionally, brain response patterns to forward and backward speech were nearly the same for the individuals with DS (Losin et al., 2009).

Another fMRI study found that individuals with DS show neural activation patterns that differ from typically developing individuals. The study employed a semantic categorization task in which participants had to decide whether a pictured animal belonged on a farm (Jacola et al., 2011). For the individuals with DS, bilateral regions of the middle frontal gyrus as well as the left parietal lobe showed higher activation than the same areas in the typically developing group. In contrast, the typically developing individuals showed more activation in bilateral areas in the occipital and parietal lobes and the left frontal lobe than the DS cohort (Jacola et al., 2011).

These neuroimaging studies demonstrate that individuals with DS show differential patterns of activation for language processing than typically developing controls. These studies also provide support for further exploration of linguistic processes that are directly involved with communication supports.
Individuals with autism spectrum disorders (ASD) can also have difficulties with language and communication (Tager-Flusberg, 2003). An fMRI study of semantic processing demonstrated that adults with ASD showed different brain activation patterns to words than their age-matched controls (Harris et al., 2006). While in the scanner, participants viewed words presented on a screen and decided whether words were positive or negative (semantic processing) or upper or lowercase (perceptual processing). Words were concrete (e.g., tongue), mental state abstract (e.g., happy), and metaphysical abstract (e.g., freedom). Behaviorally the groups performed the same however brain activation patterns differed between the groups. For semantic processing, controls had robust activation in Broca’s area (left inferior prefrontal cortex), superior medial frontal gyrus, and right cerebellum. The ASD group showed reduced activation in Broca’s area for both semantic and perceptual processing and increased activity in Wernicke’s area but no superior medial frontal gyrus, and right cerebellum activity was observed. This group also showed decreased activation differences between concrete and abstract words during semantic processing as well (Harris et al., 2006). The authors suggest that the impairments in “deep” semantic processing in ASD are linked to atypical neurodevelopment in Broca’s area.

Differences in brain activation patterns for language processing have also been shown in younger atypically developing populations (Peterson et al., 2002). In this neuroimaging study, 8-year-old prematurely born children and full-term controls passively listened to a story in 3 different conditions: traditional reading, all story phonemes randomized (semantic comprehension difficult), low-filtered randomized story (difficult to discern phonemes). The children were also asked multiple-choice questions after the scan to assess their comprehension of the story. For the phonetic processing task, controls showed a more reduced signal relative to
baseline than for the semantic processing task. The preterm children showed the reverse pattern of activity with more deactivation in the semantic processing task. Results showed that during semantic processing, preterm children were using pathways typically engaged during processing of meaningless phonologic sounds in term children instead of the semantic processing pathways (Peterson et al., 2002). The authors suggest that the atypical semantic processing shown in the preterm group may be linked to their low verbal IQ scores.

**Rationale and Predictions**

AAC is a primary communication modality for many individuals with DS (Niemeijer, Donnellan, & Robledo, 2012). AAC symbols are static and processed visually as compared to speech, which is dynamic and processed auditorily. Therefore, it is necessary to explore whether these symbols have the same semantic functions as spoken words. Understanding whether individuals with communication disorders can semantically process line drawings used in aided AAC can provide insight into the effectiveness of these tools. Due to AAC users’ communication difficulties, non-verbal brain activation measures must be used to study their linguistic processing. However, differences in communication modalities suggest that current knowledge about semantic processing from typically developing individuals and even those with developmental disorders cannot be easily generalized to individuals with DS. Thus, the purpose of the current study is to record brain responses to symbols used in aided AAC, in particular, to or to identify which ERP components are linked to semantic processing in a sample of participants with DS. I will focus on quantifying the N300 and N400 responses to symbols thought to index semantic functions in typically developing individuals. Behavioral data obtained from this sample will also indicate whether responses vary by stimulus type.
I predicted that the AAC symbols would elicit an N400 from the individuals with DS. I expected that the N400 in this sample would have a later onset similar to what has been observed in previous developmental work on semantic processing (Friedrich & Friederici, 2004; Thigpen, 2014). An N400 effect would also be observed in this sample with semantically incongruent stimuli eliciting larger negative amplitudes that congruent stimuli. Electrode site activation patterns were also expected to be different for this sample due to the atypical developmental trajectory of this group as evidenced in fMRI studies (Losin et al., 2009; Jacola et al., 2011). Behavioral responses were expected to show faster reaction times for semantically congruent stimuli. Additionally, reaction times for animate stimuli were expected to be faster than inanimate stimuli as shown in a previous semantic processing study (Mari-Beffa, Valdés, Cullen, Catena, & Houghton, 2005).
Methods

Participants

Ten individuals (4 female) with Down syndrome (DS) participated in the study. The mean age of participants was 226.72 months (18.89 years) (range = 12-28 years) (SD=57.13). All participants were from a region in Pennsylvania. The sample was recruited via advertisements sent by mail or email to their families from The Laboratory for the Study of Visual Supports in Communication and Education at The Pennsylvania State University. Individuals were also recruited via advertisements at public locations children frequently visit (e.g., library), in the local newspaper, and at the Centre County Down syndrome Society (CCDSS) events. Participants earned $20 USD for participating in the study. Individuals were excluded from the study if they had uncontrolled seizures or psychoactive medications that had changed within the past 6 months.

Procedures

The study was conducted at the Penn State Child Language Development Lab at The Pennsylvania State University. Upon arrival, the study and visit was explained in detail to both the parent(s) and the participant. After the parent(s) read the consent form, both the parent and researcher signed the consent form to provide permission for their child to participate. The researcher then read the assent form to the participant and signatures were obtained. Parents also completed a demographic questionnaire about their child.

Following consent and questionnaire completion, a researcher administered the Peabody Picture Vocabulary Test –IV to the participant (PPVT-4; Dunn & Dunn, 2007). During the PPVT-4, the participant was shown sets of four line drawings and was asked to choose which image matched the target word verbalized by the researcher. This test was given to assess the
participant’s current vocabulary level as well as ensure that they knew enough words to participate in the study.

Research assistants also assessed participants’ comprehension of words that were presented as stimuli in the study. In this assessment, participants were presented with four line drawings from the Mayer Johnson Picture Symbols dictionary, displayed on a computer screen. Then the experimenter said a word and the participant pointed to the target line drawing. Finally, parents also completed a report indicating their confidence in their child’s knowledge of specific words.

Following the vocabulary assessments, the participant was escorted to the recording room and seated in the testing chair. To select an appropriate Electro-Cap International, Inc. electro-cap, the participant’s head circumference was measured with a special color-coded measuring tape. The color-coding coincided with cap sizes for fast and accurate measurement. Electrode impedances were checked and once they met testing criteria (at 10kΩ or below for mastoid and eye electrodes and 5kΩ or below for other electrodes), the participant was given instructions on the task. The session began once the participant indicated that they understood the task. Participants were allowed to take breaks between trials. The entire testing session lasted approximately 90 minutes.

**Stimuli**

The stimuli were 120 words and their corresponding line drawings. Words were selected from the first 60 words of the PPVT-IV form A and B and the first 327 words from the MacArthur-Bates Communicative Development Inventories (MCDI; Fenson, Dale, Reznick, Thal, Bates, Hartung, Pethick, & Reilly, 1993). Words were excluded if they fit into the following categories: action verbs, body parts, colors, shapes, emotions, and general category
terms (i.e. furniture, animal, food). Line drawings that matched the words were included from the Picture Communication Symbols (Mayer-Johnson, 1992).

The auditory stimuli consist of the 120 selected words. These were voice recorded through the program, GarageBand, and later converted to sound wave files. To eliminate noise in the sound files, they were edited in GoldWave. Stimuli were randomly separated into congruent (word and symbol match) and incongruent (word and symbol do not match) pairs. The incongruent stimuli were paired by contrasting categories, e.g., food and animal (see Chart 1). The stimuli were also randomized to determine the order of stimulus presentation for the study.

While wearing the cap, participants viewed and heard visual and auditory stimuli generated by a Dell Intel (R) Core(TM) 2 Duo computer using StimPres stimulus presentation software. The line drawings were presented on a Dell CRT monitor (resolution 1024x768) while the auditory stimuli was projected through a pair of Magnavox speakers. The EEG session began with a set of seven practice trials. Following the practice trials, the participant was asked whether they understood the task. Once the participant indicated that they understood the task, the experimental session began. Before each trial a wait screen that read, “press any button to begin” appeared. When a button was pressed, a fixation cross appeared in the center of the screen for a duration of 500ms to 1500ms. Then a spoken word and a line drawing were presented simultaneously for 2000ms followed by a response input screen. The participants were provided with as much time as needed to indicate with a finger tap whether the stimuli were a “match” or “mismatch”. To decrease participants’ working memory load, an experimenter was given a video game controller to enter the participant’s response. Following response input, a positive feedback image was displayed (see Figure 2). A total of 120 trials (60 congruent, 60 incongruent) were presented in 10 blocks of 12 trials. No more than two congruent or
incongruent trials were presented consecutively. The task took approximately 20 minutes to complete.

**EEG Collection**

An electro-cap (*Electro-Cap International, Inc.*) (see Figure 3) was used with ERPSystem software to record event-related potentials (ERPs) to the visual and auditory stimuli presented in the study. The EEG sampling rate was 200 Hz, amplified by SA Instrumentation Isolated Bioamplifier, and low-pass filtered at 40 Hz. Impedances for all electrodes were at or below 5kΩ and 10kΩ or below for the eye electrodes and were measured at the beginning of the recording session. All electrodes were referenced to the left mastoid electrode at the time of acquisition. Amplitudes that exceeded 60µV were rejected as artifact. Trials with channels that produced nearly identical values for 50 points consecutively were also rejected as artifact. A blink correction was employed to remove electrodes that had amplitudes over 1000µV. One participant was excluded from analysis due to data that was too noisy resulting in all of their data being rejected as artifact. In total, 9 participants were included in the analysis.

**Analysis**

*ERPSoftware* was used offline to analyze brain responses to the visual and auditory stimuli presented. Each participant’s EEG data was preprocessed using *ERPProcess* in which the trials were sorted into bins, averaged, normalized and filtered. During acquisition, trials were labeled to differentiate congruent and incongruent trials, inanimate and animate picture symbols, as well as correct and incorrect responses. Epochs of 1000ms post-stimulus onset were averaged according to a 200ms pre-stimulus baseline. The data was high-pass and low-pass filtered at .1Hz and 30Hz respectively to reduce noise in the data. The filtered data sets were then transferred to *ERPManipulate*. 
In ERPManipulate, averaged congruent and incongruent ERP segments were created for each participant. Those ERPs were averaged across all participants to create a grand average. Mean amplitudes were calculated for the following epochs: 250ms-350ms, 350ms-450ms, and 450ms-550ms after the stimulus presentation. Averages were computed for the following electrode sites of interest: C3, C4, Cz, F3, F4, Fz, P3, P4, and Pz. These epochs and electrode sites were selected based on previous ERP studies that quantified the N400 component in developmental and non-developmental samples (Friedrich & Friederici, 2004; Kutas & Hillyard, 1980; Thigpen, 2014).

Averaged ERPs were analyzed and plotted via R 3.2 (R Core Team, 2015), RStudio .99.446 (http://www.rstudio.com) and the R packages nlme (Pinheiro, Bates, DebRoy, Sarkar & R Core Team, 2015), ggplot2 (Wickham, 2009), and dplyr (Wickham and Francois, 2015). A linear mixed effects analysis was employed to explore how ERPs were affected by epoch, channel, symbol animacy, and trial congruency. In this model, fixed effects were epoch, channel, symbol animacy, and trial congruency with an interaction term for symbol animacy and trial congruency. Symbol animacy and trial congruency were selected based on previous studies that indicated that brain responses varied by stimulus category and semantically congruent or incongruent information (Kutas & Hillyard, 1980; Marí-Beffa et al., 2005). The participants’ mean amplitude responses were entered into the model as random intercept effects to control for individual differences in brain responses. An α level of .05 was used as the statistical criterion to interpret results. Residual plots did not show evidence of heteroscedasticity or non-normality. The variable inflation factor values for all factors were less than 5 indicating that collinearity was not an issue with this model.
The behavioral response data was also analyzed and visualized using the same tools. In the linear mixed effects analysis, fixed effects were symbol animacy and trial congruency. Since a research assistant entered game controller responses on behalf of the participants, reaction times are an approximation of participants’ actual reaction times. Mean reaction times were modeled as a random intercept effects to account for variation in reaction times due to individual differences. The statistical criterion selected for result interpretation was also $\alpha = .05$.

Vocabulary assessment data from the PPVT-4, the Mayer-Johnson Picture Symbol pointing task, and the parent report were also reviewed for average scores, proportion correct scores, and average number or words known respectively.
Results

Vocabulary Assessment

Figure 4 depicts the individual standard scores on the PPVT-4. The group mean score was 60.78 (SD=14.42). Results from the Mayer Johnson Picture Symbol pointing task depicted in Figure 5 yielded a mean accuracy percentage of 99.81 (SD=0.37). Figure 6 shows the parent reports of vocabulary knowledge. The average number of known words out of 120 present was 118.56 (SD=1.88). The average number of words parents were unsure their child knew was 1.67 (SD=1.80), while no parent reported that their child did not know a word on the list. These results indicate that these individuals knew the majority of the words presented to them in the study.

Behavioral Responses

Examination of the behavioral data focused on the effects of symbol animacy (animate or inanimate) and trial congruency (congruent or incongruent) on reaction time. The linear mixed effects analysis showed no effect of symbol animacy $F(1,929)=2.87$, n.s. However, there was a significant effect of trial congruency $F(1,929)=22.02$, $p<.0001$ qualified by a significant interaction between symbol animacy and trial congruency $F(1,929)=6.18$, $p<.05$ (see Figures 7 and 8). Participants showed faster reaction times for congruent trials (animate mean = 3,048ms (SD=1,729ms), inanimate mean = 2,947ms (SD=1,569ms) than for incongruent trials (animate mean = 3,061ms (SD=1,603ms), inanimate mean = 3,529ms (SD=1,981ms). The inanimate, incongruent conditions evoked particularly long reaction times.

ERP Data

One participant was excluded from analysis due to noisy data resulting in all of their ERP data being rejected as artifact. In total, 9 participants were included in the analysis. Figure 9
shows the grand average ERPs across participants for all conditions. Figure 10 shows average difference waves (congruent-incongruent) for animate and inanimate conditions. These figures show that there are high amplitude differences between the conditions that emerge between about 200 and 600 ms post-stimulus. The linear mixed effects analysis for brain responses across three epochs of interest—250ms-350ms, 350ms-450ms, and 450ms-550ms after the stimulus presentation—quantified these effects. It showed a significant effect of channel $F(8,895)=38.82, p<.0001$ with electrode sites mainly in the left hemisphere having the largest negative magnitudes, particularly channel C3 (see Figure 11). Trial congruency was also significant $F(1,895)=10.70, p<.01$ with incongruent trials producing larger negative responses than the congruent trials (see Figure 12). Mean amplitude responses were not significantly different by epoch $F(2,895)=2.02, n.s.$ and they also did not vary significantly by symbol animacy $F(1,895)=0.14, n.s.$, but there was a significant interaction between symbol animacy and trial congruency $F(1,895)=13.23 p<.01$. Figures 13 and 14 depict the group average and individual patterns for these effects. Mean amplitudes were larger for incongruent animate and inanimate trials than for congruent trials. Out of all trial types, incongruent animate trials elicited the largest brain responses. For 4/8 participants, amplitudes to the incongruent/inanimate condition are more negative than for the incongruent/animate condition. In the congruent condition, this pattern is reversed for 4/8 participants. The data show some group consistencies, but also substantial individual differences. These results suggest that only a portion of participant data may be contributing to the symbol animacy and trial congruency interaction. Participant reaction times and brain amplitude responses were not correlated, $r^2=01, n.s.$.
Discussion

In this study, we recorded brain responses to matching and mismatching AAC symbols in adolescents and young adults with DS in order to quantify an ERP component that is linked to semantic processing. Vocabulary assessment results indicated that this sample knew the majority of the words presented to them in the study, thus reducing the likelihood that task performance would be negatively impacted by vocabulary level. Participants were slower to respond to semantically incongruent inanimate picture/word pairings, broadly consistent with predictions.

Moreover, the AAC symbols elicited a negative-going ERP response in a 300-500 ms post-stimulus window (see Figure 9). The response was larger for incongruent semantic information than for congruent information (Benau et al., 2011; Kutas & Hillyard, 1980). This indicates that visual information, such as the Mayer-Johnson picture symbols, carries semantic information. There was no statistically significant difference in the size of the effect within this time period, but the timing of the response is broadly consistent with some form of the N400 component. Contrary to prediction, the response onset of this semantic component was not temporally delayed.

Taken together, the findings indicate that young adults with DS process the semantics of visual AAC symbols in a manner similar to the way typically developing adult communicators process spoken and written words. The results of this study add to existing literature with typically developing samples that show that nonverbal stimuli and verbal stimuli recruit the same brain regions and show highly similar cortical activity during semantic processing (Friedrich & Friederici, 2004; West & Holcomb, 2002; Willems et al., 2008). These findings also align with previous ERP studies that suggest that the harder it is to integrate information into an existing representation the larger the N400 response (Holcomb, 1993; Osterhout & Holcomb, 1995) and
that the N400 amplitude is linked to the level of semantic incongruity, with larger amplitudes for a higher degree of incongruity (Kutas & Hillyard, 1984; Kutas, 1993).

Event Related Potentials (ERPs) were recorded in 13 (6 female) typically developing 8-16-year-old school-aged children. Both the N400 and N300 were examined when participants were presented with a symbol and spoken word simultaneously. Results showed an increasing N400 effect with the greatest disparity between congruent and incongruent trials in the 450ms-550ms epoch. This effect was most prevalent in the left parietal lobe. The stimuli did not elicit an N300 response (Thigpen, 2014). Similar to the findings of the typically developing controls, the DS sample data shows a disparity between brain responses on incongruent trials and congruent trials. Results from this study also show that channels in the left hemisphere tended to have the largest magnitude negative responses, including the left parietal channel (P3).

Barrett and Rugg (1990) reported similar findings in their study that explored semantic processing of pictures. These researchers reported a frontally distributed response prior to the N400 called the N300. As shown in the Barrett and Rugg (1990) findings, our results show a strong negative frontal response to the stimuli (see Figures 13 and 14). Perhaps in this study and in Thigpen (2014), the N300 is not readily identifiable because the stimuli were both visual and auditory which could mean the N300 and N400 could not be disentangled. Reproducing this study with only picture stimuli could help isolate the N300 component.

Given the developmental delays associated with DS, I expected the distribution of the N400 to vary from those shown in previous studies with adults (Jacola et al., 2011; Kutas & Hillyard, 1980; Losin et al., 2009). In addition to the frontal response, this sample also shows a robust response to incongruent information in the left hemisphere. Brain responses also varied by electrode site with channels C3, C4, F3, and P3 having the largest negative magnitudes.
In a study with 19-month-old children, the left hemisphere showed a stronger contribution to the incongruity effect, specifically for children that were in the low word comprehension group (Friedrich & Friederici, 2004). This suggests that this sample may still be developing in terms of the N400 response.

The behavioral data showed that participants had longer response times on incongruent trials than on congruent trials, particularly for inanimate symbols. The faster response times may reflect shorter processing time because there were no anomalies present in these stimuli.

Data from a semantic priming categorization task indicates that reaction times to living words is faster than those for nonliving words (Marí-Beffa, Valdés, Cullen, Catena, & Houghton, 2005). For the current study, I expected to find differences in reaction times to words from distinct categories for correct trials. However, the difference in reaction time for animate picture symbols as compared to inanimate symbols was not statistically significant for this study. Unlike in the Marí-Beffa et al., (2005) study, the participants in the current study were not primed to focus on picture symbol animacy. Therefore, this information was not pertinent to their task and they overlooked it leading to a result that was not statistically significant. Evidence from positron emission tomography (PET) studies indicates that distinct brain regions are involved when processing animate images, inanimate images, natural objects and man-made objects (Moore & Price, 1999; Perani et al., 1999). In the current study, behavioral differences were not observed for the various stimulus types, however they were observed in the brain responses.

**Implications**

The current study is an important initial step in uncovering how AAC interventions can be made more effective. Better understanding of the mechanisms underlying AAC intervention effectiveness could lead to improved device selection. Abandonment rates of AAC devices may
be high among users (Phillips & Zhao, 1993) for a variety of reasons including poor support from communicative partners and/or the device manufacturer, lack of training for users and/or partners, and difficult to use or uncomfortable technology. Improvement in the devices could lead to a reduction in abandonment. This study demonstrates how research findings from studies with AAC users might be used to inform device design. For example, the current study shows that the Mayer-Johnson pictures symbols evoke brain responses consistent with semantic functions in neurotypical participants. This suggests that the symbols evoke semantic functions in DS users, and thus, picture boards should continue to incorporate them.

This study and future studies that focus on language processing in atypically developing populations could lead to improved health, educational, and vocational outcomes for populations beyond DS. Currently, 55% of individuals with intellectual and developmental disabilities, including those with communicative disabilities, in the U.S. get an education outside of the classroom, due to limitations in skills such as communication (National Center for Education Statistics, 2013). Approximately 90% of these individuals have no functional literacy skills and fewer than 5% are employed part-time (Foley & Wolter, 2010; McNaughton & Bryen, 2007). These statistics suggest that living autonomously can be difficult for individuals that experience difficulty with language. Studying these populations more closely can lead to better communication supports in classrooms and work environments which could lead to better educational and employment outcomes for these individuals.

**Limitations and Future Directions**

The current study uses ERP, and it is therefore impossible to identify subcortical regions that are linked to semantic processing. One subcortical structure that has been implicated in semantic processing in typically developing adults is the thalamus (Wahl et al., 2008). Future
studies might incorporate functional magnetic resonance imaging (fMRI) to explore whether individuals with DS exhibit the same activation patterns to semantic information as shown in previous studies (Harris et al., 2006; Kiehl, Laurens, & Liddle, 2002).

Also, there is evidence that perceptual and physical features of symbols influence speed in visual search task (Wilkinson & McIlvane, 2013). Individuals with intellectual disabilities have also been shown to have visual perceptual weaknesses that their age-matched peers do not (Ikeda, Kasugai, Yamaguchi, Uchino, Katase, & Kanno, 2013). In the current study, participants viewed symbols that might not have been optimal for the question of interest. Future studies might include the Developmental Test of Visual Perception (DTVP) (Maslow, Frostig, Lefever, & Whittlesey, 1964; Frostig, Horne, & Miller, 1972) to ensure that the strengths and weaknesses of the participants’ visual abilities are understood.

Finally, while there are many individuals with DS who use AAC as a primary mode of communication (Beukelman & Mirenda, 2013) none of the participants in the current study used AAC devices for communication. This means the results might overestimate the extent to which AAC symbols activate semantic processing in DS. Repeating this study with a sample of AAC users would allow us to explore semantic processing in the brains of individuals whose primary modality of communication is not speech. A replication with AAC users would permit us to find out whether the N400 represents semantic processing in AAC users and if the N400 latency and distribution is the same as reported in previous studies.

Since there is such a large population that depends on AAC devices, it is also important to assess their effectiveness. Part of the effectiveness of these devices is related to whether they can elicit language processes similar to those observed in populations that do not use AAC. The current study provides support that picture symbols have semantic functions just as words and
speech do. The picture symbols shown in this study vary from those that are on many AAC devices. Therefore, future studies should involve the use of actual AAC devices to explore what brain processes are like in a typical interaction. This would improve the ecological validity of the study as well as identify potential weaknesses in AAC devices, which would in turn lead to improvement in these technologies.
References


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APPENDIX

FIGURES
**Chart 1.** Stimuli used in current study. Each word had an accompanying image. Words with parenthesis represent incongruent trials.

<table>
<thead>
<tr>
<th>Chicken</th>
<th>Ice Cream</th>
<th>Socks (bowl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airplane</td>
<td>Barn</td>
<td>French Fries</td>
</tr>
<tr>
<td>Apple (bunny)</td>
<td>Mouse (knife)</td>
<td>Zipper</td>
</tr>
<tr>
<td>Knife (dress)</td>
<td>Train (hat)</td>
<td>Blocks (stroller)</td>
</tr>
<tr>
<td>Pig</td>
<td>Dog</td>
<td>Shirt</td>
</tr>
<tr>
<td>Ball</td>
<td>Hat (bug)</td>
<td>Butter (whistle)</td>
</tr>
<tr>
<td>Truck (clock)</td>
<td>Bicycle</td>
<td>Spaghetti (umbrella)</td>
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<tr>
<td>Scissors</td>
<td>Bread</td>
<td>Kangaroo</td>
</tr>
<tr>
<td>Clock (mouse)</td>
<td>Elephant (fire truck)</td>
<td>Teddy Bear (caterpillar)</td>
</tr>
<tr>
<td>Popsicle</td>
<td>Castle (giraffe)</td>
<td>Pencil</td>
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<tr>
<td>Motorcycle (elephant)</td>
<td>Carrot</td>
<td>Duck</td>
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<tr>
<td>Bed</td>
<td>Lamb (scarf)</td>
<td>Pear (couch)</td>
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<tr>
<td>Fork</td>
<td>Turtle</td>
<td>Corn</td>
</tr>
<tr>
<td>Cake (lamb)</td>
<td>Pizza (zebra)</td>
<td>Fire (money)</td>
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<tr>
<td>Helicopter</td>
<td>Mittens (squirrel)</td>
<td>Umbrella (teddy bear)</td>
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<tr>
<td>Pretzel (mittens)</td>
<td>Hammer</td>
<td>Keys</td>
</tr>
<tr>
<td>Horse</td>
<td>Bear (truck)</td>
<td>Camera (sandwich)</td>
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<tr>
<td>Book (cake)</td>
<td>Cow</td>
<td>Bat (pear)</td>
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<tr>
<td>Shoe</td>
<td>Bunny (pumpkin)</td>
<td>Glasses</td>
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<tr>
<td>Drum</td>
<td>Candle (pizza)</td>
<td>Crayons (grapes)</td>
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<tr>
<td>Firetruck (pretzel)</td>
<td>Balloon</td>
<td>Crib</td>
</tr>
<tr>
<td>Monkey</td>
<td>Bird</td>
<td>Ruler</td>
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<td>Toothbrush (motorcycle)</td>
<td>Turkey (present)</td>
<td>Towel (lamp)</td>
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<td>Popcorn</td>
<td>Grapes (socks)</td>
<td>Bowl (tree)</td>
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<tr>
<td>Dress (apple)</td>
<td>Strawberry</td>
<td>Banana</td>
</tr>
<tr>
<td>Boat</td>
<td>Whistle (turkey)</td>
<td>Pants</td>
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<tr>
<td>Giraffe (train)</td>
<td>Spoon</td>
<td>Chair</td>
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<tr>
<td>Cat (flag)</td>
<td>Caterpillar (spaghetti)</td>
<td>Fish (vest)</td>
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<tr>
<td>Frog</td>
<td>Cup</td>
<td>Button (blocks)</td>
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<td>Squirrel (candle)</td>
<td>Bottle</td>
<td>Penguin</td>
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<td>Bus</td>
<td>Vest (bat)</td>
<td>Cobweb (camera)</td>
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<td>Butterfly</td>
<td>Telephone</td>
<td>Door (towel)</td>
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<td>Zebra (castle)</td>
<td>Tree (door)</td>
<td>Feather</td>
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<td>Lion</td>
<td>Envelope</td>
<td>Stroller (cobweb)</td>
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<td>Scarf (book)</td>
<td>Couch (owl)</td>
<td>Money (fish)</td>
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<td>Coat</td>
<td>Belt</td>
<td>Bee</td>
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<td>Pumpkin (toothbrush)</td>
<td>Doll</td>
<td>Sandwich (button)</td>
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<tr>
<td>Flag (bear)</td>
<td>Lamp (butter)</td>
<td>Bubbles</td>
</tr>
<tr>
<td>Boots</td>
<td>Flower</td>
<td>Present (crayons)</td>
</tr>
<tr>
<td>Bug (cat)</td>
<td>Cookies</td>
<td>Owl (fire)</td>
</tr>
</tbody>
</table>
Figure 1. Examples of AAC devices. (A) Low-technology picture board, (B) high-technology speech generating device with limited words, (C) high-technology voice output device unlimited expression of words (Stephen Hawking pictured).
**Figure 2** Schematic of stimulus presentation.
Figure 3 32-channel Electrocap montage.
**Figure 4.** Participant Peabody Picture Vocabulary Test-IV standard scores.

![bar chart showing PPVT-IV scores for different participants]
Figure 5. Participant accuracy percentages on the Mayer-Johnson pointing task
Figure 6. Parent assessment of child’s vocabulary knowledge. (A) Known words, and (B) Unsure words.

(A)
Figure 6 continued

(B)

Parent Vocabulary Assessment

Number of List Words Unsure

AH  AM  BF  DD  GB  HS  KB  TR  ZW

Participant
Figure 7. Averaged participant behavioral responses for congruent and incongruent trials. Reaction time is in milliseconds.
Figure 8. Averaged participant behavioral responses for each trial type. Reaction time is in milliseconds.
Figure 9. Grand average of participant response for each condition. Anterior electrode sites are located at the top of the image. Negative voltage is up.
**Figure 10.** Difference wave of averaged participant responses for congruent and incongruent trials categorized by animate and inanimate symbols. Anterior electrode sites are located at the top of the image. Negative voltage is up.
Figure 11. Averaged participant event-related potential responses for each channel per trial type, collapsed across epoch. Amplitude is in microvolts.
Figure 12. Averaged participant event-related potential responses for congruent and incongruent trials. Amplitude is in microvolts.
Figure 13. Averaged participant brain responses for each trial type. Amplitude is in microvolts.
**Figure 14.** Averaged participant event-related potential responses for each trial type. Amplitude is in microvolts. An additional participant provided incomplete data for some of the conditions. That participant’s data is not shown in the figure but was included in the statistical analyses.
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