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# Neural Activity Associated with Visual Search for Line Drawings on AAC Displays: An Exploration of the Use of fMRI

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#### ABSTRACT

Visual aided augmentative and alternative communication (AAC) consists of books or technologies that contain visual symbols to supplement spoken language. A common observation concerning some forms of aided AAC is that message preparation can be frustratingly slow. We explored the uses of fMRI to examine the neural correlates of visual search for line drawings on AAC displays in 18 college students under two experimental conditions. Under one condition, the location of the icons remained stable and participants were able to learn the spatial layout of the display. Under the other condition, constant shuffling of the locations of the icons prevented participants from learning the layout, impeding rapid search. Brain activation was contrasted under these conditions. Rapid search in the stable display was associated with greater activation of cortical and subcortical regions associated with memory, motor learning, and dorsal visual pathways compared to the search in the unpredictable display. Rapid search for line drawings on stable AAC displays involves not just the conceptual knowledge of the symbol meaning but also the integration of motor, memory, and visual-spatial knowledge about the display layout. Further research must study individuals who use AAC, as well as the functional effect of interventions that promote knowledge about array layout.

#### Introduction

All individuals, including those with disabilities, have the right to access effective communication as well as academic, social, and vocational opportunities (National Joint Committee for the Communicative Needs of Persons with Severe Disabilities, 1992). Well-designed interventions can help individuals with communication disabilities achieve optimal functioning, enabling service provision within less restrictive settings and reducing challenging behaviors (Durand, 1993; Emerson et al. 2001; Lalli & Goh, 1993; Petty, Allen, & Oliver, 2009). One body of clinical practice that can effectively support communication involves visual aided augmentative and alternative communication (aided AAC; Beukelman & Mirenda, 2013). These interventions make use of external communication aids such as low-technology books or high-technology speech generating devices that present visual-graphic symbols (such as letters, words, or pictures) to the individual. The individual navigates the AAC displays to locate symbols, icons, or line drawings for

desired concepts, and then selects one or more to create a message.

## Message Preparation in Aided AAC

A common clinical observation concerning at least some forms of visual aided AAC is that message preparation can be frustratingly slow. Whereas with speech the average speaker can produce 150–250 words per minute, in aided AAC the rate can be as low as 15-25 words per minute (Beukelman & Mirenda, 2013), often resembling the huntand-peck behavior of a novel typist. This slowed rate of communication presents attention and memory challenges (Thistle & Wilkinson, 2012, 2013; Wilkinson & Hennig, 2009), and can have unwanted consequences such as communication passivity (Light Binger, & Kelford Smith, 1994) and negative perceptions of the individual who uses AAC (Bedrosian, Hoag, & McCoy, 2003; Hoag, Bedrosian, McCoy, & Johnson, 2004). The rate of message preparation has also been cited as a factor contributing to limited use or abandonment of AAC systems by

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individuals and their families or caregivers (Fager, Hux, Beukelman, & Karantounis, 2006). Efforts to foster success with AAC, including enhancing the speed of message preparation, have focused, on communication targets such as selecting appropriate vocabulary (Fallon, Light, & Page, 2001), improving methods for teaching symbol meanings (Wilkinson & Albert, 2001), developing interventions for fostering use (Cosbey & Johnston, 2006; Drager et al., 2006; Harris & Reichle, 2004), using letter or word prediction or semantic compaction systems to reduce keystrokes in generative language (Beukeleman & Mirenda, 2013), and training communication partners (Johnson, Inglebret, Jones, & Ray, 2006; Kent-Walsh & McNaughton, 2005).

One important dimension that differentiates message preparation via AAC versus spoken communication is the modality. Aided AAC that involves visual symbols/ aids differs from spoken language in two critical ways: access depends on visual processing, and the vocabulary in the lexicon consists of symbols laid out in spatial groupings on an external device. The basic cognitive, linguistic, and neural mechanisms underlying AAC use therefore cannot simply be extrapolated from knowledge about spoken language, which involves processing of auditory symbols and a comprehensive vocabulary stored in an internal lexicon. Because aided AAC is most often accessed through vision, success may reflect how well the visual aspects of displays match the visual processing skills of their viewers. Displays that promote rapid identification and selection of a target are likely to result in greater success, whereas displays that are confusing, poorly laid out, or difficult to commit to memory seem likely to result in poorer outcomes (cf. Wilkinson & Jagaroo, 2004). This might be analogous to the familiar experience of trying to access the contents of a simple, clear, and streamlined website as compared to a poorly organized website with many extraneous details. In addition to processing of visual information, effective aided AAC may also depend on ease of access by users to stored information concerning the spatial configuration of the array, as well as the ease of planning, sequencing, and executing the motor response. If our hypothesis is correct, then aligning the physical and perceptual features of aided AAC displays with principles of human visual, memory, and motor processing could optimize the effectiveness of these displays for communication and learning.

## Research Goal: Applying Brain Imaging to Understand Search Facility in AAC

Functional magnetic resonance imaging (fMRI) techniques afford researchers the ability to examine neural activity associated with various cognitive processes. (For further background, interested readers are referred to the following appendices, which are published online only as supplementary materials: Supplementary Appendix A provides an image of the cortex of the brain, with the regions of interest identified; Supplementary Appendix B includes a table that provides a guide to the relevant neuroanatomy; and Supplementary Appendix C offers an overview of some of the imaging and data acquisition terms used in this paper as well as some of the rationale for decisions made regarding the terms used). In this study, we examined differential neural activation under conditions that promoted visual search of targets on a simulated AAC display as compared to conditions that impeded such search and selection. What differences are there in brain regions associated with visual, memory, and motor functioning when participants responded to AAC displays that facilitate search, as compared to displays that impede search?

To answer this question, we examined neural activity associated with search and selection of line drawings (also referred to as symbols) on simulated AAC displays under two experimental conditions; one in which the arrangement of the line drawings remained stable (unchanged) from trial to trial, such that their locations could be anticipated by participants, and the other in which the symbol locations were unpredictable or shifted on each trial, such that target locations could never be predicted. The former experimental condition was designed to facilitate visual search by enabling learning to occur, while the latter experimental condition was designed to simulate the hunt and peck approach required in effortful visual search. We hypothesized that search would be promoted when the symbols remained stable on the array, because (a) the layout of the spatial display can be committed to memory, allowing the stored information about the display to be accessed during search and response; (b) the stable array allowed for establishment of motor learning patterns, because an individual can anticipate and plan the response given the knowledge of the spatial display; and (c) visual-spatial aspects of the array can be used during search, since responses can be produced based on where the symbols appear, instead of (or in addition to) their shape or form. Our hypotheses concerning the expected neural correlates of conditions of this greater (stable) or less rapid (unpredictable) visual search were then developed based on prior evidence from brain imaging studies.

Because the symbols remained in predictable locations in the stable condition, storage and retrieval of information about the display was possible; this was prevented in the unpredictable condition due to the trial-by-trial shuffling of symbol location. We therefore anticipated greater activation of brain regions associated with memory encoding and retrieval tasks in the stable experimental condition relative to the unpredictable one. Greater activation was expected in medial temporal lobe (MTL) regions, including right-lateralized entorhinal and perirhinal areas, that code for spatial memory (e.g., Bellgowan, Buffalo, Bodurka, & Martin, 2009; Hayes, Ryan, Schnyer, & Nadel, 2004; Sulpizio, Committeri, Lambrey, Berthoz, & Galati, 2013). We also anticipated greater activation in the hippocampal region (specifically, parahippocampal cortex) as this region has been demonstrated to be involved in long-term spatial memory in animal models as well as humans (e.g., Rosenbaum, Zeigler, Winocur, Grady, & Moscovitch, 2004; Squire & Zola-Morgan, 1991; Zola-Morgan, Squire, Amaral, & Suzuki, 1989). Finally, we anticipated that retrieval of such information would be accompanied by increased activity in the dorsolateral prefrontal cortex (DLPFC), which has been shown to be activated during both retrieval and working memory tasks (Curtis & D'Esposito, 2003; Fletcher & Henson, 2001; Fletcher, Shallice, Frith, Frackowiak, & Dolan 1998; Ranganath, Johnson, & D'Esposito, 2003). This region has been implicated in maintaining sensory information in mind or, as argued more recently, preparing an upcoming intended action based on current information (see, for example, Mars & Grol, 2007; Passingham & Sakai, 2004; Pochon et al., 2001).

Because the stable array allowed participants to anticipate the location of each symbol on the display, we anticipated that this condition would enable motor learning, whereas the unpredictable display would not. For instance, a participant who has learned that the line drawing for ROOSTER always appears in the upper right hand corner of the display can prepare for the motor movement on a trial where ROOSTER is the target. On the basis of reviews/meta-analyses by Doyon and Benali (2005) and Hardwick et al. (2013), we anticipated increased neural activity in the stable compared to the unpredictable condition in cortical areas shown to be involved in motor learning. Specifically, we anticipated activity centered in the frontal lobe (primary motor cortex, supplementary motor cortex, premotor cortex) as well as the sensorimotor activity areas of the postcentral gyrus and posterior areas that are engaged in motor learning tasks (Dayan & Cohen, 2011; Floyer-Lea & Matthews 2004; Jankowski, Scheef, Huppe, & Boecker, 2009; see also Sakai et al., 1998).

In addition to the motor cortices, we anticipated greater activation in subcortical motor loops in the stable condition. These include the striatum (caudate and

putamen), which are particularly involved in motor sequence learning (Doyon et al., 2009; Floyer-Lea & Matthews, 2004; Hardwick, Rottschy, Miall, & Eickhoff, 2013; Jankowski et al., 2009; Lehéricy et al., 2005). Also of interest was the cerebellum. Although much remains to be learned about the motor, and non-motor, functions of the cerebellum, it has been shown to be a key structure for motor learning and may offer continuous feedback on motor adaptation tasks (Bo, Peltier, Noll, & Seidler, 2011; Hardwick et al., 2013; Orban et al., 2010).

In terms of visual-spatial processing, we expected substantial activation of both primary and secondary visual cortex under both conditions, and hence, no differential effect. Of greater interest were the ventral and dorsal cortical visual pathways (Unglerleider & Mishkin, 1982). The ventral occipito-temporal "what" path connects the striate, prestriate, and inferior temporal areas and has been shown to be involved in object identification based on visual properties such as color, form, and texture rather than position (e.g., Mishkin, Ungerleider, & Macko, 1983). The dorsal occipito-parietal "where" pathway connects the striate, prestriate, and inferior parietal areas, and is considered to be involved in visually locating objects in space (Mishkin et al., 1983), as well as visually guiding motor actions toward objects (Ungerleider & Haxby, 1994). The stable condition allows for reliance on the spatial configuration as a cue, a cue that is unavailable in the unpredictable condition. Given that participants could access spatial configuration as a cue only in the stable condition, we anticipated increased activation of the dorsal stream regions in that stable condition relative to the unpredictable one. In contrast, as it is impossible to select a target based on its remembered location in space in the unpredictable condition, the search required examination of individual line drawings until the target was found. Thus we predicted that item-by-item search would be reflected in greater activation in the ventral stream in the unpredictable condition.

#### Method

#### **Participants**

Eighteen right-handed college students without disabilities (according to self-report) participated. This study focused on college students without disabilities in order to examine the neural activity in individuals for whom there was no concern about visual, motor, or cognitive/ language disabilities (Higginbotham & Bedrosian, 1995). If the expected patterns emerged in this population, we would be in the position to make testable predictions about the activation we might see in individuals who have disabilities and show varying levels of facility with AAC. Participants were recruited via flyers as well as a link from the university Institutional Review Board website. The mean age was 25;4 (years;months) (range: 20–35), with seven males and 11 females. Participants were screened for contraindications to fMRI according to institutional procedure prior to participation.<sup>1</sup> Participants received \$20 in compensation for their participation. All experimental procedures were approved by the Institutional Review Board of The Pennsylvania State University and all participants provided written informed consent.

#### **General Task and Response**

The task was a 0-delay matching to sample task. Each individual trial contained three epochs: (a) a jittered or varying-length fixation period in which a simple fixation cross was presented against a white background; (b) a sample period, in which a single color photograph of an animal was presented in the center of the screen, and (c) a response period, in which an array of 20 line drawings of animals was presented in a grid layout. The jittered fixation period provided a brief break for participants and varied in length between 1000 and 12000 ms, in order to deconvolve the hemodynamic response. The photograph in the sample period cued the participant as to which line drawing was the correct target in the subsequent response period. The response period was the epoch during which the participant's task was to locate and select the just-cued animal from the 20-item array.

Responses during both the sample and the response period were produced via a joystick with a response button. Participants lay prone in the magnet and held the joystick box on their torso with the left hand and controlled the joystick with the right hand. The sample and response periods were of different lengths on each trial because the task was self-paced, meaning that each period ended when the participant clicked on a stimulus (rather than the timing being pre-set by the investigators). Although the self-paced nature of the task meant that individual participants spent somewhat different lengths of time in the scanner, the key contrast in this study was within-subjects, that is, a comparison of each individual participant's performance on the stable trials versus that same participant's performance on the unpredictable trials. In other words, for the comparison of interest in this study, each participant served as his or her own control/contrast, consistent with the strengths and controls of within-subject research designs.

Data were examined during pre-processing to ensure that the use of the joystick did not introduce undue motion artifact. The method for treating motion artifact adhered to well-established practices in fMRI (Huettel, Song, & McCarthy, 2009; Johnstone et al., 2006) and those of the second author's research protocols (Dennis et al., 2008; Dennis, Turney, Webb, & Overman, in press). Specifically, standard practices are to exclude participants with >1 voxel motion, as smaller estimates of motion are well handled by standard motion correction techniques and by including motion parameters as nuisance regressors in the fMRI model.<sup>2</sup> Our review of the raw data indicated that no participant moved more than one voxel, or 2.5 mm. Therefore, no data were discarded due to excess motion. All of the remaining minimal motion artifacts were controlled in the fMRI analysis by entering it as a nuisance regressor of no interest.

#### Stimuli

The stimuli in the sample period were color photographs of animals obtained from the Internet (Google images<sup>3</sup>). The line drawings for the response period were obtained from the Boardmaker Picture Symbol Dictionary<sup>®</sup> (PCS; Mayer Johnson, 1992),<sup>4</sup> one of the most widely used commercially available symbol sets used in AAC.

Twenty animals from three loose overarching categories were presented in the stable condition (farm animals, African mammals, insects), and 20 different animals from three other categories in the unpredictable condition (ocean dwellers, forest creatures, birds). Supplementary Appendix D (online only) presents a listing of the animals presented within each condition and a rationale for the use of different stimuli under different conditions. These categories were selected for practical reasons, given constraints of basic-level categories as well as the Boardmaker PCS Dictionary. Specifically, we sought highly familiar animals that could be expected to be well known to adults and that also had depictions within the PCS dictionary.

The exemplars for each condition were entered into the MRC Psycholinguistic Database (http:// websites.psychology.uwa.edu.au/school/MRCDatabase/ uwa\_mrc.htm) to evaluate the comparability of the concepts across the two experimental conditions. The MRC is a well-established database in psycholinguistic research that provides empirically-derived ratings of concepts on a variety of measures, including, for our purposes, imagability (how readily visualized it is), familiarity (how common it is rated to be), and concreteness (tangibility), as well as number of phonemes and syllables of the associated labels. One-way ANOVA indicated that the two 20-word sets in our experimental conditions did not differ on any of these five ratings, suggesting that the concepts within each were comparable on these measures. The potential impact of using two separate stimulus sets is considered in the Discussion.

#### **Experimental Conditions**

Figure 1 provides an example of the sample photograph and the response display for a trial. The line drawings were arranged in three rows, containing seven, six, and seven animals in the top, middle, and bottom rows, respectively. The middle row contained six animals so that the center key would be blank, as the photograph appeared in that location during the sample period.

In the stable condition, the positions of all line drawings in the array remained constant. The line drawing for the cow, for example, was always in the top row farthest left position. Line drawings in the stable condition were grouped within their category such that the seven farm animals were in the top row, the six jungle animals were in the middle row, and the seven insects were in the bottom row (participants were not told of this organization). This stable layout was intended to allow participants to learn the locations of each of the 20 line drawings.

In the unpredictable condition, the relative locations of both the target items, as well as the locations of the 19 distracters, shifted to different positions on the grid on each trial. This varying of location was intended to prevent participants from learning the locations of each of the 20 items, thus requiring a search that could not benefit from the presence of memory for the display or automatic motor or visual pathways.

#### **Procedures**

Participants received a block of 40 trials of pre-training before entering the magnet, containing 20 trials of stable condition and 20 trials of unpredictable condition. This pre-training served several functions. First, it enabled a pre-screen to demonstrate that participants were capable of matching each animal photograph (the sample) with its associated line drawing (target), that is, that they understood the meaning of each photograph and line drawing. As expected, given that these were adult college students, all accuracies were above 90%. Second, this pre-training provided participants with equal experience with the two conditions. Finally, the pre-training allowed us to infer, through observation of the differences in the response times to select the target, that the participants had learned the layout of the stable but not the unpredictable array.

Participants entered the magnet, either the same day or within a few days of the pre-training. The first block of trials in the magnet presented the identical 40-trial block as in pre-training, but imaging data were not acquired for analysis purposes. The purpose of repeating the pretraining block a second time was to (a) familiarize the participant with controlling the joystick while lying prone in the magnet, and (b) provide a memory refresher for those individuals whose training had not directly preceded the imaging session.



Figure 1. Examples of the two phases of an experimental trial. The top panel represents the display during the sample period. Upon the participant's selection of the sample picture via mouse click, the sample display disappeared and was replaced by the choice array, depicted in the bottom panel.

Following this initial familiarization, two experimental blocks, each containing 40 trials (20 stable, 20 unpredictable) were run while the imaging data were acquired. Thus, by the end of each imaging session, a total of 80 trials of imaging data were obtained per participant (40 stable, 40 unpredictable). Each block of 40 trials took an average of 6 min for each participant.

An iterative process of trial and block construction was conducted to ensure that trial structure was balanced across conditions internally within each 40trial block, and shuffled across the three separate 40-trial blocks (Supplementary Appendix D presents specific details about the trial number, trial type, target animal, and correct location for the pre-training block as well as the two experimental blocks, and also the process for balancing). Internally, each of the three 40-trial blocks (one pre-training, two experimental) were constructed to maintain the following constraints: (a) each of the 20 animals within each condition - stable and unpredictable - appeared as the target on one trial, (b) each location on the 20-item array served as the correct location on one trial within each condition, stable and unpredictable, (c) the order of stable and unpredictable trials was intermixed across the full 40-trial block, so that the participant could not predict which trial type was upcoming, and (d) the target locations on trials in direct sequence with one another varied. Across the three separate 40-trial blocks, two further constraints were implemented: (a) the order of the correct target/location was shuffled such that the order of target and location for the pre-training block, the first experimental block, and the second experimental block were different from one another, and (b) the arrays for the unpredictable condition were shuffled such that they varied not just from trial to trial within a block but also across blocks. The trials were intermixed in order to enable the fMRI analyses of interest. Observed differences in latency of behavioral responding to the stable compared to the unpredictable trials verified that despite the intermixing, responding was reliably and significantly faster in the stable condition.

#### Image Acquisition

Images were obtained using a Siemens 3 T Magnetom Trio MRI<sup>5</sup> scanner equipped with a 12-channel head coil. Responses were recorded using an MRI safe joystick. The potential for participant head movement was reduced using foam pads and scanner noise was minimized using earplugs. A T1-weighted sagittal localizer was acquired to align scans to the anterior and posterior (AC-PC) commissures. A high resolution anatomical image (MPRAGE) was acquired with a 1400 ms TR, 2.03 ms TE, 256 mm field of view (FOV),  $256^2$  matrix, 160 axial slices, and 1 mm slice thickness for each participant. Echoplanar (EPI) functional images were obtained using a descending acquisition, 3000 ms TR, 30 ms TE, and 200 mm FOV. In all, 53 axial slices were acquired per TR with a 2.0 mm slice thickness and 0.5 mm gap, resulting in 2.5 mm isotropic voxels, and an  $80 \times 80$  image matrix (see Supplementary Appendix C for definitions of terms).

#### **Image Processing**

Preprocessing and statistical analysis of the fMRI data was performed using SPM8 (Statistical Parametric Mapping; Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm) using a common processing stream. As a first step, time-series data were corrected to account for differences in slice acquisition times through the standard slice timing algorithm in SPM8, which interpolates acquisition time points. This step is especially important to do for eventrelated designs in order to account for signal differences between each volume. Next, data were spatially realigned to a common reference point (first volume) in order to minimize variance between volumes and to adjust for movement between slices. Functional images were then coregistered to the anatomical MR images. This is done by overlaying the structural and functional images with the goal of linking up the low resolution functional scans (EPI) to corresponding high resolution anatomical scans (T1). Images were then spatially normalized to the standard Montreal Neurological Institute (MNI) space (acting as a template brain)<sup>6</sup> by resampling at 3 mm isotropic resolution, with the coordinates later converted into Talairach space (Talairach & Tournoux, 1988) for reporting. By averaging the signal across participants and aligning this to the template MNI space and reporting in Talairach coordinates, we are able to derive group statistics. Lastly, the data were spatially smoothed using an 8 mm Gaussian smoothing kernel to further improve signal to noise ratio.

#### Data Analysis Approach

Behavioral Responding in Visual Search. Behavioral data were collected on each and every trial during the imaging sessions, in the form of accuracy and speed of locating the target on that trial. The behavioral data were not of primary interest in the study, except for the following purposes: (a) to verify that responding in the stable condition was faster than in the unpredictable condition, indicating that the expected learning of the display had occurred, (b) to serve as an exclusion/inclusion gateway for determining which trials would be included in the main imaging analysis, and which trials would be treated as regressors of no interest.

Trials were included in the fMRI analysis if they met two criteria: First, the selection was a correct match to the sample that had just been displayed (an accurate selection); and second, the latency was not excessively long, as determined by a mathematical criterion for identifying outliers. This latter criterion was added because piloting of the procedures had made clear that there were occasional trials on which the participant correctly located the target, but had difficulty controlling the joystick. This led to occasional correct trials that had excessively long latencies (outliers) and self-report of frustration on those trials by the pilot participants. The method used to identify these outliers involved two steps. First, we calculated the median response time for all correct trials for each of the two experimental conditions in each block (median was selected because it is not as prone to influence from outliers as the mean). We then calculated the standard deviation of latencies for all correct trials. Any trial with a latency of greater than one standard deviation above the median was flagged as an outlier and treated as a regressor of no interest in fMRI analysis.

The mean number of trials forwarded for fMRI analysis on the basis of these criteria (correct, and not excessively long as established by the mathematical algorithm) was 32.6 trials in the stable condition and 32.9 trials in the unpredictable condition (out of a total possible of 40 trials). Paired *t*-tests confirmed that there were no differences between conditions in the number of trials across conditions, indicating that the number of trials included in the fMRI analysis was equivalent for the stable and unpredictable conditions.

fMRI Analyses. Trial-related activity was modeled in the General Linear Model (GLM), with a stick function corresponding to the trial onsets (i.e., onset of the sample period) convolved with a canonical hemodynamic response function (hrf) and its temporal (first) derivative.<sup>7</sup> Statistical parametric maps (SPMs) were identified by applying linear contrasts to the parameter estimates (beta weights) for the events of interest. Regressors associated with correct responses in unpredictable and stable trials were used in defining contrasts of interest. Incorrect trials and correct trials that had a response time of greater than one standard deviation above the participant-specific median latency time were also modeled, yet treated as a regressor of no interest, as were regressors associated with subject-specific head motion.

We contrasted neural activity associated with a correct response in the stable condition with activity associated with a correct response in the unpredictable condition. This contrast allowed us to see what regions were more active during the stable condition, which we had predicted would involve the memory systems, the dorsal visual pathway, and motor areas. We also looked at the reverse contrast to compare activity associated with a correct response in the unpredictable condition to that associated with a correct response in the unpredictable condition. This contrast allowed us to evaluate whether the ventral pathway was more active in the unpredictable condition, when the participant was required to search based on object identity alone.

In order to obtain results corrected for multiple comparisons, we used Monte Carlo simulations (https://www2.bc.edu/sd-slotnick/scripts.htm) to define individual voxel and cluster extent thresholds across all contrasts (e.g., Forman et al., 1995; Garoff-Eaton, Kensinger, & Schacter, 2007; Quadflieg et al., 2008; Slotnick & Schacter, 2004). This procedure takes into account the acquisition matrix ( $80 \times 80$ ), number of slices (53), voxel dimensions (2.5 mm<sup>3</sup>), intrinsic smoothness (13 mm), and resampling of voxels (resampled to 3 mm<sup>3</sup>) in order to simulate data and estimate the rate of Type I error given the protocol parameters. In this study, an individual voxel threshold of p < 0.01 was used in combination with a cluster extent threshold of 18 resampled voxels (486 mm<sup>3</sup>) in order to identify results corrected for multiple comparisons at p < 0.05.

#### **Results**

# Behavioral Responses: Accuracy and Latency to Select the Target

Reaction times for correct trials verified that speed of responding was faster for the stable condition than the unpredictable condition. This pattern was an indication that learning of the locations of concepts had occurred, but only for the stable array. Figure 2 illustrates that average response latencies were faster for the stable trials than unpredictable ones. Repeated measures ANOVA indicated that the difference between conditions was of statistical significance with a large effect size, F(1,17) = 19.98, p < 0.000, eta = 0.73.

#### fMRI Results

Table 1 provides information about the brain regions that showed statistically significant differences in activation under stable and unpredictable experimental conditions. Regions showing greater activity in the stable compared to unpredictable condition included



Figure 2. Mean reaction time to locate target, across experimental conditions. Error bars represent standard deviations.

				Coordinates (T&T)			
	BA	Н	X	Ŷ	Z	t	mm <sup>3</sup>
Stable > Unpredictable							
Orbitofrontal cortex	11	L	-33	42	-14	4.25	837
Motor cortex	4	L	-33	-18	60	3.2	837
Postcentral gyrus	2	R	42	-26	30	3.24	648
Putamen		R	24	2	-7	4.1	567
Parahippocampal gyrus	28	L	-15	-22	-13	3.63	1269
Middle temporal gyrus	21	R	68	-22	-6	3.59	864
	21	L	-50	-25	-8	4.48	567
	20/21	R	48	-34	-10	5.64	675
Superior temporal gyrus	27	L	-42	-44	11	3.95	486
Superior parietal lobe	40/7	L	-50	-45	50	4.94	3267
Inferior parietal lobe	39/40	R	50	-52	34	4.33	1404
·		L	-50	-52	34	4.1	1917
Precuneus	5/7	М	-6	-33	52	4.24	1134
	7/31	R/L	15	-62	57	4.22	10098
Cingulate gyrus	31	R	12	-34	41	3.68	729
Primary visual cortex	17/18	R	21	-94	3	4.5	891
,		L	-12	-94	-2	5.27	3834
Cerebellum		R	27	-75	-16	4.86	3699
		L	-36	-78	-18	4.74	8424
Sub-gyral/extra		М	3	-38	11	4.64	1188
Sub-gyral/extra		М	3	-47	-40	3.78	702
Unpredictable > Stable							
Superior temporal gyrus	42	L	-53	-12	13	4.28	513
Medial frontal gyrus	46	L	-24	26	22	4.05	486

Table 1	Results	of fMRI	analysis
	nesuits		anaiysis.

This table reports areas distinctly activated for the stable and unpredictable conditions (regions listed anterior to posterior); BA, Brodmann's area; H, hemisphere; L, left; R, right; *t*, statistical *t*-value; T&T, Talairach and Tournoux coordinates. Voxel clusters are listed in mm<sup>3</sup> by multiplying the number of voxels by the resampled voxel size.

Shaded rows indicate areas of activation that were not predicted a priori.

motor cortex, specifically pre- and postcentral gyrus, bilateral middle and left superior temporal gyrus, inferior and superior parietal lobes including bilateral precuneus, bilateral primary visual cortex, left parahippocampal gyrus, and bilateral cerebellar regions. Figure 3 illustrates the regions of greater activation under the stable condition relative to the unpredictable display condition. Figure 4 illustrates the region of greater activation under the unpredictable condition relative to the stable condition. This latter contrast showed increased activity only in superior temporal gyrus and medial frontal gyrus.



Figure 3. Areas of greater activation under the stable display condition. Activation was observed in (a) left parahippocampal gyrus, (b) bilateral parietal cortex and (c) motor cortex and cerebellum (x, y, and z refer to Talairach coordinates).



Figure 4. Greater activation under the unpredictable display condition. Activity was observed in the left superior temporal gyrus (x, y, and z refer to Talairach coordinates).

#### Discussion

As anticipated based on prior literature, activation was significantly greater in the stable condition compared to the unpredictable condition in areas that support spatial and long-term memory systems (the parahippocampal gyrus and the middle temporal gyrus), in cortical and subcortical motor learning regions (motor cortex, postcentral gyrus, putamen, and cerebellum), and in the dorsal visual pathway (superior and inferior parietal cortex, precuneus). In the one exception to expectations concerning greater activity in the stable condition, no differences in activation were found for the dorsolateral prefrontal region. Only the superior temporal gyrus showed greater activation under the unpredictable condition that inhibited search facility, compared to the stable condition that facilitated search.

#### Scientific and Clinical Implications

Relative to traditional tasks conducted in an fMRI, the experimental procedure we used was fairly complex in terms of the number of stimuli, the use of a directed behavioral response (joystick), and its self-paced nature. We opted to use this particular task because we felt it was important to simulate the type of task confronting an individual searching for a symbol on an AAC array. The unpredictable condition does not resemble recommended clinical practice, as clinicians would never move symbols on a display on a regular basis. However, the purpose in this study was, within each individual participant, to enable or prohibit search and selection of target symbols on an AAC array.

Understanding these caveats, the findings were largely in line with our predictions about activation in areas previously found to be active during engagement of functional systems (motor, memory, vision), and offer confirmation of the utility of our procedure despite its complexity. Our data suggest that search and selection of symbols on an AAC grid display likely involves a combination of: (a) knowing the meanings of the line drawings, (b) remembering the spatial configuration of the array, (c) establishing/using automated motor patterns, and (d) establishing/using visual-spatial information for access. If any of these components are compromised, slow or less efficient search and selection of AAC symbols might result.

Hippocampal Memory System. The greater activation in the stable condition of the medial temporal lobe, specifically the PHG and hippocampal region, suggest that facility of search for AAC symbols appears to be associated, at least in part, with stored knowledge about the configuration of the spatial array itself. This finding is highly consistent with studies of spatial and episodic memory in both animals and humans, many of which used different methodologies but reported similar engagement of this region (Hayes et al., 2004; Rosenbaum et al., 2004; Squire & Zola-Morgan, 1991; Sulpizio et al., 2013; Zola-Morgan et al., 1989).

Some forms of intellectual disability involve difficulties with establishing or retrieving visual long-term memories (Carlesimo, Marotta, & Vicari, 1997; Jarrold, Baddeley, & Phillips, 2007) as well as aspects of working memory (Baddeley & Jarrold, 2007; Brock & Jarrold, 2005; Edgin, Pennington, & Mervis, 2010; Purser & Jarrold, 2005; Travers, Klinger, & Klinger, 2011). The current research raises the possibility that such memory challenges may contribute to slow or effortful search and selection of AAC symbols, instead of or in addition to conceptual or language challenges. For instance, it seems possible that an individual who is showing difficulty in moving beyond hunt-and-peck message preparation may be facing challenges in storing or retrieving information about the display layout in longterm memory. From an assessment standpoint, clinicians may need to be aware of this possibility and potentially consult with a psychologist or educator with expertise in memory assessment to determine if this may be occurring. In turn, if memory challenges are affecting facility with AAC, then adjusting therapy to provide greater numbers of opportunities to learn the spatial layout may be an important aspect of clinical interventions. Clearly, there is an urgent need for (non-imaging) research to explore what proportion of clients who struggle with speed of message preparation also demonstrate long-term memory difficulty, what kinds of assessments might be clinically valuable to specialists to determine if such difficulties are present, whether AAC systems can be designed to reduce or bypass certain memory, motor, or visual-spatial task demands, and whether interventions designed to promote retention of the display design would be effective.

Motor System. The increases in activity in cortical and subcortical motor regions (motor cortex, postcentral gyrus, putamen, and cerebellum) in the stable condition compared to the unpredictable condition suggest facility with search and selection of AAC symbols may involve motor learning and anticipation of the motor demands for responding. Our findings are consistent with previous work indicating that the posterior parietal cortex, particularly the inferior parietal lobe, plays a role in spatial awareness and the organization of action (Rizzolatti & Matelli, 2003). The posterior parietal activity in the inferior parietal lobule and the precuneus, which are both functionally related to the striatum, has also been reported in motor sequence learning tasks (Doyon et al., 2009). The activation in the putamen is consistent with motor learning literature, which has highlighted the important role of the putamen in motor learning (Doyon et al., 2009; Floyer-Lea & Matthews, 2004; Hardwick et al., 2013; Jankowski et al., 2009; Lehéricy et al., 2005). Finally, greater cerebellar activity for the stable display condition was consistent with the expectations that this condition enabled motor learning and adaptation (Bo et al., 2011; Hardwick et al., 2013; Orban et al., 2010).

There have been some fMRI studies on the acquisition of automaticity in motor plans and sequencing in individuals with clinical degenerative motor conditions, in particular Parkinson's disease. Individuals with Parkinson's have difficulty achieving automaticity and therefore require more training to reach similar levels of automaticity as individuals without disabilities. Imaging studies have found that the areas of the brain that are activated during automatic motor movement in individuals with Parkinson's disease are similar to control participants without disabilities, however the amount of activation is different (Doyon et al., 1997; Wu & Hallett, 2005). Specifically, individuals with Parkinson's disease continued to show increased brain activation in the bilateral cerebellum, bilateral premotor cortex, bilateral prencuneus, and bilateral DLPFC after automaticity was achieved, where the control group of participants without disabilities did not (Wu & Hallett, 2005).

Although the challenges of access are well-recognized in AAC for individuals with frank motor production limitations like cerebral palsy (Treviranus & Roberts, 2003), our data extend the analysis to suggest the potential importance of motor learning. A direction for further inquiry will be to determine whether individuals who show slower or less fluent AAC access are less likely to be developing established automatic motor patterns for responding to displays. If true, then consultation with occupational therapists or other experts in motor behavior might prove fruitful, to determine whether motor learning difficulties may exist in a client who struggles to prepare messages. Moreover, further study is needed on whether provision of rich opportunities to practice the motor behaviors would in turn contribute to greater facility in searching and selecting AAC symbols.

Visual-spatial Pathways. Because AAC relies on vision for access, the dorsal and ventral visual pathways were of particular interest in this study. We proposed two hypotheses: (a) the stable condition in which the layout of the array was learned would involve greater dorsal visual stream activity, as this stream reflects processing about where things occur in space, and (b) the unpredictable condition that required search for the line drawing based on its form would involve greater ventral stream activity, as this stream reflects processing of an object's identity.

We found greater activity in the dorsal stream occipital/visual and parietal regions, for the stable condition, supporting the first part of this hypothesis.

Specifically, facility with search for the line drawing engaged the "where" pathway that previous studies suggest is active when visually locating objects in space and producing visually-guided actions towards items (Mishkin et al., 1983; Ungerleider & Haxby, 1994; Unglerleider & Mishkin, 1982). Greater activation of dorsal regions therefore appears to be associated with the facility or fluency of search for AAC symbols on stable grid displays.

Contrary to expectations, there was no greater activation in the ventral pathway under the unpredictable condition than the stable condition. This finding may be due to the fact that both stable and unpredictable task conditions involved some level of object identification. If so, then this pathway would be activated equally under both task conditions. This conclusion is supported by a comparison of activity in the experimental conditions versus baseline (fixation period), which shows large amounts of ventral visual activity in both conditions.

There is some evidence that some conditions, such as fragile X syndrome and developmental dyslexia, appear to be associated with dorsal stream vulnerabilities (Grinter, Maybery, & Badcock, 2010). If facility with finding line drawings or other types of symbols on stable AAC grid displays is associated with dorsal stream activity based on a remembered location, an individual with a weak dorsal stream might rely upon other neural mechanisms. Clearly, research is needed to support or refute these possibilities, and to examine whether clinical tools to assess and promote this functioning could be useful.

Dorsolateral Prefrontal Cortex and the Working Memory System. We did not find differential activation in the DLPFC across experimental conditions. There are a number of possible reasons. First, the DLPFC is typically engaged for intended action, likely when current information is being integrated with stored long-term information (Mars & Grol, 2007; Passingham & Sakai, 2004; Pochon et al., 2001). Given high accuracy rates in our sample of college students, the task might not have been hard enough to differentially engage the DLPFC. Alternatively, the DLPFC might always be engaged to a similar degree across task conditions, no matter how difficult. Further research is needed to examine and disentangle these possibilities.

*Consideration of Ocular Movement.* In the unpredictable condition, participants had to examine the array serially on each trial to find the target. Search under this condition would therefore be expected to involve more ocular (eye) movement (and, possibly, more motor movement). Differences in neural activity might therefore be attributed not to our hypothesized memory, motor, and visual processes, but rather to more basic (and less interesting) differences in ocular movements. Logic dictates that this alternative is unlikely, however, given our results. Specifically, greater ocular behavior in the unpredictable condition would result in greater neural activation in that condition. If ocular activity was responsible for the differences, the pattern of our results would have been one of greater activation in the visualspatial pathways under the unpredictable/effortful search condition than the stable condition. Yet the observed pattern was the reverse. It therefore seems unlikely that differences in ocular activity can account for the observed pattern of results.

#### **Limitations and Future Directions**

The current study represents the first step in understanding neural mechanisms contributing to facility of search on AAC displays. As a first step, the study has some limitations, but also opens up a number of avenues for further exploration.

Clearly, one limitation is the sample population we studied. We studied college students as the first step because it was necessary to map out neural activity in individuals for whom there were no neural or linguistic concerns. However, direct research is needed to support or refute our proposals with individuals with disabilities who might use AAC. For instance, further research is required to investigate whether individuals at risk for memory, motor learning, or dorsal stream vulnerabilities are in fact associated with reduced facility of AAC use. Other research avenues might explore whether a multidisciplinary intervention can be developed to enhance dorsal system function, instantiate automatic motor responses, or promote retention of the array in longterm/spatial memory. In addition, it will be of interest to examine the role of lexical knowledge and semantic networks in influencing outcomes.

Another limitation is that our study examined only the endpoint of the different conditions, that is, we deliberately pre-trained our participants so that when they entered the imaging scanner, the stable and unpredictable condition trials had already been distinguished (as confirmed by the difference in the latency to respond to the target, behaviorally). This meant that we could not examine the trajectory of the neural activity from the very outset of exposure – before the participants had learned which displays were stable and which were unpredictable – to the point at which the displays were well-learned. We opted to start this way for several reasons: (a) the task of finding a target in an array of 20 symbols was far more complicated than is typical in fMRI work, and (b) the access method (joystick) is somewhat rare. Our logic was, therefore, that we should begin by imaging when we would expect the greatest differentiation between the conditions (i.e., at the culmination of the learning, as this would be the period where any effects, if they were there, would be detected). Having demonstrated that the predicted effects were in fact detectable, we might now indeed try to map the learning trajectory, to see the point at which the activity begins to differ between conditions.

Another limitation was that the displays we used contained only animal concepts represented by the PCS symbols. This study cannot determine what aspects of AAC design might expedite familiarization with a layout. Are there ways that the design of the displays themselves might promote storage in long-term memory, establishment of motor learning, or visual-spatial processing? In terms of design, Wilkinson and colleagues (Wilkinson et al., 2008; Wilkinson & Snell, 2010; Wilkinson & McIlvane, 2013) have demonstrated that speed of responding during visual search is reliably affected by small changes to the display arrangement, in individuals with and without intellectual disabilities. Perhaps these more optimal displays might also facilitate acquisition of the spatial arrangement, thus promoting greater use of the memory, motor, and dorsal pathways. For intervention, it will be important for clinicians to consider how design decisions might impact the growth and expansion of displays. In particular, clinicians may need to carefully consider modifying and upgrading pages to ensure that communication efficiency is not compromised. Furthermore, it may be important for clinicians to offer additional repeated practice with pages that are rarely used or provide direct reminders of the location of a target symbol.

The study included only single-meaning line drawings (PCS) and the search was for a single target on a traditional grid display, in a context that was not one of functional communication. It would be of great interest to determine how the findings apply to other AAC symbols and displays, including semantic compaction systems, visual scene displays, word prediction, and so forth. For instance, in semantic compaction an advantage is that once learned, the system offers rapid and generative message preparation, but there is a trajectory for learning the various combinations. An evaluation of the neural activity associated with early and later performance with semantic compaction would offer a potentially detailed glimpse of the trajectory of some of the processes observed in our simpler paradigm.

Finally, of necessity, the two experimental conditions included two separate sets of animals, for the reasons outlined in the Methods. Using two different arrays might introduce a possible alternative explanation for the results. Perhaps there is something about farm animals, African mammals, and insects (the stable stimuli) that would be expected to affect neural activity in a selectively different way than ocean dwellers, forest creatures, and birds (the unpredictable stimuli). While we acknowledge this limitation, there is little neural evidence or indication in the literature concerning categorization to suggest that this confound would have been likely. Clearly, future research could disambiguate this possibility by using other categories or counterbalancing the conditions in which each stimulus set appeared.

#### Conclusion

These data provide some of the first insights into the neural bases associated with processing of AAC displays, and suggest that the ability to locate targets on AAC displays may rely on not just conceptual knowledge of the symbol's meaning but also knowledge about the spatial configuration of the display on which the symbol appears. When individuals with disabilities show continued difficulty with AAC, it may be important to consider activities and specific system designs that will help to promote the engagement of memory, motor learning, and visualspatial processing systems, respectively.

#### Notes

- Contraindications to fMRI include, but are not limited to, implanted metal, cochlear implants, pace makers, heart stents, ferromagnetic ink in tattoos, pregnancy, aneurysm clips in the brain, claustrophobia, and non-removable body piercings.
- In event-related fMRI designs, each trial must be modeled and the corresponding neural activation accounted for in order to accurately model the variance in the model. Regressors of no interest account for variance that is not associated with events of interest in the primary analysis.
- Google Inc. 1600 Amphitheatre Parkway, Mountain View, CA 94043, United States. https://www.google.com/ imghp?hl = en&tab = wi&ei = CTbfVYuQFoHA-AGZ56PAAw&ved = 0CBUQqi4oAQ
- The Picture Communication Symbols ©1981–2011 by Mayer-Johnson LLC. All rights reserved. Used with Permission. Boardmaker is a trademark of Mayer-Johnson LLC. http:// www.mayer-johnson.com/boardmaker-software/
- The Siemens 3 T Magnetom Trio MRI scanner is a product of Siemens Medical Solutions USA, Inc., 40 Liberty Boulevard, Malvern, PA 19355, USA; http://www.usa.siemens.com
- 6. In accord with standard realignment and normalization procedures in SPM8, we used both rigid body and affine registrations. During realignment, rigid body transformations (translations and rotations in the X, Y, and Z directions) were computed to find the resulting image that minimized differences between slices, within a subject. Then in normalization, affine transformations (zooms and shears) were computed to maximize the fit between the EPI template brain and the anatomical scans, as well as to correct for anatomical differences between subjects.
- The temporal derivative was included to account for small latency differences in hemodynamic delays due to the selfpaced nature of the task (Calhoun, Stevens, Pearlson, & Kiehl, 2004).

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## **Declaration of interest**

The authors report no conflicts of interests. The authors alone are responsible for the content and writing of this paper.

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