An ACT-R Representation of Information Processing in Autism

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Abstract

The low-level cognitive processes involved in autism are not well understood and are a target of ongoing research. This paper proposes that autistic behavior can be modeled as an adaptive response to underconnectivity in certain areas of the brain. In the ACT-R architecture, this is represented by a reduction in source activations between the declarative module and other modules, corresponding to underconnectivity between the dorsolateral prefrontal cortex and other regions (anterior cingulate cortex, motor, parietal, and fusiform). Resulting errors in contextual memory retrieval can reward strategies using visual problem representation in the parietal area.

Keywords: Autism; modeling; underconnectivity

Introduction

Autism is a condition involving a qualitative impairment in social interaction and communication, as well as repetitive behaviors or narrow, obsessive interests. The low-level cognitive processes involved in autism are not well understood and are a target of ongoing research. The following behavioral pattern of impaired/intact capabilities is emerging. No impairment has been found for simple visual skills in tasks such as guided saccade (Luna et al., 2002); simple motor skills in tasks such as finger tapping (Minshew, Goldstein, & Siegel, 1997); inhibition in tasks such as Stroop (Ozonoff & Jensen, 1999) and “go-no-go” (Schmitz et al., 2006); and simple memory in tasks such as recognition (Bennetto, Pennington, & Rogers, 1996), letter sequence (Minshew & Goldstein, 2001), unrelated free recall (Smith, Gardiner, & Bowler, 2007), and syntactic priming (Preissler, personal communication, November 11 2007) Impairment has been found for contextual memory in tasks such as semantically related free recall (Smith, Gardiner, & Bowler, 2007), word and sentence span (Minshew & Goldstein, 2001), and sentence comprehension (Müller et al., 1998).

Self-report of people with autism indicate a preference for visual representation. Examples of this visual mode of thinking include Temple Grandin’s design of livestock facilities (Grandin, 1995) and Daniel Tammet’s multiplication of large numbers (Tammet, 2006). Using fMRI studies, this visual representation has been shown to occur in the parietal area of the brain. For example, Kana et al. (2006) found that an autism group activated parietal brain regions associated with imagery for comprehending both low and high imagery sentences, suggesting that they were using mental imagery in both conditions. In contrast, imaging studies have found lower activation for autistic groups compared to control groups in the dorsolateral prefrontal cortex (DLPFC) area of the brain during working memory (Koshino et al., 2005; Luna et al., 2002) and sentence comprehension (Just et al., 2004; Müller et al., 1998) tasks. This does not indicate a general impairment in this area, as Müller et al. (1998) found a higher activation of the DLPFC in an autistic group compared to a control group when repeating sentences.

Brain imaging can also be used to measure connectivity of brain regions by calculating the temporal correlation of activation. The pattern of results in the current limited functional connectivity MRI (fcMRI) literature of autism suggests that functional connectivity between subcortical nuclei and cerebral cortex tends to be increased whereas cortico-cortical functional connectivity tends to be reduced. In particular, Turner et al. (2006) found a pattern of greater connectivity in an autism group from the subcortical caudate area of the brain to areas across frontal, parietal, and occipital lobes. Between cortical areas, underconnectivity has been found from DLPFC to parietal and fusiform gyrus regions of the brain (Just et al. 2004; Koshino, 2007).

In summary, autism researchers have found no impairments for simple skills (including simple memory), but have found impairments in contextual memory and corresponding lower activation in the DLPFC. A preference for visual representation has been found with corresponding activation in the parietal area of the brain. These results can be contrasted with those from individuals with Attention Deficit Hyperactivity Disorder (ADHD), which show impairment for inhibition in tasks such as Stroop and corresponding lower activation in the anterior cingulate cortex (ACC) area of the brain (Bush et al., 1999)

Many theories have been proposed for the information processing profile found in people with autism. Most of these theories are expressed with high level constructs that leave gaps in the details of processing. Computational models offer more detail, but the few computational models of autism that have been developed have been limited to a small number of tasks (Cohen, 1998; Kriete & Noelle, 2005; McClelland, 2000; O’Laughlin & Thagard, 2000). This paper proposes the first step of an account of autism findings with a representation of information processing in autism based on the ACT-R cognitive architecture (Anderson et al., 2004). Cognitive architectures provide a detailed explanation of processing from perception to cognition to motor activity, and psychological research in one area is captured in the architecture for other projects to use.

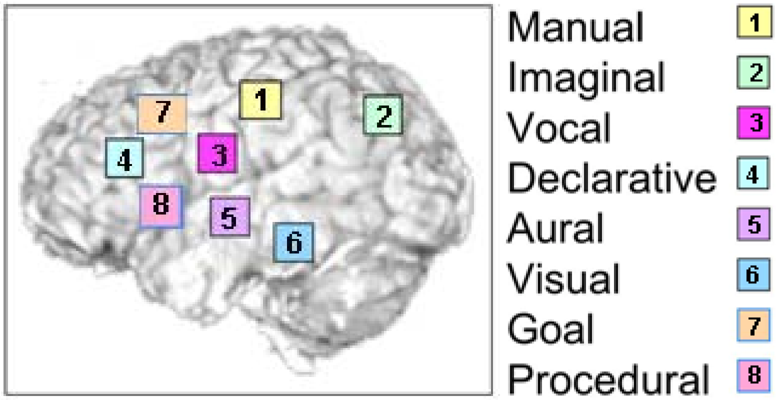

Figure 1: An illustration of the locations of the regions of interest. The Goal (7) and Procedural (8) areas are deeper in the brain, with Procedural being sub-cortical.

High Level Constructs

Some of the high level constructs used to explain autistic behavior include central coherence (Frith, 1989), executive function (Pennington & Ozonoff, 1996), working memory (Russell, Jarrold, & Henry, 1996), complexity (Minshew & Goldstein, 1998), and underconnectivity (Just et al., 2004). These constructs have been useful in trying to understand autism, but relying on them without looking at low level processing can lead to conflicting results and gaps in understanding of autistic behavior. For example, Edgin and Pennington (2005) noted that executive function deficits may be less pervasive in autism than was originally thought. Recent studies have shown intact performance on executive function measures in groups with autism when extraneous task demands have been minimized. McMahon-Griffith (doctoral dissertation, 2002) has found that lessening the amount of experimenter feedback on tasks such as the Wisconsin Card Sorting Task (WCST) can help improve performance in those with autism to a level equivalent to typical performance. Also, other studies (Ozonoff, 1995; Pascualvaca et al., 1998) have found that the deficits on executive function measures were greater when administered by humans than when administered by computer. In their study of spatial cognition, Edgin and Pennington found no evidence for impairments in executive function or in processing global/local information, and they thought this contradicted theories that rely on these constructs. Koshino et al. (2007) noted that although several behavioral studies have found deficits in working memory in autism (e.g., Bennetto et al. 1996; Minshew et al. 1997; Luna et al. 2002;), some others have not (e.g., Russell et al. 1996; Griffith et al. 1999; Ozonoff and Strayer 2001). The detailed processing account of computational models can make task requirements and processing explicit and help to shed light on these results.

ACT-R

ACT-R (Anderson et al., 2004) is a computational theory of human cognition incorporating both declarative knowledge (e.g., addition facts) and procedural knowledge (e.g., rules for solving multi-column addition) into a production system where procedural rules act on declarative chunks. In ACT-R declarative knowledge is represented in structures called chunks and held in the Declarative module, whereas procedural knowledge is represented as rules called productions and held in the Procedural module. Rules also have access to other modules including the Visual module for perception, the Manual module for action, the Imaginal module for holding visual problem representation, and the Goal module for keeping track of current intentions. These modules are proposed to occur in specific areas of the brain: Manual in the motor cortex (BA 3/4), Imaginal in the parietal cortex (BA 39/40), Declarative in the DLPFC (BA 45/46), Goal in the ACC (BA 24/32), Visual in the fusiform gyrus (BA 37), and Procedural in the caudate of the basal ganglia (Figure 1). The ACT-R theory also includes Aural and Vocal modules but these will not be discussed for ease of exposition.

The locations of these modules have been supported by a number of brain imaging studies with tasks such as Tower of Hanoi (Anderson, Albert, & Fincham, 2005), fan memory (Sohn et al., 2005), associative memory (Anderson, Qin, Jung, & Carter, 2007), anticipation of conflict monitoring (Sohn et al., 2007), algebra (Danker & Anderson, 2007; Stocco & Anderson, in press), and mental calculation (Anderson & Qin, in press).

In addition to the symbolic level of facts and rules, ACT-R includes a subsymbolic level of representation where facts have an activation attribute which influences their probability of retrieval and the time it takes to retrieve them. Rules have a utility attribute which influences their probability of being used. The activation Ai of a chunk i is computed from two components – the base-level and a context component. The base-level activation Bi reflects the recency and frequency of practice of the chunk. The equation describing learning of base-level activation for a chunk i is

$$B_i = \ln(\sum_{j=1}^{n} t_j^{-d}) \quad \text{(Equation 1)}$$

where n is the number of presentations for chunk i, tj is the time since the jth presentation, and d is the decay parameter.

The equation for the activation Ai of a chunk i including context is defined as:

$$A_i = B_i + \sum_k \sum_j W_{kj} S_{ji} \quad \text{(Equation 2)}$$

where the base-level activation Bi reflects the recency and frequency of practice of the chunk as described above. The elements k in the sum are the modules. The elements j in the sum are the chunks which are in the slots of the chunk in module k. W_{kj} is the amount of activation from source j in module k. S_{ji} is the strength of association from source j to chunk i.

The weights, W_{kj}, of the activation spread defaults to an even distribution from each module. The total amount of source activation for a module is called W_k and is settable for each module. The W_{kj} values determined by the following equation:

$$W_{kj} = W_k / n_k \quad \text{(Equation 3)}$$

where n_k is the number of chunks in the slots of the chunk in module k. The strength of association, S_{ji}, between two chunks is 0 if chunk j is not in a slot of chunk i or is not itself chunk j and is set using the following equation when chunk j is in a slot of chunk i or is itself chunk j:

$$S_{ji} = S - \ln(fan_j) \quad \text{(Equation 4)}$$

where S is a parameter to be estimated (set with the maximum associative strength parameter) and fan_j is the number of chunks in which j is the value of a slot plus one for chunk j being associated with itself.

Recall probability in ACT-R

If a retrieval request is made and there is a matching chunk, that chunk will only be retrieved if it exceeds the retrieval activation threshold, τ. The probability of this happening depends on the activation A_i and the amount of noise in the system which is controlled by the parameter s:

$$recall\ probability_i = \frac{1}{1 + e^{\frac{\tau - A_i}{s}}} \quad \text{(Equation 5)}$$

As A_i tends higher, the probability of recall approaches 1, whereas, as τ tends higher, the probability decreases. In fact, when $\tau = A_i$, the probability of recall is 50 percent.

Choice probability in ACT-R

If there are a number of productions competing with expected utility values U_j the probability of choosing production i is described by the formula

$$\Pr obability(i) = \frac{e^{U_i/\sqrt{2}s}}{\sum_j e^{U_j/\sqrt{2}s}} \quad \text{(Equation 6)}$$

where the summation is over all the productions which are currently able to fire. The production with the highest utility (after noise is added) will be the one chosen to fire. The utilities of productions can be adjusted according to the rewards they receive. If $U_i(n-1)$ is the utility of a production i after its n-1st application and $R_i(n)$ is the reward the production receives for its nth application, then its utility $U_i(n)$ after its nth application will be

$$U_i(n) = U_i(n-1) + \alpha[R_i(n) - U_i(n-1)]$$

(Equation 7)

where α is the learning rate. This is also basically the Rescorla-Wagner learning rule (Wagner & Rescorla, 1972). According to this equation the utility of a production will be gradually adjusted until it matches the average reward that the production receives.

Representing Autism

A main hypothesis of this paper is that autistic behavior can be modeled as an adaptive response to underconnectivity in certain areas of the brain. This is represented by a reduction in source activations (W_k) between the Declarative module and other modules, corresponding to underconnectivity between DLPFC and other areas (ACC, Motor, Parietal, and Fusiform). This reduction in source activations only affects the Declarative module, so connectivity between the Procedural module (Caudate) and other modules is maintained (Figure 2). Behaviorally, reducing source activations lowers the context activation without reducing base activation, resulting in retrieval errors of context-dependent information. Unimpaired connectivity of the Procedural module to the rest of the modules results in unimpaired performance of the simple rules used in basic tasks.

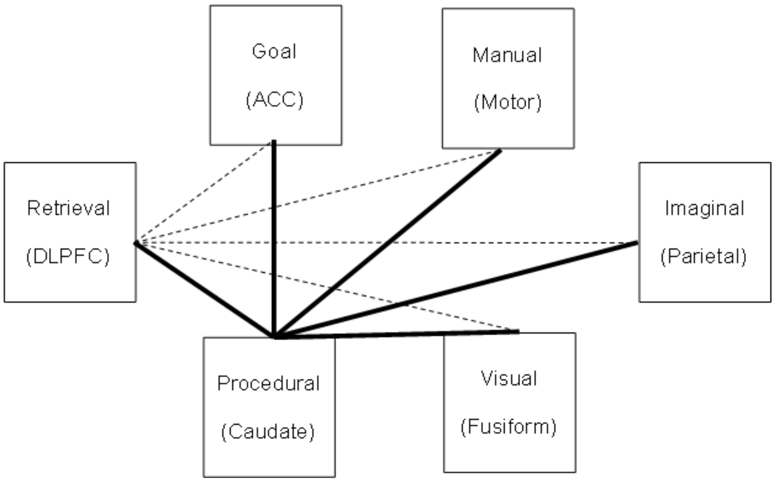

Figure 2: Representing autism as connectivity of ACT-R modules and corresponding brain areas. Dashed lines indicate impaired connectivity represented by a reduction in source activations, and bold lines indicate unimpaired connectivity.

This connectivity representation is consistent with fcMRI studies, as described in the Introduction. Directly matching predicted ACT-R regions, Turner et al. (2006) found enhanced connectivity in individuals with autism from caudate to DLPFC (BA 46) and motor (BA 4), with no group differences for parietal (BA 39/40) or ACC. In addition, Villalobos (2005) found connectivity in individuals with autism between basal ganglia and visual (BA 17) areas. For cortical connectivity, Just et al. (2004) found a significant reduction in connectivity for individuals with autism from DLPFC to intraparietal sulcus and inferior extrastriate regions, corresponding to reduced connectivity from the Declarative module to the Imaginal and Visual modules of ACT-R. Koshino et al. (2007) found reduced connectivity from frontal regions including the DLPFC to the fusiform gyrus, corresponding to reduced connectivity from the Declarative module to the Visual module.

The ACT-R theory includes retrieval of information based on independent factors (time and number of reinforcement) and contextual factors (related information in current context). It also includes the ability to have rule-based strategies to set up verbal or visual problem representations. Successful retrieval based on independent factors for individuals with autism is supported by activation of the DLPFC when successfully repeating sentences (Müller et al., 1998) and syntactic priming (Preissler, personal communication, November 11 2007). With decreased source activations between the Declarative module and other modules, activation for retrieving information requiring contextual information will decrease (Equations 2 & 3) and therefore ACT-R predicts that more errors will occur when retrievals are attempted (Equation 4). With increased experience with these errors, ACT-R productions that avoid retrieval would be reinforced (Equations 5 & 6). For example, non-autistic control subjects have been found to store letters verbally in DLPFC in an n-back retrieval task (Koshino et al., 2005). With poor experience with retrieving from DLPFC, ACT-R would predict that individuals with autism would prefer another strategy such as storing letters visually in a parietal region, and this is what has been found (Koshino et al., 2005). This avoidance of DLPFC retrieval by individuals with autism (indicated by lower activation in imaging studies) has also been found in face recall (Koshino et al., 2007). These studies by Koshino et al. found equivalent task performance in autistic and control subjects. When a task requires retrieval based on contextual cues, alternate strategies may not exist and individuals with autism can show a deficit in performance. For example, Müller et al. (1998) found poorer sentence comprehension in individuals with autism and lower DLPFC activation compared to controls. In addition, unimpaired free recall for unrelated items but impaired free recall for related items was found in an autistic group by Smith, Gardiner, and Bowler (2007). These results were not due to lack of mnemonic strategies as the autism group was explicitly instructed to take advantage of the semantic relations. A verbal rehearsal protocol also showed no difference in rehearsal between the autism and control groups. Use of mnemonic strategies by non-autistic controls that add contextual information may explain their better performance for word and sentence spans compared to autistic subjects (Minshew & Goldstein, 2001). Contextual confusion was found by Bennetto, Pennington, & Rogers, (1996) in autistic subjects with free recall intrusions from previous lists.

Demands on DLPFC from set shift with increasing dimensions may also cause errors in individuals with autism. In non-autistic controls, Konishi et al. (1998) found greater activation in DLPFC for a three-dimensional set shifting condition over a two-dimensional condition. Four out of six studies examined by Goldberg et al. (2005) showed that individuals with autism were not worse than controls in the two-dimensional CANTAB Internal/External Dimension set shift task, but 11 out of 13 studies reviewed by Sargeant, Geurts, and Oosterlaan, (2002) found poor performance for individuals with autism in the three-dimensional Wisconsin Card Sorting Task.

Limitations

This ACT-R representation of autism focuses on cognitive processing and so does not account for the impairments found in more complex visual (Luna et al., 2002) or motor (Minshew, Goldstein, & Siegel, 1997) tasks. It also does not account for impairment in social behavior which may involve use of the amygdala (Baron-Cohen et al., 2000) or "mirror neurons" such as the paracingulate cortex (Gallagher et al., 2000) or pars opercularis (Dapretto et al., 2006). However, the ACT-R architecture could be modified to address these issues at a future time. For example, recent changes in ACT-R now allow dynamic pattern matching which enables instruction processing, and this ability may be related to the syntactic processing capability of the pars opercularis (Dapretto & Bookheimer, 2000).

Future Work

The next step is to validate this ACT-R representation of autism by applying it to a wide set of tasks currently used in the autism literature. A good start would be a subset of the Cambridge Neuropsychological Test Automated Battery (CANTAB) due to its implementation in software and its previous use with autistic subjects. Some modifications would be made to enhance the functionality of CANTAB. For example, more dimensions would be added to the Internal/External Dimension set shift task in order to test the hypothesis that performance in groups with autism declines with increased dimensions. Also, sentence recall and sentence comprehension tasks would be added to test the hypothesis that performance declines with complexity.

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