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ATTENTION FUNCTION AND DYSFUNCTION IN AUTISM

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1. ABSTRACT

Impairments of attention are among the most consistently reported cognitive deficits in autism, and they continue to be a key focus of research. This is in no doubt due to the importance of normal attention function to the development of many so-called "higher level" cognitive operations, and to the likely involvement of attention dysfunction in certain clinical features of autism. Autistic individuals display a wide range of attentional abilities and deficits across the many domains of attention function, including selective, sustained, spatial, and shifting attention operations. This unique pattern of attention function and dysfunction has profound implications for the development and treatment of autistic children. The present review will explore this pattern of attentional strengths and weaknesses and the neural defects that underlie them.

2. INTRODUCTION

Autism is a Pervasive Developmental Disorder characterized by impairments in social interaction and communication in addition to behavioral stereotypies and cognitive deficits (1). The cognitive deficits seen in autism are wide ranging, but impairments of attention are among the most consistently reported and thoroughly investigated. In fact, attentional impairment was a prominent feature of the first published description of an autistic child (2):

> He displayed an abstraction of mind which made him perfectly oblivious to everything about him . . . and to get his attention almost requires one to break down a mental barrier between his inner consciousness and the outside world. (2, p. 218)

Since the time of Kanner's original description, attentional impairments have remained a key focus of autism research for several reasons, one being that attentional abnormality likely contributes to many of the clinical features of autism. For example, overly focused attention might contribute to the development of an autistic person's restricted pattern of interests or activities. Intact attentional processing is crucial to the development of many so-called higher level cognitive functions. Therefore, attentional abnormalities could also underlie many of the higher level cognitive deficits reported in autism (e.g., deficits of language or of executive functions). This is not to say that attentional impairment is a “core deficit” in this disorder. However, impairments of attention would be expected to place autistic children at a disadvantage when they are learning and developing other social, language, and cognitive skills. Finally, in recent years, developments in the cognitive neuroscience of attention have established links between specific attention operations and the neuroanatomic systems which underlie them (3-15). These links have in turn allowed investigators to be guided by the attentional impairments observed in autistic individuals when refining hypotheses regarding the neural defects in autism. This, of course, is a crucial step for autism research, as the neural defects in autism may turn out to be key phenotypic markers for the genetic defect(s) underlying this disorder.

The present review will examine the performance of individuals with autism across a range of attention operations. As one might predict from the clinical presentation of autistic individuals, their profile of

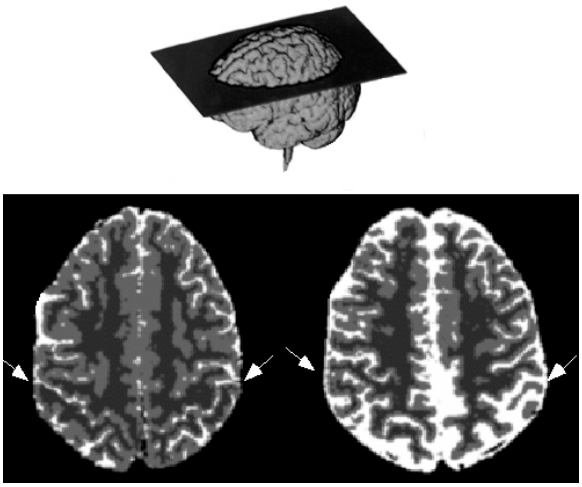

Figure 1. Parietal abnormalities in autism. Axial magnetic resonance (MR) images at a comparable slice location in a young normal control subject (left) and a young adult autistic patient (right) show increased sulcal width (white arrows) in superior parietal regions in autism as compared to normal. Three-dimensional reconstruction shows approximate position of axial slices. (Adapted from 20)

attentional strengths and weaknesses is quite unique. Although the natural assumption may be that strengths reflect normal brain function and weaknesses reflect functional impairment, autism studies have revealed relationships between abnormal neuroanatomy and neurophysiology and both abnormal and normal attentional performance. Thus, while attentional impairments surely result from abnormalities in brain function, certain attentional strengths may have an abnormal physiological basis as well.

3. SELECTIVE ATTENTION

In the early 1970s, Lovaas and colleagues demonstrated a phenomenon which they termed "stimulus overselectivity," wherein children with autism responded to a restricted range of environmental stimuli, suggesting that their attention was overly focused or "overselective" (16). In the original Lovaas and colleagues study (17), autistic, mentally retarded, and normal children were trained to respond to a complex stimulus consisting of visual, auditory, and tactile elements. After training, the children were presented with test trials in which each element was presented separately. The results showed that normal children responded equally to all three elements, while autistic children responded primarily to only one (mentally retarded children responded at a level between these two extremes).

While clinical observation and empirical investigation both support the phenomenon of stimulus overselectivity, there exist contexts in which an autistic person may actually appear to have an abnormally broad focus of attention. For example, individuals with autism often tend to be more distractible than normal, suggesting that their attention may in fact be “underselective.” Burack investigated this phenomenon in the visual modality by examining the differential impact of distracter stimuli and an exogenously imposed focus (i.e., a window highlighting the location on the screen in which target stimuli were to be presented) on attentional performance (18). In this experiment, one of two possible target stimuli, a picture of a circle or a plus sign, appeared on every trial in the center of the screen. On each trial, the number of distracter stimuli was varied (0, 2, or 4), as was the presence or absence of the highlighted window, a sort of prosthetic focus. Subjects pressed one button if they saw a circle and another if they saw a plus sign. Compared to subjects with mental retardation and normal controls, autistic subjects showed the greatest decrease in reaction times (RTs) in the presence of a window when no distracters were present. However, when the distracters were present, RT did not improve in the presence of the window. Thus, autistic subjects' inability to focus attention optimally (i.e., their "inefficient attentional lens") was aided by the prosthetic focus. However, this improvement was negated by the distracter stimuli.

Therefore, depending on the context, individuals with autism may have an abnormally narrow or an abnormally broad focus of attention. The variability and inconsistency in attentional focus across subjects may help to explain certain apparently inconsistent aspects of the clinical presentation of autism. For example, overfocused attention may lead to the apparent lack of awareness autistic individuals seem to show for certain environmental stimuli, while a widened focus might account for their apparent overarousal and hyperstimulation by other stimuli (18). However, this begs the question: How can two seemingly contradictory attentional deficits manifest in the same disorder? One possible answer lies in a specific neuroanatomic abnormality seen in some autistic patients.

The first published MRI study of the autistic brain (19) demonstrated increased sulcal widths in the parietal lobes of an autistic patient. In a follow-up to that study, 43% of a sample of autistic patients showed radiologically detectable parietal abnormalities (Figure 1), the most common being bilaterally increased sulcal widths in the superior posterior parietal lobes (20). Based on that evidence and the fact that unilateral parietal lesions produce attentional neglect of sensory events contralateral to the lesion (21), it was hypothesized that deficits in the distribution of attention must be present in autistic patients, and further that this might help to explain the phenomenon of stimulus overselectivity (22).

In order to investigate this hypothesis, the P1 "attention effect" to visual stimuli at an attended spatial location was examined with event-related potentials (ERPs) and compared to effects at neighboring spatial locations in normal controls and in autistic patients with (P+) and without (P-) reduced parietal lobe volumes. ERP attention effects are examined by comparing the ERP amplitude in response to a stimulus being attended to the amplitude in response to the same stimulus when it is being ignored. Subjects viewed a display consisting of five boxes in a row

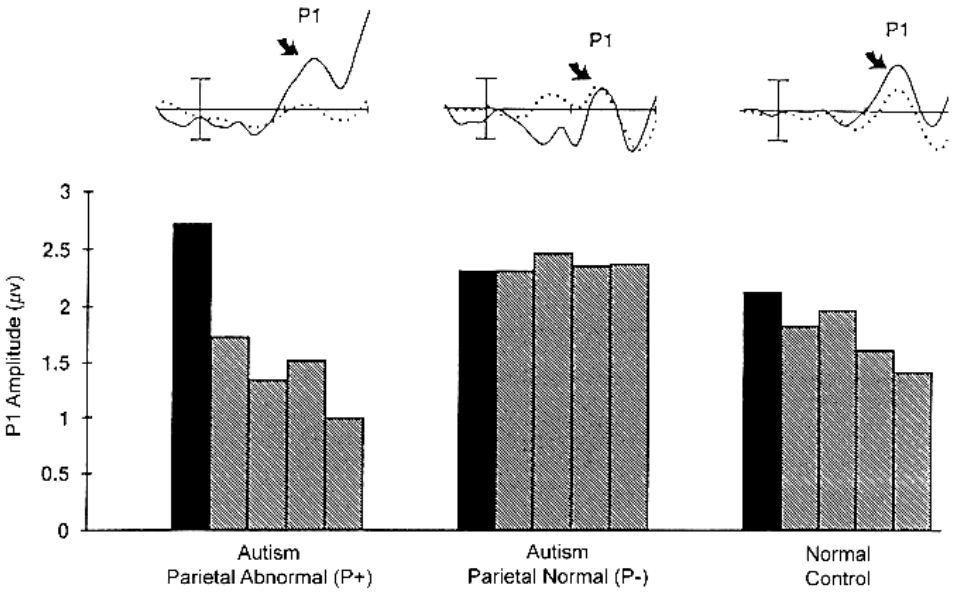

Figure 2. Spotlight of spatial attention in autism. Bar graphs for the autistic P+, autistic P-, and normal control groups, collapsed across the five spatial locations, showing average P1 peak amplitude at posterior electrode sites (O1, O2, Oz, and Cbz) to attended stimuli (dark bar) compared to when attention was focused one, two, three, and four spatial locations away (light bars in order left to right). Waveforms at the top show P1 to attended and unattended (dotted line) stimuli for the three groups at peripheral locations adjacent to center (i.e., "boxes" 2 and 4) recorded at Oz. (Adapted from 22).

located just above the horizontal meridian. White circles were presented for 100 msec in the center of one box at a time. During a block of trials, a red box marked the location to be attended. All circles presented in that box were targets, and all circles presented in the four remaining boxes were non-targets. The circles were presented randomly in equal numbers at each of the five locations. Subjects pressed a button each time a target stimulus appeared, and the P1 ERP responses to target and nontarget stimuli were recorded. The P1 attention effect was the difference between the amplitude of the P1 response to a stimulus at a given location when that location was being attended and the amplitude of the P1 response to that same stimulus at the same location when it was unattended. As shown in Figure 2, normal control subjects had a moderately graded distribution of attention across spatial locations, while P+ subjects showed an enhancement of attention at the attended location but a relatively narrow distribution of attention overall. P- subjects, on the other hand, showed a broad and non-graded distribution of attention (i.e., no significant difference between P1 effects at attended compared to unattended locations) (22) (Figure 2). Thus, whether an attentional focus is small and overselective or inefficiently broad and underselective may depend upon the presence or absence of parietal lobe abnormality.

Although attention was inefficiently distributed in P+ subjects, there were other supernormal features of their attention in this paradigm. For instance, as already stated, the P1 attention effect at the attended location was greater than normal in these subjects. In addition, they had significantly faster RTs to correctly detected targets than both normal controls and P- subjects. Moreover, the latencies of their P3b potentials at central, parietal, and occipital scalp sites in response to target stimuli were significantly shorter than normal [P3b is a neurophysiological sign of covert attention independent of overt motor action (59)]. And finally, more recent work with this paradigm has shown that the amplitude of the P3 response to central target stimuli in P+ subjects is greater than both normal controls and P- subjects (23-26). Thus, although it is narrowly focused, attention within a central focus appears to be supernormal.

This supernormal attention may help to explain findings from recent studies showing normal or even better than normal autistic performance in certain selective attention paradigms. For example, based on the fact that autistic patients show poor generalization of learning from a training context to novel situations, Plaisted *et al.* (27) hypothesized that autistic individuals must differ in their ability to process common versus unique features; unique features being processed well, while common features are processed poorly. To test this hypothesis, the authors asked autistic subjects and normal controls to perform a perceptual learning task, in which the goal was to learn to make a difficult visual discrimination. In this context, autistic subjects were significantly more accurate than controls at solving novel discriminations between highly similar stimuli, thus supporting their hypothesis. These authors also examined visual search performance in autism (28). Here, they predicted that autistic individuals would show faster than normal target detection because: (A) they appear to be superior to normal subjects at discriminating unique visual features (27), and (B) when they perform the

embedded figures task, a neuropsychological test which involves visual search, they are faster and more accurate than matched controls. As predicted, subjects with autism were faster to find conjunctive targets (i.e., targets that were the same color as one type of distracter and the same form as another) than their normal counterparts. This finding supports the view that the ability to detect unique items is enhanced in autism. Finally, Pascualvaca and colleagues (1998) have recently shown that autistic individuals are not impaired on a digit cancellation task, a common neuropsychological measure of focused or selective attention.

Therefore, in certain contexts, it is possible to elicit selective attention performance that is within normal limits or even superior to normal. One explanation for this phenomenon is that these studies may in fact have capitalized on the lack of a normal attentional gradient in their autistic subjects. As mentioned above, a substantial proportion of autistic individuals appear to show volumetric reductions in the parietal lobe which in turn result in a narrowing of the spotlight of visuospatial attention. Such a narrow spotlight of attention may actually be an advantage when experimental conditions call for subjects to search for targets and discriminate them from similar distracter stimuli. That is, an autistic individual with a narrow spotlight of attention will be less distracted by similar stimuli that fall outside of the spotlight.

Thus far, we have only examined the ability of autistic individuals to establish a focus of attention. Like many aspects of this heterogeneous disorder, this ability appears to vary among autistic individuals. This variability appears to depend on several factors, including the nature of the stimuli requiring attention and the state of the subjects' parietal lobe anatomy. However, even if an attentional focus is successfully established, it must be maintained as long as it is relevant to the task at hand. Thus arises the next question in this inquiry: Can autistic individuals sustain their attention to task-relevant information?

4. SUSTAINED ATTENTION

In order to meet diagnostic criteria for Autistic Disorder, an individual must demonstrate "restricted repetitive and stereotyped patterns of behavior, interests, and activities" (1, p. 71). This feature of the disorder implies that autistic individuals possess the ability to sustain attention, at least in certain contexts. This has been supported by several studies examining the performance of autistic individuals on the Continuous Performance Test (CPT; 29), a commonly used measure of sustained attention or vigilance (30-32). These studies failed to show any significant differences between autistic and normal subjects in the number of target hits, correct rejections, or false alarms (30), or in d' (31,32). Pascualvaca *et al.* (64) administered three separate versions of the CPT to a sample of autistic subjects. In one visual condition, subjects were instructed simply to respond to every "X" that appeared on the screen. In a second visual condition, they were to respond to "X" only if it appeared after "A." Finally, in an auditory condition, subjects responded to every "O" that they heard after they heard "L." None of these versions discriminated between autistic and normal control groups. In a study conducted by Casey *et al.* (1993), which examined visual and auditory CPT performance in a sample of "autistic savants," the savant subjects had slightly fewer hits in both the visual (97% vs 100%) and the auditory (91% vs 100%) conditions. However, these slight differences were attributed to a ceiling effect in the normal controls, and sustained attention ability was judged to be "largely intact" (33).

The studies above seem to support the notion that individuals with autism are not impaired in their ability to sustain attention. However, anyone who has experience working with autistic individuals will confirm that they do in fact have difficulty sustaining attention to certain tasks or activities. Is this because such tasks are too complex? Do autistic individuals lack motivation to sustain attention in certain contexts? Or, does autism involve a general sustained attention deficit that has gone undetected by the aforementioned studies?

These questions prompted Garretson, Fein, and Waterhouse (76) to examine the differential effects of task difficulty and motivation on performance of a modified version of the CPT. In order to manipulate task difficulty, the authors varied the rate of stimulus presentation; in the "slow" condition, a new stimulus appeared every 3 seconds for a duration of 1.5 seconds, while the "fast" version introduced a new stimulus every second for a duration of 0.7 seconds. In addition, two different types of reinforcement, "social" and "tangible," were employed. As a social reinforcer, subjects were told "Good work [child's name]" after every fifth target hit. Alternatively, in the tangible reinforcement condition, every fifth hit was rewarded with either a pretzel or a penny, depending upon the child's preference. Task difficulty did not differentially affect performance in autistic and normal control groups, which argues against a general impairment of sustained attention. Instead, the only group difference was seen in the slow/social condition, wherein autistic children performed significantly poorer than normal controls and significantly poorer than their own performance in the tangible condition, suggesting an abnormal response to social reinforcement. Thus, it may be the case that clinical reports of impaired maintenance of attention are due to motivational as opposed to ability-related factors.

While highlighting the importance of accounting for motivational factors when designing and interpreting neurobehavioral investigations of autism, Garretson et al.'s study also points to a possible abnormal interaction in autism between those neural systems mediating attention and those mediating motivation and the response to reward. Sustained attention is an operation that has been associated with the prefrontal cortex (12), and a variety of frontal lobe abnormalities in autism have been reported, including: lack of attention-related ERP negativities (34); reduced blood flow in children (35) and adults (36); thickened cortices, increased neuronal density, and disorganized patterns of lamination (37); and increased volume which is

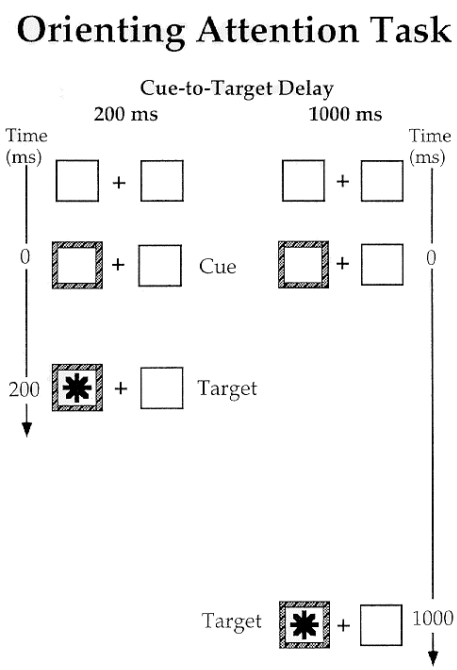

Figure 3. Posner paradigm. Diagram of a typical Posner spatial target detection paradigm. (Adapted from 48).

correlated with cerebellar hypoplasia (38). There is also evidence for limbic abnormalities in autism including increased cell packing density in the hippocampus and amygdala (39,40), decreased size of perikaryon and decreased dendritic branching in hippocampal neurons (41), and decreased cross-sectional area of the dentate gyrus as measured on MRI (Saitoh and Courchesne, unpublished observation). The prefrontal cortex has numerous direct and indirect connections with limbic regions (e.g., hippocampus, amygdala, and parahippocampal and cingulate gyri) (42), and according to Weinberger, "the special anatomical relationship between the prefrontal cortex and limbic circuits makes it eminently reasonable that disease of limbic structures has an impact on function of the prefrontal cortex" (42, p. 243). Therefore, although the frontal lobe abnormalities of autism are apparently not of sufficient type or severity to impair sustained attention in all contexts, it may be the case that when adequate sustained attention requires the neural systems mediating this operation to work in concert with limbic regions mediating motivation and the response to reward, the combined abnormalities in autism are sufficient to impair performance.

Selective and sustained attention paradigms typically test the ability to attend to events occurring at a single point in space. However, one could argue that most of what we attend to is not static. Rather, relevant stimuli requiring our attention are nearly always moving about us.

5. SPATIAL ATTENTION: THE DISTRIBUTION OF ATTENTIONAL RESOURCES

Spatial attention in autism has been investigated extensively using the Posner spatial target detection task (43). In the typical Posner design (Figure 3), subjects are asked to fixate their eyes on a central location and press a button as quickly as possible when they detect a target (e.g., a bright asterisk) at one of two positions along the horizontal meridian. Prior to the target's appearance, cues are introduced that direct the subject's attention either to the location at which the target will appear (valid trials) or the opposite location (invalid trials). The RT response to the target is analyzed as a function of the location of the cue relative to the target and the time that elapsed between the appearance of the cue and the appearance of the target (cue-to-target delay), which ranges from 50 to 1000 msec. Covert shifts of spatial attention made in the context of the Posner task are proposed to involve three elementary operations: disengaging from the current focus of attention, moving attention to the new location, and engaging attention at the new location (5). Inferences have been made about the ability to execute these operations and the neural substrates underlying such abilities based upon differential patterns of Posner task performance in different patient groups.

To examine the ability to disengage attention from a current focus, one can compare the RT to targets occurring after valid and invalid cues. On invalid trials, the target appears in a location other than where attention is currently focused. Thus, attention must be "disengaged" from the current focus for target detection to occur. When a marked discrepancy is seen between RTs to validly cued targets on the one hand, and invalidly cued targets on the other, a deficit in the disengage operation is inferred. Such a deficit has been observed in patients with damage to the posterior parietal lobe, wherein such patients are slow to disengage from a focus of attention to a new target in the contralesional visual field (43). When the RT to targets is slow regardless of where attention was engaged prior to target appearance, a deficit in the movement of attention is inferred. Patients with damage to the superior colliculus and other midbrain regions resulting from progressive supranuclear palsy have shown such a "move" deficit (5). If a RT deficit is seen despite the fact that targets have been validly cued and the cue-to-target delay is sufficiently long to allow attention to move to that location, a deficit in the engagement of attention at the new location is inferred. An "engage" deficit of this sort is seen in patients with lesions of the pulvinar nucleus of the thalamus (44). Such patients are slow to respond to contralesional targets even after long delays. Guided by this model of visuospatial attention, several investigators have examined attention function in autism utilizing the Posner task.

Casey *et al.* (33) administered the Posner task to a sample of “autistic savants.” Compared to normal volunteers, savants showed a significantly larger validity effect (i.e., an increase in RT on invalid relative to valid trials), suggesting that they had greater difficulty disengaging attention. This validity effect was more pronounced when targets were presented in the left visual field (LVF), possibly suggesting a right parietal defect. In a study by Wainwright and Bryson (45), autistic subjects failed to show a validity effect at a short (100 msec) cue-to-target delay. However, at a long (800 msec) delay, the

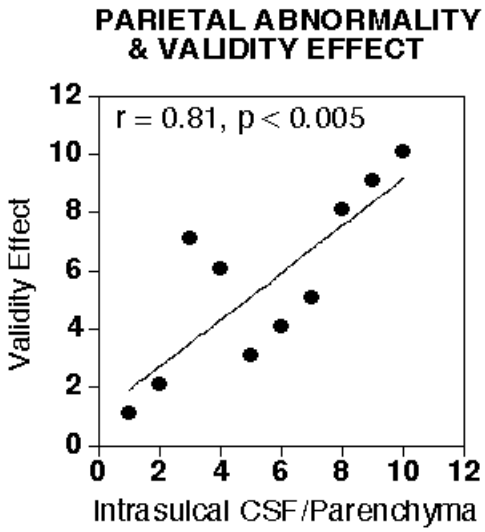

Figure 4. Effect of parietal abnormality on spatial attention in autism. Scatter plot and linear regression line showing the relationship between the ratio of intrasulcal CSF to parenchyma and the overall validity effect in autistic patients with (P+) and without (P-) parietal abnormality. (Adapted from 47).

validity effect in autistic subjects was greater than normal, once again suggesting difficulty disengaging attention. Furthermore, as in the Casey *et al.* study, the validity effect obtained was greater for LVF targets.

The apparent field (or hemisphere) effect from these studies prompted Wainwright and Bryson to take a closer look at whether spatial attention impairments are lateralized in autism. This study (46) included three experiments. In Experiment 1, subjects were asked simply to detect stimuli presented to the right or left of fixation. In Experiment 2, they had to detect stimuli at fixation in addition to stimuli presented to the right and left. Experiment 3 was the same as Experiment 2 apart from the fact that subjects were required to both detect and identify target stimuli. All three experiments addressed the question of whether autistic subjects demonstrate the LVF advantage (i.e., whether detection of targets in the LVF is faster than for targets on the right) typically observed in normal subjects. In other words, is autism characterized by a specific right parietal impairment (as suggested by Casey *et al.* and Wainwright and Bryson)?

In Experiment 1, autistic and normal subjects showed a normal LVF advantage. In Experiment 2, the LVF advantage was seen in normal subjects, but no field advantage was observed in autism. Rather, it was as if the field effect had been abolished by the presence of central targets. Moreover, autistic subjects showed faster RTs to central than peripheral targets. In Experiment 3, no field effect was seen in the normal subjects, while autistic subjects again responded significantly faster to central stimuli than to stimuli appearing in either peripheral location. Thus, a specific right hemisphere impairment was not demonstrated in this study. Like normal controls, autistic subjects showed a LVF/right hemisphere advantage in the absence of central stimuli. When they were present, the response to central stimuli was faster than for peripheral stimuli in autistic subjects, which seems to support an abnormal distribution of attentional resources and a narrow spotlight of attention. This was also suggested by the fact that the presence of central stimuli extinguished the LVF advantage in autistic subjects.

Townsend, Courchesne, and Egaas (47) directly addressed the question of how parietal lobe abnormalities impact the ability to disengage attention in autism. In this study, the Posner task was administered to normal control subjects and to autistic patients with (P+) and without (P-) parietal lobe abnormalities (as rated by a neuroradiologist), typically in the form of reduced posterior parietal cortex volume. No significant difference was found between the validity effects in normal controls and P- patients; controls were 12% slower and P- patients were 10% slower to detect targets in an unexpected location (342 ± 38 vs. 305 ± 31 msec, and 448 ± 83 vs. 410 ± 76 msec, respectively). P+ patients, on the other hand, were 29% slower to detect targets in an unexpected as compared to an expected location (497 ± 159 vs 392 ± 118 msec.). This validity effect was significantly larger than that seen in controls and P- patients. Unlike the Casey *et al.* and Wainwright and Bryson studies, the validity effect in this study was bilateral. Parietal volume loss was also assessed using a ratio of intrasulcal cerebrospinal fluid (CSF) to posterior parenchyma. When all autistic patients were analyzed together and their validity effects were correlated with the CSF/parenchyma ratio, there was a strong positive correlation between size of validity effect and amount of parietal volume loss (Figure 4).

Thus, autism clearly appears to involve impairment in the disengagement of attention, and, consistent with Posner's model, this impairment can be attributed to neuroanatomic abnormality in the parietal lobe. However, this is not the only attentional impairment to emerge when autistic individuals perform the Posner task.

6. SPATIAL ATTENTION: THE RAPID ORIENTING OF ATTENTIONAL RESOURCES

There is one aspect of the Posner task, the initial step of how quickly the cue orients attention, which is not examined in most studies employing this design. On valid trials, the more quickly attention is oriented to the cue, the more rapid the detection of (and RT to) the target will be. The converse is also true; the more slowly attention is oriented, the slower the RT. An index of the speed of orienting attention, then, is one that compares RTs on valid trials with short cue-to-target delays (e.g., 100 msec) with RTs on valid trials with long delays (e.g., 800 msec). The greater the discrepancy (i.e., the attention orienting index), the poorer the ability to rapidly orient attention to the cued location. To determine whether autistic patients have a deficit in the rapid orienting of attention, Townsend and colleagues tested such patients on the Posner task and analyzed this index of attention orienting (47,48). In these

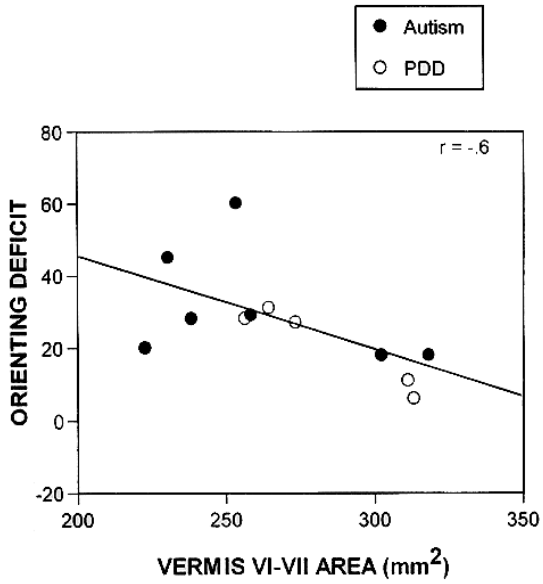

Figure 5. Effect of cerebellar abnormality on orienting attention in autism. Pearson correlation between orienting deficit scores and area of cerebellar vermis lobules VI-VII for twelve autistic and PDD-NOS children. (Adapted from 52).

studies, RTs in normal controls were nearly as fast with only a 100-msec delay as they were at 800 msec. In contrast, autistic patients were significantly slower to respond with a 100-msec delay than they were at an 800-msec delay.

While the disengage, move, and engage deficits seen in the context of the Posner paradigm have all been associated with anatomic abnormalities in brain regions long thought to be crucial to normal attention function (i.e., parietal lobe, superior colliculus, thalamus), deficits in the rapid orienting of attention appear to be related to abnormality in a structure not traditionally associated with attention, the cerebellum. The cerebellum has long been viewed as a structure involved exclusively in motor control. However, over a decade ago, it was first suggested that the cerebellum might also be involved in normal attention function, and that developmental cerebellar abnormality might contribute to the attentional impairments seen in autism (49). Since that time, the cerebellum has been shown to be the most consistent site of neuroanatomic abnormality in autism (37,50), and there is now extensive empirical support for its role in attention (for reviews, see 13,51).

In order to investigate whether the attention orienting deficit is related to the cerebellar neuroanatomic abnormality of autism, the performance of autistic individuals with varying degrees of hypoplasia of cerebellar vermis lobules VI and VII has been examined along with the performance of non-autistic patients with acquired focal neocerebellar lesions. This examination has shown that autistic patients with more cerebellar vermis hypoplasia are slower to orient attention than patients with less hypoplasia (15). Furthermore, neocerebellar lesion patients show a similar attention-orienting deficit, a deficit not seen in patients with focal frontal or parietal lesions.

The impact of cerebellar abnormalities on attention orienting was further examined in autistic children (mean age = 7.5 years) in a study by Harris *et al.* (52). In that study, children with autism were on average 31% slower to detect validly cued targets preceded by short (200 msec) delays than those preceded by long (1000 msec) delays. On the other hand, normal children were only 17% slower at the short delays, and children with Pervasive Developmental Disorder-Not Otherwise Specified (PDD-NOS) were 20% slower. Combining the autistic and PDD-NOS subjects into a single group and correlating the size of the orienting deficit with the size of cerebellar vermis lobules VI and VII yielded a significant inverse correlation (r = -.60), with larger orienting deficits being related to smaller (i.e., more abnormal) vermis areas (Figure 5). The size of the orienting deficit was not significantly correlated with any other neuroanatomic region measured in this study, including corpus callosum, hippocampus, frontal lobe, and total brain. Together with the findings in adults, these results provided strong evidence for the role of the cerebellum in the rapid deployment of attentional resources and for the role of cerebellar abnormality in the impairment of this operation in autism.

A recent study employing the spatial selective attention paradigm originally developed by Townsend and Courchesne (22) provided new and interesting evidence for the cerebellar role in attention operations (23-26). Independent components analysis (ICA) of the electroencephalographic data from normal subjects during this task revealed a new ERP elicited by target stimuli that was most prominent at frontal electrode sites (53). This ERP waveform, which was designated P3f, was not seen, however, in autistic subjects or in patients with acquired neocerebellar lesions. In addition, there was a significant negative correlation between the area of vermis lobules VI-VII and the averaged P3b latency over frontal electrode sites in normal control subjects. Moreover, the magnitude of P3b was significantly reduced in autistic and cerebellar lesion patients, and its timing was more variable (this variability did not account for the difference in average amplitude). These findings suggest that the cerebellum is crucial to the normal elicitation of frontal and parietal ERP responses. This is quite a remarkable finding, as decades of ERP research have revealed few if any anatomic regions which have such a profound effect on the P3 response. Interestingly, these abnormal neurophysiological findings emerged despite normal performance in autistic and cerebellar lesion patients.

Because the cerebellum traditionally has been viewed as a structure involved exclusively in motor control, the demonstration that it appeared to play an important role in impairing orienting attention in autism naturally led to the question of what role motor impairment has in the slowing of responses. Although there were already strong arguments against motor impairments accounting for impaired orienting in the detection task (e.g., the fact that

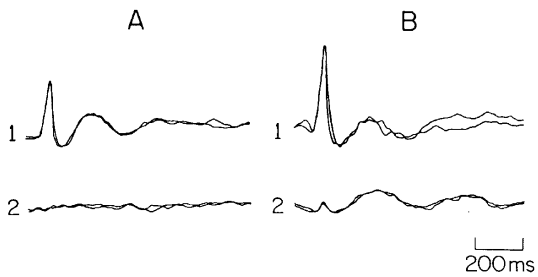

Figure 6. Sensory effects of cerebellar stimulation. Combined effects of background illumination, flash, and cerebellar stimulation on superior colliculus evoked potentials. A-1, control response to flash; A-2, abolition of such response by addition of background light; B-1, response to flash after cerebellar stimulation; B-2, response to flash, under background illumination, after cerebellar stimulation. Superimposed averages, 64 stimulus presentations. (Adapted from 57).

autistic patients respond as fast as normal when given adequate time to orient attention), Townsend and colleagues nevertheless designed a special version of the Posner task in which accuracy of discrimination, not speed of detection, was the dependent variable, thus removing the motor demands from this task (48).

In this spatial target discrimination task, the target is a block figure "E" (as opposed to an asterisk in the detection task) which can be oriented in one of four directions (i.e., up, down, left, or right). During the task, trials proceed as in the detection task; a brief cue is followed by a short or long delay, after which the target appears in either the valid or the invalid location. After 50 msec, the target is masked by a figure that includes all possible features of the target in any orientation. The subject's task is to move a joystick to indicate the direction in which the target was pointing. The masked target is displayed until the subject responds, or for a maximum of 2 seconds. Therefore, the speed of motor response, and thus any motor slowing resulting from cerebellar neuroanatomic abnormality, is irrelevant in this design. The results from this new discrimination task were similar to those seen in the detection task; normal controls were just as accurate at the 100 msec cue-to-target delay as they were at the 800 msec delay, while autistic patients were 25% less accurate at the short delay (48).

A more recent investigation by Townsend and colleagues (15) examined detection and discrimination performance in a larger sample of autistic patients and in a sample of individuals with acquired neocerebellar lesions. On the detection task, normal control subjects' responses after short as compared to long cue-to-target delays were 27 msec slower, while autistic subjects' responses were 122 msec slower. Cerebellar lesion patients' responses to ipsilesional targets were 92 msec slower, while responses to contralesional targets were 73 msec slower. On the discrimination task, at short compared to long delays, normal control subjects were 1.6% more accurate, while autistic subjects were 14% less accurate. Cerebellar lesion patients were 15% less accurate when responding to ipsilesional targets and 12% less accurate when responding to contralesional targets. Moreover, in this task, when all subject groups were pooled together, larger orienting effects (i.e., difference in accuracy at the validly cued location at short compared to long delays) were significantly correlated with smaller cerebellar vermis lobules VI and VII ($r = 0.44$). Thus, by employing discrimination rather than detection as the dependent variable, Townsend and colleagues eliminated any concerns about slowed motor response preparation or execution impacting performance in autistic and cerebellar lesion patients, and thus confirmed the involvement of the cerebellum in the rapid deployment of attentional resources.

Use of the Posner task with autistic individuals has been quite fruitful in demonstrating two distinct attentional impairments that are associated with two distinct neural abnormalities. Autistic subjects with parietal lobe abnormalities have difficulty disengaging attention from a current focus, while cerebellar abnormality slows the speed at which autistic individuals can orient attention to a new focus. The disengage deficit in autistic patients with parietal volume reduction certainly comes as no surprise, as this role of the parietal lobe is widely accepted by mainstream cognitive neuroscientists. On the other hand, the role of the cerebellum in the rapid deployment of attentional resources has not enjoyed such widespread acceptance. This is understandable, but only because the limited view of the cerebellum as a motor structure is steeped in tradition. However, there is ample evidence that the cerebellum plays a very important role in attention.

Attention is an anticipatory operation; it is the enhancement of neural responsiveness in advance of relevant sensory information. Animal studies have shown that the cerebellum is in a position to effect such a preparatory process. For example, in the original report of the discovery of the reticular activating system (RAS), cerebellar stimulation was found to modulate the RAS response (54), and subsequent experiments found that cerebellar stimulation triggers behavioral and parietal EEG alerting responses in primates (e.g., 55). Furthermore, when the cerebellum is stimulated in advance of sensory information, neural responsiveness to subsequent sensory events is altered in brainstem, thalamic, cerebral, and hippocampal sites. Such effects have been documented for visual, auditory, somatosensory, and nociceptive stimuli (56-58). This cerebellar activation in advance of sensory information leads to a signal-to-noise enhancement of subsequent sensory responses. For instance, when background luminance is sufficient to reduce to noise levels the colliculus response to a flash stimulus, stimulation of cerebellar vermis lobules VI and VII in rats causes the colliculus response to that flash to emerge above noise levels if the cerebellar stimulation occurs in advance of the visual stimulus (57) (Figure 6). This cerebellar property may be crucial to attention functioning because it allows

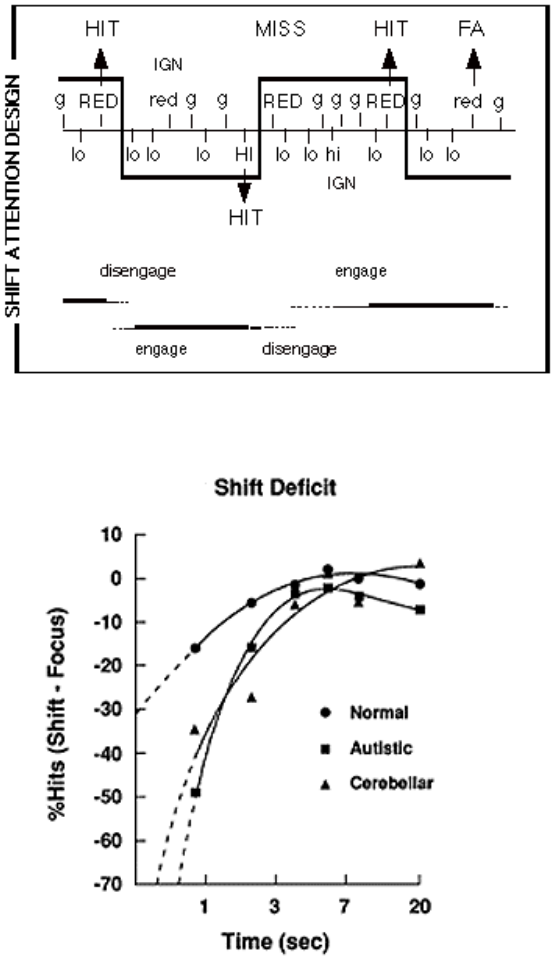

Figure 7. Shift attention task design and shift attention performance in autistic and cerebellar lesion patients and normal controls. (Top) Schematic of the auditory-visual shift attention task. Visual stimuli were red and green flashes; auditory stimuli were 2 kHz ("hi") and 1 kHz ("lo") tone pips. "HIT" = correctly detected target; "MISS" = failure to respond to a target; "FA" = an erroneous response to a rare stimulus that was in a modality to be ignored; "IGN" = a rare stimulus that was correctly ignored. In the example of the shift experiment, the subject pressed a button (arrow) to the first rare visual target stimulus. This served as a cue to shift attention to the auditory stimuli, ignore ("IGN") the visual stimuli, and respond to the next auditory target, which in turn served as a cue to shift attention back to the visual stimuli. The heavy line indicates the subject's attentional field. (Adapted from 8). (Bottom) Shows time-related shift attention deficits in 6 patients with acquired neocerebellar lesions (triangles) and 13 patients with autism (squares) compared to 25 normal controls (circles). Larger negative difference values indicate a larger decrement in performance on the shift task relative to a baseline control sustained attention task. This difference in the median percent hits is graphed as a function of elapsed time since the immediately preceding target. Natural log time scale in seconds. (Adapted from 9).

the optimization of neural conditions for the acquisition of sensory information.

This cerebellar property may also help explain the poor performance of autistic and cerebellar lesion patients when they must rapidly orient attention to detect a brief visual stimulus. In the Posner task, the cue essentially serves as a conditioned stimulus signaling the appearance of a subsequent target. We suggest that the normal cerebellum facilitates detection performance by learning this association and using the cue as a signal to enhance signal-to-noise conditions in preparation for the upcoming target. Neuroanatomic abnormalities of the cerebellum would thus be expected to impair this preparatory enhancement mechanism and, so, impair the rapid detection or discrimination of a target stimulus.

We have previously proposed a model of cerebellar function in which the cerebellum learns sequences of information (i.e., temporal associations) so that it may predict which neural systems will be needed in upcoming moments and provide preparatory enhancement of neural responsiveness in those systems (9,13,51). In our laboratory, we have developed a paradigm that may serve as another window onto how impairment of this fundamental cerebellar function ultimately affects attentional performance.

7. SHIFTING ATTENTION

Based on its privileged physioanatomical position allowing it to affect known attention systems, it was hypothesized over a decade ago that the cerebellum contributes to attention operations in a manner analogous to its role in motor control (49). Thus, it was predicted that the cerebellum allows attention to be shifted rapidly, accurately, smoothly, and effortlessly. To investigate this hypothesis, autistic patients and patients with acquired focal neocerebellar lesions were tested in an original paradigm (Figure 7) in which cues presented at unpredictable time intervals directed patients to initiate shifts of their focus of attention between visual and auditory sources of information (8,9). Performance on this task was compared to performance on a task that was identical apart from the fact that it did not require subjects to shift their focus of attention; visual and auditory stimuli were presented simultaneously, but attention was sustained on a single source of information (e.g. visual). Neurobehavioral and neurophysiological evidence demonstrated an impaired ability to shift the mental focus of attention rapidly and accurately in autistic and neocerebellar lesion patients.

Within 2.5 seconds or less following a cue to shift attention, autistic and neocerebellar lesion patients were significantly worse than normal subjects at correctly detecting target information in the new focus (8,9) (Figure 7). All of the RTs for the autistic and neocerebellar lesion patients were well within a 200 to 1400 msec time window allotted for responses (their median RTs being in the range of 500 to 600 msec), eliminating the possibility that motor responses were simply so slow that they were not detected.

Also, as long as they were not required to shift attention (i.e., while attention was sustained on a single modality), these patients were not significantly impaired when responding to two target stimuli occurring rapidly in succession. In other words, as long as the patients did not have to change preparatory states, their attention and motor performance were not impaired.

In order to verify that the autistic and neocerebellar lesion patients had not mentally shifted their attention when they missed targets, the P3b ERP response to all hits and misses was recorded. The P3b is absent when a target stimulus is ignored or missed (34,60). Like normal subjects, the autistic and neocerebellar lesion patients exhibited a P3b response to correctly detected targets, but not to missed stimuli that occurred 2.5 seconds or less following a cue. These findings confirmed that when these patients missed targets that rapidly followed a cue, they were not covertly attending and thus had not fully shifted their attention to the new focus. Furthermore, in normal subjects the cue to execute a mental shift of attention elicits a shift attention difference ERP, the Sd potential (10). Sd is the difference between the ERPs elicited by correctly detected targets in the shifting attention task and those in the focused attention tasks. Its regional distribution may vary according to whether the eliciting cue signals the need to shift attention in order to process auditory information or visual information (unpublished observations, E. Courchesne, N. Akshoomoff, J. Townsend and O. Saitoh), and so may reflect operations involved in setting up a new focus of selective attention. This potential is absent in autistic patients and in neocerebellar lesion patients.

To ensure that differences in performance during focused and shift attention conditions were not due to task difficulty, subjects also performed a difficult auditory discrimination task with attention focused (9). Autistic subjects detected a 10-15 Hz difference from a 50 msec duration 1000 Hz tone as well or better than control subjects—even with short (less than 500 msec) intervals between stimuli. A recent study has found similar results in autism for speed of visual processing. In that study, autistic children (IQ 1 SD below average) processed visual information as quickly as age-matched control children (IQ 1 SD above average) and more quickly than age- and IQ-matched mentally handicapped control subjects (61).

These experiments employing the auditory-visual shift paradigm provided solid evidence for cerebellar involvement in rapid and accurate attention shifting, and for the impairment of this function in autistic individuals. They also helped to illustrate how the central nervous system functions when the cerebellum is damaged. Without the preparatory aid provided by the cerebellum, other systems can continue to perform their prescribed functions. However, they will do so suboptimally in situations where prediction and preparation might aid performance. For instance, cerebellar pathology does not eliminate the ability to shift attention, but instead makes attention shifts slow and inaccurate. In the shifting attention task, the appearance of a target stimulus cues subjects to attend to a new stimulus dimension and prepare for a new target. Thus, this task entails a predictive relationship between events that the healthy cerebellum is theoretically able to learn. In turn, the cerebellum can provide preparatory signals to neural systems required to detect and respond to the next target. When given adequate time to shift attention, autistic and neocerebellar lesion patients are not impaired. However, within 2.5 seconds or less following a shift cue, they are significantly worse than normal subjects and patients with focal cerebral lesions at detecting target stimuli in the new dimension. In other words, in the absence of normal preparatory output from the cerebellum, other neural systems involved in detecting target stimuli are not prepared to respond during the shortest of time intervals.

As already mentioned, autistic and neocerebellar lesion patients were not impaired on a task which is identical to the shift task apart from the fact that it does not require subjects to shift attention. This was the case despite the fact that the cerebellar cortex is normally active and thus appears to be involved in such a focused or selective attention task (14). This may at first seem paradoxical. However, it is compatible with the notion that the cerebellum provides preparatory signaling to other brain regions involved in attention tasks. The sequence of events in the focused task is randomly ordered and thus cannot be learned by the cerebellum. As the sequence cannot be learned, the cerebellum is incapable of providing much useful preparatory output to neural systems involved in detecting and responding to upcoming target stimuli. Although the normal cerebellar cortex is active in its attempts to learn, it is not effectively aiding the rest of the central nervous system and thus does not have a noticeable advantage over the damaged cerebellum in this context. However, if there were a predictive relationship to be learned (e.g., the relationship between the cue and the requirement to shift attention to a new modality in the shifting attention task), and thus useful preparatory output from the cerebellum, then additional activation reflecting such output would be predicted in the cerebellar output nuclei. And, in fact, there is fMRI evidence for such activation the dentate nucleus in normal subjects during the shifting attention task (62).

In addition to studies in our laboratory, other groups have also investigated shifting attention in autism, albeit with different approaches. For example, Casey *et al.* (1993) examined the continuous shifting of attentional set in autistic savants. These authors used a visual discrimination task in which the attribute to which subjects had to attend in order to respond correctly was varied on a trial-by-trial basis. Autistic and control subjects did not differ on this task in terms of accuracy or speed of response. It should be noted, however, that subjects were given as much time as they needed to attend to the stimuli before determining the correct choice and executing a response. Therefore, the key aspect of the shift attention deficit, i.e. slowness of shifting, was not probed by this study.

In what may have been a demonstration of the implications of the shift attention deficit in a more "real-

world" setting, Swettenham *et al.* (63) examined the spontaneous selection and shifting of gaze direction during a finite period of free play in very young children (i.e., approximately 20 months of age) suspected of having autism (as autism cannot be diagnosed definitively at this young age). Compared to normal and developmentally delayed children, the children with probable autism demonstrated less spontaneous attention shifting overall. They were also more prone to shifting gaze between objects than between people. This latter finding may have reflected avoidance of social stimuli or of more complex visual stimuli (63).

Pascualvaca *et al.* (64) investigated the ability of autistic individuals and normal controls to perform three tasks aimed at assessing shifting attention in different contexts: 1) the Wisconsin Card Sort Test (WCST), a neuropsychological measure of rule-based categorization commonly used to assess abstraction and cognitive flexibility, among other things; 2) an easier computerized analog of the WCST in which correct responses were reinforced with visual and auditory effects, unlike the social reinforcement of the standard WCST; and 3) a "same-different" task in which subjects were shown three stimuli and asked to determine whether they were the same or different in terms of color, form, or size. This third task was analogous to the visual discrimination task of Casey *et al.* (33). The first two tasks involved periodic shifts of cognitive set, in which the rule of correct categorization changed, while the third task involved the continuous shifting of attention among the different visual attributes of the stimuli in order to arrive at a correct response. On the WCST, autistic subjects completed fewer categories and committed more perseverative and nonperseverative errors than normal controls, while performance on the other two tasks was comparable in autistic and normal subjects.

Pascualvaca and colleagues suggested that the pattern of performance across the three tasks in their study reflected autistic subjects' ability to "shift their attention continuously" and their difficulty shifting attention when "already engaged in a particular activity." As they pointed out, this is consistent with the shift attention experiments conducted in our laboratory, wherein subjects were required to attend to one modality for a period of time before they had to shift attention rapidly to a different modality in order to detect target stimuli. As for the discrepant performances on the two set-shifting tasks, this appears to be consistent with the demonstration by Garretson, Fein, and Waterhouse (76; see above) that attention performance in autistic individuals benefits from tangible but not from social reinforcement. That is, the tangible visual and auditory effects of the computerized task aided performance, while the standard social reinforcement of the WCST (i.e., the examiner telling the subject whether he is correct or incorrect) did not.

The Pascualvaca *et al.* study also demonstrated, as in our shifting attention experiments, that autistic individuals appear to have no difficulty shifting attention when given adequate time. This is a very important point, because the shifting attention findings have frequently been misinterpreted in both the autism and cerebellum literature. The fact that rapid shifting of attention is impaired in autism and in patients with lesions of the neocerebellum does not mean that shifting attention is a core deficit of autism, nor does it mean that shifting attention is a fundamental function of the cerebellum. As eloquently stated by Pascualvaca et al., the "deficit is not in shifting attention per se, but may be secondary to difficulties in the coordination and modulation of attentional resources, as well as in the activating effects of motivation." (64, p. 477). Likewise, we suggest that the shifting attention task is simply a useful probe of a more general impairment in the rapid and accurate deployment or adjustment of neural resources, be they motor, cognitive, or affective. In the case of shifting attention, this impairment leads to difficulties coordinating, modulating, and activating attentional resources, and in the Pascualvaca *et al.* study, perhaps motivational resources as well.

8. PERSPECTIVE

8.1. Summary

In sum, an examination of autistic performance across a wide range of attentional operations reveals a unique pattern of strengths and weaknesses in this population. Individuals with autism tend to show an abnormal distribution of attentional resources across space that is a function of their parietal lobe defect. They are also impaired when they must rapidly re-allocate their attentional resources to new spatial locations or to new target modalities, and a variety of evidence points to the role of cerebellar abnormality in this deficit. When attention is sustained on a single location (i.e., not distributed across spatial locations or rapidly shifted between locations or modalities), the performance of autistic individuals is not impaired in most cases. The one instance in which autistic subjects do perform abnormally on such a task is the context in which performance is manipulated by social reinforcement. In this case, autistic subjects perform worse than normal controls. This abnormal response to social reinforcement has been shown in other contexts, and may reflect an abnormal interaction between frontal regions subserving sustained attention and limbic regions mediating the response to reward. However, it is also possible that this is yet another reflection of cerebellar abnormality in autism. The cerebellum is known to be involved in association learning (65-69), and we have proposed that it learns such associations so that it can generate moment-to-moment predictions about which neural systems will be needed in upcoming moments, allowing it to effect the preparatory enhancement of neural responsiveness in these systems. The cerebellum is known to have rich connections with limbic circuits (70), and the abnormal response to social reinforcement may reflect cerebellar impairment in the learning of associations and the subsequent provision of preparatory enhancement for limbic regions responding to motivational information. Finally, a wholly different interpretation that should be considered regarding the social reinforcement findings is the possibility that the processing of socially reinforcing information requires a very distracting shift of attention to a person in a different location from the to-be-attended

stimuli. The distraction of responding to social reinforcers and attempting to process such a complex (human) stimulus would interrupt a task much more severely than would a more "tangible" reinforcer such as a pretzel or a penny. This would have less to do with motivation and more to do with attention dysfunction.

8.2. Implications for behavior and treatment

The unique pattern of attentional strengths and weaknesses seen in autism has profound implications for the developing child. The abnormal distribution of attentional resources across space brought about by parietal lobe defect impairs the ability to properly perceive and integrate complex visual stimuli and thus appreciate the relationships between aspects of such stimuli. So, for example, an autistic child may learn to identify his father's face not by the overall appearance, but rather by some more focal feature (e.g., a chipped tooth). Such limited recognition might be detrimental to the natural formation of parent-child attachment, a form of autistic socioemotional deficit that can be particularly distressing to families of autistic children.

The inability to orient attention rapidly and accurately to positions in space places autistic children at a serious disadvantage when learning to comprehend the complexities of the world. Slow and inaccurate orienting of attention prevents one from taking in every element of the continuous flow of information occurring in one's environment. The result is a fragmented sense of the world which, among other things, will impede individuals from learning about causal relationships and make the sharing of attention with other individuals difficult if not impossible. Such deficits of shared attention in autism are well documented (71,72). In fact, Dawson et al. (73) have shown that autistic individuals are impaired when orienting attention to social stimuli, and this impairment is significantly correlated with errors in shared attention. Impairments of shared or joint attention are potentially devastating to development, as joint social attention is thought to be a key milestone making normal language and social development possible (74).

Just as the inability to move attention rapidly and accurately among spatial targets is detrimental to development, so too is the inability to shift attention rapidly and accurately between sensory modalities. The social world is made up of a complex and ongoing sequence of often-unpredictable visual, auditory, and tactile stimuli. Unless one is capable of rapidly shifting attention among these various modalities, information will surely be missed and thus not learned by the developing child.

Attempts can certainly be made to compensate for the loss of learning caused by these various deficits through direct intervention and teaching with individual patients. However, impairment in the autistic child's ability to use reward-related information to modulate attentional resources can undermine many of the standard principles by which we teach and learn. Therefore, successful interventions will grow out of the careful planning of individualized programs that capitalize on the attentional strengths and bypass the weaknesses of individuals with autism.

8.3. Implications for future research

In this review, we have discussed in relative isolation the separate contributions of parietal and cerebellar neuroanatomic defects to attention abnormalities in autism. This is because the relationship between these defects and their behavioral manifestations is unknown. However, this is an important area of inquiry for future studies. In the first step of the cerebrocerebellar system, regions of parietal cortex that are involved in attention operations (e.g., Area 7) send projections to the pons, and pontocerebellar connections then carry signals to the cerebellar cortex. Likewise, the thalamic targets of output from the deep cerebellar nuclei send projections to posterior parietal cortex (for a review of cerebellar anatomic connections, see 75). Thus, the anatomical stage is set for these regions to interact in the modulation of attentional operations, and abnormalities in either system might contribute to dysfunction in the other. For instance, slowness in shifting attention might impede the timely analysis of relevant sources of information, thus restricting the optimal distribution of attentional resources subserved by the parietal lobe. On the other hand, slow shifting among spatial locations might be compensated for somewhat in the context of a normal attentional gradient, while a narrow spotlight of attention might further exaggerate this deficit. These and other possibilities could be examined in future studies aimed at delineating both the separate and combined effects made by parietal and cerebellar anatomic defects to attention dysfunction in autism.

Although this review has focused exclusively on attention function in autism and its relationship to parietal and cerebellar abnormalities, it must be made clear that a wide range of sensory, motor, affective, and cognitive deficits and a range of neuroanatomic abnormalities characterize this disorder. In the current state of knowledge about autism, where the primary goal must be to understand its genetic basis, no deficit can be considered more important than any other. There is clearly no "core deficit" which at once characterizes and explains this complex condition. Rather, autism is a collection of multiple deficits resulting from multiple neural defects. As the present review has shown, even within the limited domain of attention, autistic individuals demonstrate a range of deficits with multiple associated forms of neuropathology. Furthermore, in certain contexts, physiological abnormality appears to be accompanied by normal or even supernormal behavioral performance, pointing to the possibility that successful compensatory mechanisms for developmental neural abnormality are also a feature of the autistic brain. The processes through which such mechanisms might develop represent a key area of future research, for understanding how they naturally develop will likely provide important clues for how clinicians might best intervene early in the development of an autistic child.

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