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Self-ordered pointing in children with autism: failure to use verbal mediation in the service of working memory?

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Abstract

This study tested the hypothesis that children with autism are impaired in using verbal encoding and rehearsal strategies in the service of working memory. Participants were 24 high-ability, school-age children with autism and a comparison group matched on verbal and non-verbal IQ, receptive and expressive vocabulary, and visual memory. Working memory was assessed using verbal and non-verbal variants of a non-spatial, self-ordered pointing test [Petrides, M., & Milner, B. (1982). Deficits on subject-ordered tasks after frontal- and temporal-lobe lesions in man. Neuropsychologia, *20*, 249–262] in which children had to point to a new stimulus in a set upon each presentation without repeating a previous choice. In the verbal condition, the stimuli were pictures of concrete, nameable objects, whereas in the non-verbal condition, the stimuli were not easily named or verbally encoded. Participants were also administered a verbal span task to assess non-executive verbal rehearsal skills. Although the two groups were equivalent in verbal rehearsal skills, the autism group performed significantly less well in the verbal, but not the non-verbal, self-ordered pointing test. These findings suggested that children with autism are deficient in the use of verbal mediation strategies to maintain and monitor goal-related information in working memory. The findings are discussed in terms of possible autistic impairments in episodic memory as well as working memory.
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Executive functions are comprised of a number of mental operations necessary for the conscious, deliberate, and flexible control of non-routine actions. There is now evidence of a broad range of executive function impairments in autism, including deficits in working memory (Bennetto, Pennington, & Rogers, 1996; but see Ozonoff & Strayer, 2001; Russell, Jarrold, & Henry, 1996); combined working memory and inhibitory control (Hughes & Russell, 1993; Joseph, McGrath, & Tager-Flusberg, in press; Russell, Mauthner, Sharpe, & Tidswell, 1991); mental set shifting (Hughes, Russell, & Robbins, 1994; Ozonoff & Strayer, 1997; Ozonoff, Strayer, McMahon, & Filloux, 1994; Ozonoff et al., 2004; Rumsey, 1985); and planning, particularly as measured on the Tower of Hanoi and Tower of London tasks (Ozonoff & Jensen, 1999; Ozonoff & McEvoy, 1994; Ozonoff, Pennington, & Rogers, 1991; Ozonoff et al., 2004). Nevertheless, executive control deficits are found in many childhood disorders, and a more precise delineation of the executive impairment in autism is needed at both the neuropsychological and brain levels of explanation (Ozonoff, 1997; Robbins, 1997).

Working memory is a key component of executive control that has received significant attention in autism research, but for which the findings have been inconsistent. As conceived by Baddeley and Hitch (1974, 1994) (Baddeley, 1986), working memory is a limited capacity system allowing for the simultaneous on-line maintenance and processing of task-relevant information. Bennetto et al. (1996) and Russell et al. (1996) investigated working memory skills in children with autism using similar measures, all of which required participants to respond to a series of items from a focal processing task (e.g., counting the dots on a card, supplying a word missing from a sentence) while simultaneously maintaining a mental record of all prior responses. Whereas Bennetto et al. found that their high-ability participants were significantly impaired relative to normal controls, Russell et al. found that the performance of their relatively low-ability participants with autism, although inferior to a normal control group, was

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similar to that of a mental-age-matched, non-autistic control group. Further, in a recent study using a variety of tasks, Ozonoff and Strayer (2001) failed to find working memory deficits in high-ability children and adolescents with autism.

The lack of more consistent evidence of a working memory impairment in autism has been somewhat surprising given that the most consistently replicated and robust finding of executive dysfunction in autism comes from studies using the Tower of Hanoi or Tower of London, which as complex planning tasks would be expected to draw upon the ability to generate, maintain, and continuously update a sequence of actions in working memory. Furthermore, although there is no evidence of an impairment in simple response inhibition in autism (Hughes & Russell, 1993; Ozonoff & Strayer, 1997; Ozonoff et al., 1994), tasks that require a combination of working memory and inhibition (Roberts & Pennington, 1996) appear to be especially challenging for individuals with autism (Hughes & Russell, 1993; Russell, 1997), suggesting that working memory capacities may be deficient at least under some circumstances in autism. In sum, although research thus far has failed to isolate an autistic deficit in working memory per se, the possibility that weaknesses in some aspects of working memory contribute to the broader executive impairment seen in autism remains unresolved and worthy of further scrutiny.

Drawing on Luria's classic ideas about the central role of verbal processes in children's development of self-control (Luria & Yudovich, 1971), Russell and his colleagues (Russell, Jarrold, & Hood, 1999) have proposed that autistic executive deficits derive at least in part from a failure to use internal or subvocal speech to regulate non-routine behaviors via verbal working memory. Specifically, Russell has argued that a weakness in the use of verbal self-reminding to maintain response rules in working memory makes individuals with autism vulnerable to errors in standard executive tasks that pit an arbitrary response rule against a prepotent response tendency. Accordingly, a failure to subvocally rehearse and remind oneself of an arbitrary response rule could explain autistic deficits on measures such as the Windows task, in which participants must point to an empty container to receive a candy reward visible in an adjacent container (Hughes & Russell, 1993), and on the Luria hand game (Luria, Pribram, & Homskaya, 1964), which requires participants to point a finger when the examiner makes a fist, and vice versa (Hughes, 1996).

Our goal in the present study was to further test Russell's (1997) hypothesis by directly comparing verbal and non-verbal working memory skills in children with autism. We did this using verbal and non-verbal variants of the non-spatial, self-ordered pointing test (SOPT) devised by Petrides and Milner (1982). In the SOPT, children were presented with a set of 4, 6, 9, or 12 picture stimuli illustrated on a single sheet of paper. Each stimulus set was presented repeatedly, in a new spatial arrangement each time, for as many times as the number of stimuli in the set. The child's task was to point to a different picture on each presentation, and thus to avoid touching the same picture more than once. As such, the SOPT evaluated children's ability to generate and monitor a sequence of responses in working memory without the aid of spatial cues (Petrides, 1994, 1996). In the verbal condition of the SOPT, the stimuli to be remembered were pictures of concrete, nameable objects. In the non-verbal condition, the stimuli were abstract designs that were not easily named or encoded verbally.

An important conceptual distinction bearing upon this investigation comes from Baddeley and Hitch's (1974, 1994) (Baddeley, 1996a,b) tripartite model of working memory, which distinguishes between a "central executive" and two modality-specific subsystems that participate in the online maintenance of verbal and visuospatial information. The *central executive* of working memory functions as a top–down, attentional selection and control mechanism (see also Shallice and Burgess (1993)), which in the SOPT would involve monitoring the pointing choices made thus far, and generating subsequent choices based on continuously updated mental representations of prior choices. The central executive is dependent on two subsidiary information-maintenance subsystems. The *phonological loop* is responsible for maintaining verbal information in active memory, whereas the *visuospatial sketchpad* is responsible for the maintenance of visual and spatial information. The phonological loop functions via a subvocal rehearsal process, whereby linguistically coded information is continuously refreshed in a short-term phonological store. In the SOPT that we administered, the phonological loop would be expected to contribute to performance to the extent that visual information could also be coded linguistically and maintained in verbal working memory for the duration of any given trial.

The distinction between the verbal working memory functions of the central executive and the phonological loop was particularly important for the present investigation because of the possibility that a (potentially language-based) deficit in phonological rehearsal skills, rather than an impairment in the central executive, could result in poor performance on the verbal SOPT by children with autism. For this reason, we also assessed children's phonological rehearsal skills, using a verbal span task. This task required participants to listen to a sequence of words and then point to the corresponding items in a picture array in the same order as the words were spoken. Although the verbal span task was similar to the SOPT in requiring sequential pointing to pictures, its purpose was to measure the ability to maintain verbal information in the phonological loop without the 'central executive' demands entailed by the SOPT (i.e., generating, monitoring, and continuously updating a pointing sequence). Russell et al. (1996) found that children with autism performed as well as normal controls on a similar verbal span task, suggesting no impairment of phonological rehearsal capacities in autism.

In summary, our main goal was to assess the potential facilitating effect of verbal mediation on working memory, such that children would be able to use language-based encoding and rehearsal processes to enhance working memory capacity. Based on prior findings (Russell et al., 1996), we did not expect that children with autism would be impaired in verbal rehearsal skills associated with the phonological loop, but would rather exhibit deficits in their ability to spontaneously adopt verbal mediation strategies to monitor and maintain their choices in working memory. This would point to a failure of the central executive of working memory in autism.

1. Methods

1.1. Participants

Participants were 24 school-age children with autism (21 males) and a comparison group of 24 non-autistic children (19 males), all of whom were recruited through community sources to participate in a study of language and social cognition. Participants in the autism group were judged to meet DSM-IV (APA, 1994) criteria for autism or PDDNOS by an expert clinician. Clinical diagnoses were confirmed using the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & LeCouteur, 1994), an experimenter-administered, parent interview which yields ratings for social, communication, and repetitive behavior symptoms based primarily on behaviors reported for the 4–5-year-age period, and the Autism Diagnostic Observation Schedule (ADOS; Lord, Rutter, DiLavore, & Risi, 1999; Lord et al., 2000), an interactive behavioral observational instrument which assesses concurrent autism symptoms in the social and communication domains. All children in the autism group met criteria for autism on the ADI-R, with the exception of two children, who were one point below the diagnostic cut off score for repetitive behaviors. Of the 24 children in the autism group, 20 met ADOS cut off scores for a diagnosis of autism, 2 met for a less severe ADOS diagnosis of autism spectrum disorder, and 2 did not meet ADOS diagnostic criteria. The latter two children met ADOS cut off scores for autism in the social symptom domain (but not in the communication domain) and met full criteria for autism on the ADI-R, and were therefore included in the sample. Children with Rett syndrome, Childhood Disintegrative Disorder, or with autism-related neurological conditions (e.g., neurofibromatosis, tuberous sclerosis, Fragile-X syndrome) were not included in this study. All comparison group participants were assessed for autistic symptomatology with the ADI-R and ADOS and were confirmed not to meet diagnostic criteria for autism or PDDNOS on these instruments and according to expert clinical judgment.

The comparison group was matched to the autism group on age and on verbal and non-verbal IQ as measured by Differential Ability Scales (DAS; Elliott, 1990). In addition, because of the potential effects of language level on verbal span and SOPT performance, the groups were matched on expressive and receptive vocabulary as measured by the Expressive Vocabulary Test (EVT; Williams, 1997) and the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997), respectively. A recent study (Condouris, Meyer, & Tager-Flusberg, 2003) demonstrated that these vocabulary tests, when combined into a composite language measure, were significantly correlated with the CELF (Semel, Wiig, & Secord, 1995; Wiig, Secord, & Semel, 1992), an omnibus test of expressive and receptive language ability, and with measures of spontaneous language production in verbal children with autism. Finally, because of the likely contribution of visual encoding and memory abilities to SOPT performance, the groups were matched on visual recognition memory as measured by the DAS recognition of pictures subtest (which did not contribute to DAS IQ scores). In this subtest, children viewed one or more pictures for 5 s (or for 10 s in later trials) and then picked them out from a larger set including distracter items in an immediate recognition trial. Difficulty ranged from identifying 1 out of the 3–4 out of the 8 items for a total of 20 possible trials. One point was given for each error-free trial, and testing was discontinued after four consecutive trials with errors. Although all the pictured objects in this task were nameable, the majority of trials included only one or a limited number of categories (e.g., all horses, brushes and combs), reducing the usefulness of verbal mediation strategies (Elliott, 1990). As can be seen in Table 1, autism and comparison participants were well matched on all variables.

1.2. Measures

All measures were administered in two visits scheduled approximately 2 weeks apart. During the first visit, diagnostic assessments and IQ, language, and visual memory tests were completed. During the second visit, the verbal span test and SOPT were administered in random order as part of a larger batter of executive function tasks.

Table 1
Participant characteristics

	Autism ($n = 24$): M (S.D.), range	Comparison ($n = 24$): M (S.D.), range	$t(46)$, p
Age	8;11 (2;4), 5;9–14;2	8;11 (2;2), 5;10–13;10	0.0, .99
DAS full scale IQ	96 (18), 70–141	92 (13), 63–114	0.9, .38
DAS verbal IQ	94 (19), 57–133	89 (12), 68–111	1.2, .25
DAS non-verbal IQ	99 (20), 64–153	94 (14), 60–114	0.8, .42
EVT standard score	92 (18), 40–136	93 (12), 67–118	0.3, .78
PPVT-III standard score	95 (20), 57–134	99 (11), 68–121	0.8, .43
Recognition of pictures score	13.8 (3.9), 6–19	13.6 (3.5), 7–19	0.2, .88

1.2.1. *Verbal span*

The verbal span test was similar to the “non-verbal recall” span task used by Russell et al. (1996). Children heard the examiner speak a sequence of words at the rate of one word per second. For each trial, a fixed sequence was randomly preselected from a set of nine words, all of which were single-syllable, high-frequency concrete nouns (arm, boat, brush, chair, dress, knife, mouse, ring, tree). After each sequence was spoken, participants were immediately presented with a 3×3 grid containing nine line drawings corresponding to the set of nine words, and were instructed to touch the pictures in the same order as the words were spoken. For each trial, the arrangement of the pictures in the grid changed so as to prevent children from using a fixed visual representation of the array to help encode the word sequence. The changing array also introduced a visual search component to the task similar to that in the SOPT. Children were given two different trials of each sequence length, which ranged from two to seven words. One point was given for each trial correct. Testing was discontinued when a child failed both trials of any one sequence length.

1.2.2. *Self-ordered pointing (Petrides & Milner, 1982)*

The SOPT was administered in a verbal and non-verbal condition, counterbalanced for order. In the verbal condition, children viewed pictures of concrete, single-syllable, nameable objects (car, book, etc.). These pictures were taken from the standardized set developed by Snodgrass and Vanderwart (1980) and were selected for their high name agreement and familiarity. In the non-verbal condition, children saw abstract designs that were difficult to name or encode verbally. These designs were taken from the Dover Clip Art series that is available via the world wide web and copyright-free. See Figs. 1 and 2 for examples of the verbal and non-verbal SOPT stimuli. Each condition included 4 test trials of increasing length (4, 6, 9, and 12 items) preceded by a 4-item demonstration and a 4-item practice trial to ensure that the task demands were understood. In a four-item trial, for example, four sheets of paper were presented sequentially, with each sheet depicting the same four stimuli, but in a different spatial arrangement each time. Children were instructed to touch a different picture on each presentation. For any given trial, the number of sheets presented was equal to the number of stimuli on the first sheet. Each of the different sized sets was composed of unique stimuli. Further, within each set, each picture came from a different category so as to preclude the use of semantic or visual clustering strategies (e.g., touching all animal pictures or circular designs first) that have been observed in studies using the original Petrides stimuli (Bryan & Luszcz, 2001; Daigneault & Braun, 1993). This design feature was incorporated because of evidence that individuals with autism do not spontaneously adopt such strategies when encoding and recalling verbal and visual information (Bowler, Matthews, & Gardiner, 1997; Minshew

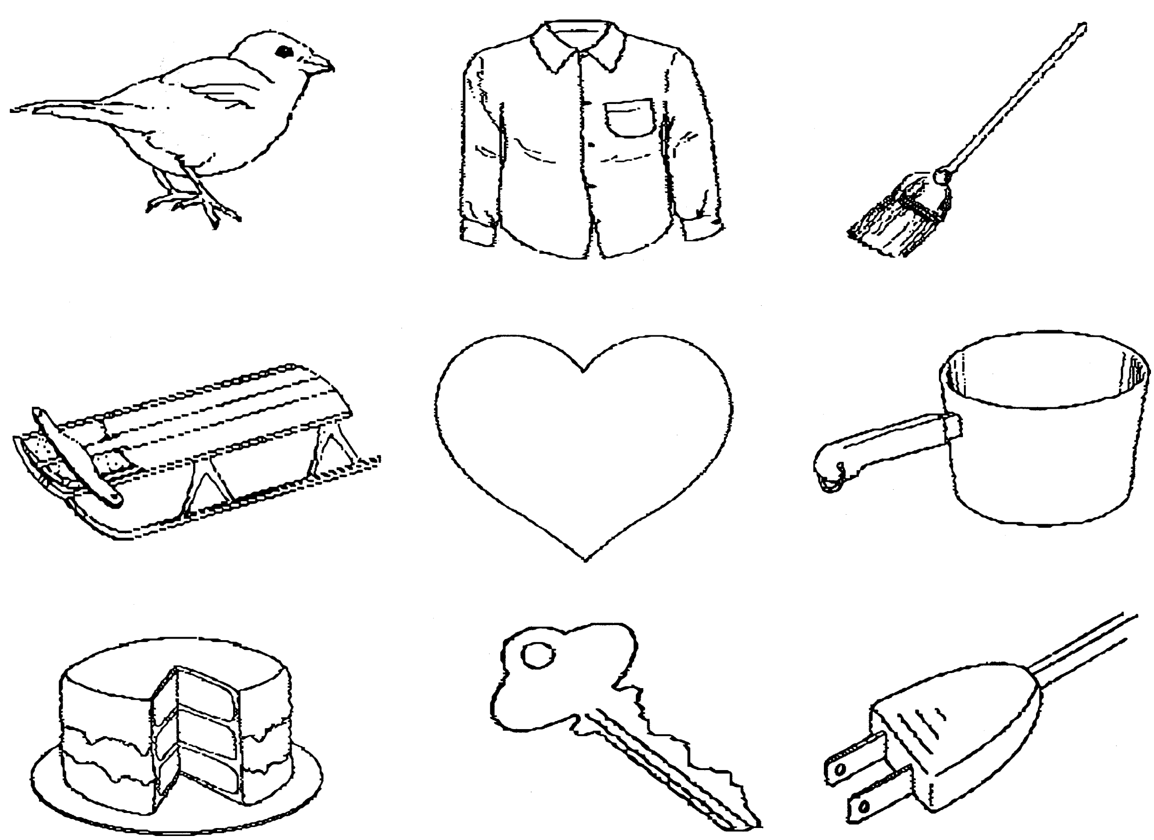

Fig. 1. Verbal self-ordered pointing stimuli (set size = 9).

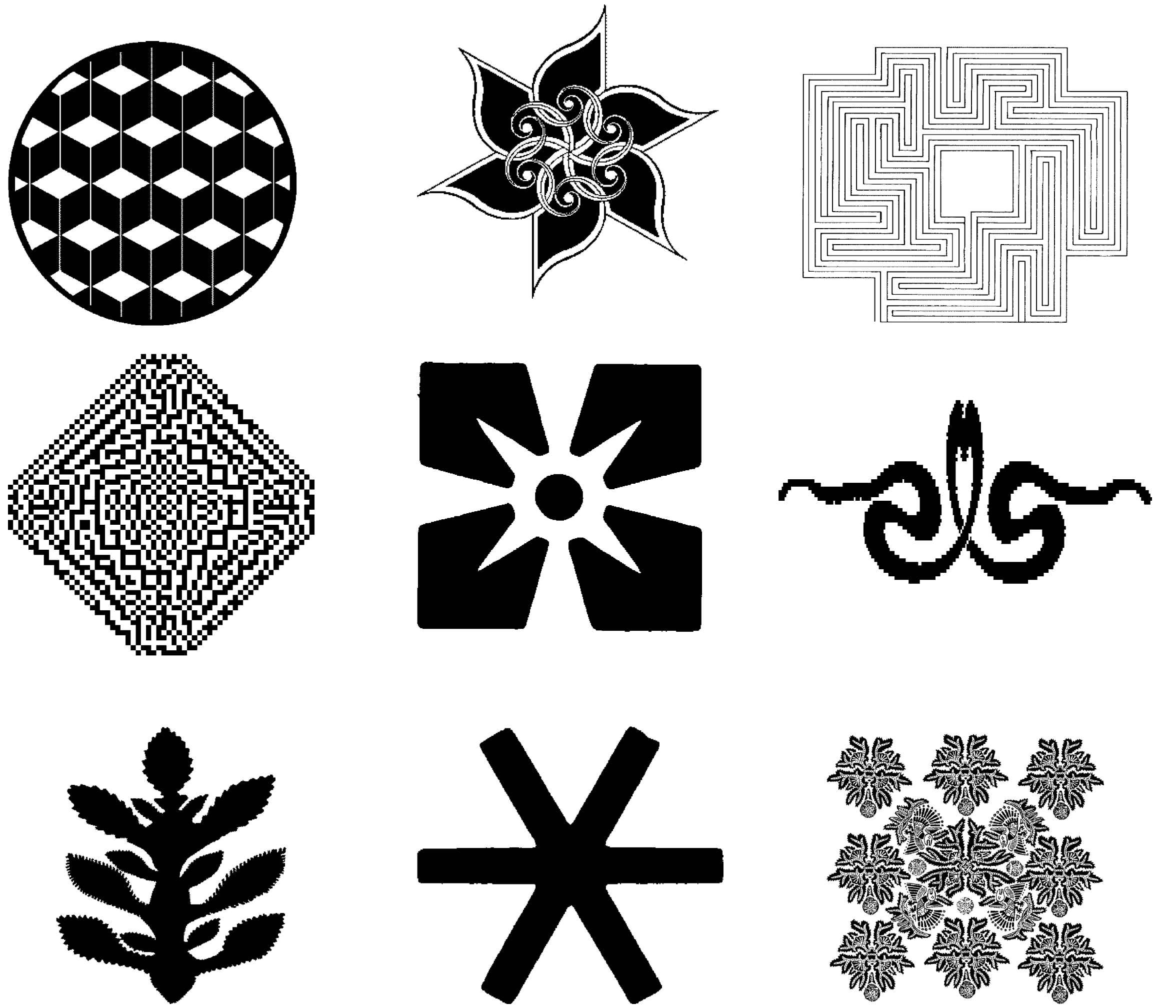

Fig. 2. Non-verbal self-ordered pointing stimuli (set size = 9).

& Goldstein, 1993, 2001; Tager-Flusberg, 1991). It therefore served to provide a measure of verbal working memory ability that was not confounded by group differences in the use of organizational strategies. Administration of the SOPT was facilitated by fitting all the sheets of pictures for each condition into transparent sleeves and presenting them with the aid of a loose leaf binder. During administration, if a child pointed to the same location consecutively (a strategy that would be highly successful given that no picture ever appeared in the same place), he or she was told prior to the next trial, “You have to pick a different spot now. Pick a *new* one in a *different* spot”. This instruction was rarely necessary.

We assessed SOPT performance in three different ways. First, following the usual approach (Petrides & Milner, 1982), we calculated the number of SOPT errors, defined as points to any picture already selected. Our main prediction was that children with autism, in contrast to comparison participants, would not exhibit an advantage in the verbal condition of the SOPT relative to the non-verbal condition of the SOPT. Second, in addition to overall rate of error, we measured children’s SOPT span, defined as the number of consecutive novel pointing responses prior to the first error. This measure would help to confirm that any difference in error rates between groups or conditions actually reflected an increased ability to monitor and maintain a sequence in working memory. Finally, we assessed the number of perseverative responses, defined as the number of errors that occurred as a result of pointing to the same item that was chosen on the immediately preceding page. This measure was included to ensure that any differences between groups or conditions were not due to lower-level inhibitory failures such as have been observed in other populations on the SOPT (e.g., West, Ergis, Winocur, & Saint-Cyr, 1998).

2. Results

The two groups performed equivalently on the verbal span task, $t(46) = 0.6$, n.s. The autism group obtained a mean score of 5.7 (S.D. = 1.9) and the comparison group obtained a mean score of 5.4 (S.D. = 1.8). In order to evaluate the relationship between language level and task performance, a composite variable was constructed from the mean of each child’s age-equivalent scores for the PPVT-III and EVT, which were strongly correlated in the present sample, $r(46) = .84$, $p < .001$. Language level was significantly correlated with verbal span in both the autism group, $r(22) = .66$, $p < .001$, and the comparison group, $r(22) = .48$, $p < .02$.

To assess SOPT performance, a mixed-model ANOVA with the between-subjects factor group (autism, comparison) and the within-subjects factors condition (verbal, non-verbal) and set size (4, 6, 9, 12) was conducted with total SOPT errors as the dependent variable. There was no main effect of group, $F(1, 46) = 0.6$, n.s. As would be expected, there was a main effect of set size, $F(3, 138) = 86.0$, $p < .001$, reflecting more errors as set size increased. Further, there was a main effect of condition, $F(1, 46) = 9.4$, $p < .01$, with better performance in the verbal than in the non-verbal condition. As can be seen in Fig. 3, there was also a group × condition interaction, $F(1, 46) = 10.8$, $p < .001$. Follow-up independent-samples t-tests showed that the autism group ($M = 5.5$, S.D. = 2.8) performed similarly to the comparison group ($M = 6.3$, S.D. = 2.7) in the non-verbal condition, $t(46) = 1.0$, n.s., but the autism group ($M = 5.6$, S.D. = 2.7) made significantly more errors than the comparison group ($M = 3.9$, S.D. = 2.1) in the verbal condition, $t(46) = 2.4$, $p < .02$. In addition, paired-samples t-tests showed that the comparison group benefited significantly from the verbal condition relative to the non-verbal condition, $t(23) = 4.7$, $p < .001$, whereas the autism group did not, $t(23) = 0.2$, n.s. Finally, there was a trend toward a group × condition × set size interaction, $F(3, 138) = 2.2$, $p < .10$, reflecting an increasing between-group disparity in performance in the verbal condition as set size and working memory load increased, as can be seen in Fig. 3. Independent-sample t-tests confirmed an increasing difference in mean errors between groups as memory load increased in the verbal condition, with $t(46) = 0.5$, 1.5, 1.8, 2.2 and $p = .61$, .15, .07, .03 for sets 4, 6, 9, and 12, respectively.

A second ANOVA with the same factors was conducted with the number of consecutive novel responses prior to the first error as the dependent variable. Although this measure of SOPT span was not independent of number of errors, it would provide a clearer assessment of whether the reduced amount of errors for the comparison group in the verbal condition was due to an enhanced ability to monitor and maintain a sequence in working memory as would be reflected by longer runs of error-free performance. This analysis yielded a similar pattern of effects as was found for SOPT errors, including no main effect of group, $F(1, 46) = 0.0$, n.s., a main effect of condition, $F(1, 46) = 5.3$, $p < .05$, and a group × condition interaction, $F(1, 46) = 6.6$, $p < .02$. As illustrated in Fig. 4, the comparison group exhibited longer spans in the verbal than in the non-verbal condition, whereas the autism group did not.

Given that children with autism appeared to differ from the comparison group mainly in their failure to benefit from the availability of verbal encoding and rehearsal strategies in the verbal condition of the SOPT, it was important to confirm that the autism group's even performance across the verbal and non-verbal conditions was not simply due to a floor effect. To determine if each group's performance was indeed above chance, a criterion span was identified for each SOPT set size on the basis of the number of consecutive novel responses prior to the first error that would be expected to occur by chance less than 5% of the time (with the exception of error-free performance on a set size of 4 which would be expected to occur by chance less than 10% of the time). As shown in Table 2, the proportion of each group exceeding the criterion was significantly above chance expectation (binomial test, one-tailed) for all set sizes and both conditions. In addition to this non-parametric approach, we also confirmed with one-sample t-tests (two-tailed) that each group's mean scores for each set size in each condition were significantly higher than the spans that would be expected to occur at approximately 50% chance.

A final mixed-model ANOVA with the same factors as in the previous analyses was conducted to assess whether there were any differences in the amount of perseverative responding. Perseverative responding was defined as the number of

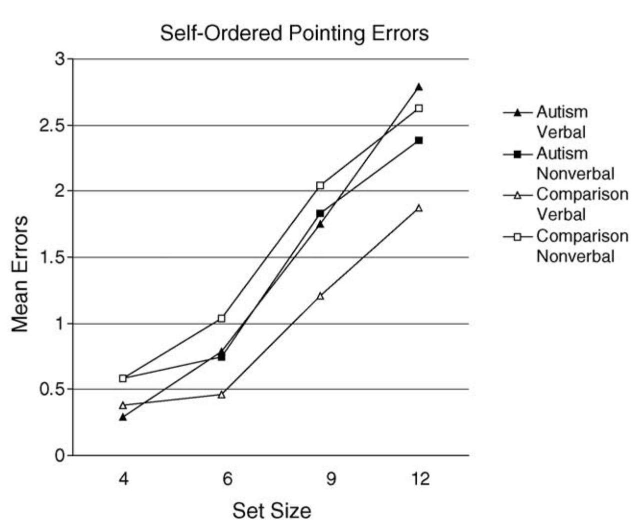

Fig. 3. Self-ordered pointing errors.

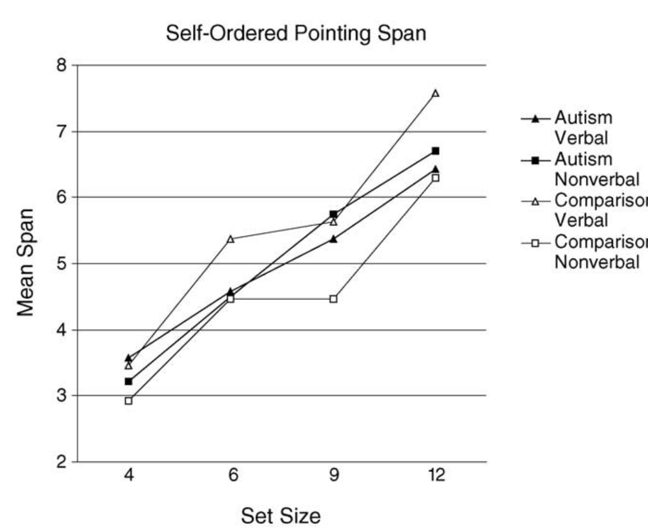

Fig. 4. Self-ordered pointing span.

Table 2
Proportion of each group meeting or exceeding criterion span for above-chance performance

Set size	Criterion span[a]	Exact probability[b]	Proportion meeting or exceeding criterion[c]	
			Autism ($n=24$)	Comparison ($n=24$)
Verbal				
4	4	.094	.75***	.67***
6	6	.016	.46***	.63***
9	7	.039	.38***	.42***
12	8	.047	.25**	.63***
Non-verbal				
4	4	.094	.46***	.46***
6	6	.016	.42***	.29***
9	7	.039	.42***	.17*
12	8	.047	.42***	.29***

[a] Number of consecutive novel responses prior to first error expected to occur by chance at less than a .05 level of probability, with the exception of error-free performance on a set size of four which would be expected to occur by chance at less than a .10 level of probability.
[b] Exact probability of obtaining the criterion span by chance.
[c] Binomial test, one-tailed: *$p < .05$, **$p < .01$, ***$p < .001$.

Table 3
Age-partialled correlations between SOPT span and other measures

	Autism ($n=24$)		Comparison ($n=24$)	
	Verbal SOPT	Non-verbal SOPT	Verbal SOPT	Non-verbal SOPT
Language level	.13	.12	.41*	−.05
Verbal span	.13	.10	.11	.31
Visual memory	−.09	.44*	.34	−.14

* $p < .05$.

errors in any given set that occurred as a result of pointing to the same item as was chosen on the immediately preceding page. This analysis revealed no difference between groups, $F(1, 46) = 0.3$, n.s., and no group × condition interaction, $F(1, 46) = 0.0$, n.s. There was only a main effect of condition, $F(1, 46) = 10.6$, $p < .01$, with both groups making more perseverative errors in the non-verbal than in the verbal condition. Overall, the proportion of errors that resulted from perseverative responding was not large: 14% in the verbal condition and 25% in the non-verbal condition.

In a final set of analyses, Pearson product–moment correlations were calculated to assess the degree of association between language level, verbal span, visual memory, and SOPT performance. As would be expected, age was significantly associated with most of these variables in both groups. As shown in Table 3, after the effects of age were removed, language level was significantly correlated with verbal SOPT performance in the comparison group, but not in the autism group. In contrast, visual memory was significantly associated with non-verbal SOPT performance in the autism group only. Verbal span was not correlated with SOPT performance in either group.

3. Discussion

The SOPT assesses the ability to monitor a series of actions or events within working memory. We used the SOPT to test the hypothesis that children with autism are deficient in the use of verbal mediation strategies to augment working memory capacity and, by extension, to regulate action. Our findings supported this hypothesis. Children with autism performed as well as comparison participants in a non-verbal version of the SOPT. However, unlike the comparison participants, they did not show an improvement in performance when stimuli could be verbally encoded and rehearsed in working memory in the verbal condition of the SOPT. Data analyses revealed no evidence of increased perseverative responding in the autism group, consistent with prior research that failed to find evidence of low-level disinhibition in higher-ability individuals with autism (Hughes & Russell, 1993; Ozonoff & Strayer, 1997; Ozonoff et al., 1994). Further, the weak performance by children with autism on the verbal SOPT could not be attributed to deficient phonological rehearsal capacities because the autism group performed as well as the comparison group on the verbal span task that was administered. Rather, their poor performance appeared to result from central executive limitations relating to the ability to monitor and maintain a sequence of pointing choices in verbal working memory. This was reflected in their relatively diminished spans of error-free pointing on the verbal SOPT and the tendency for their performance to decline as set size, the number of alternative choices, and the self-monitoring demands placed on the central executive of working memory increased (see Petrides (1994, 1996)).

Children with autism performed significantly less well than the comparison group on the verbal SOPT even though the two groups were equal in their language skills. The divergence in performance between groups may be at least partially explained by the fact that language ability was positively correlated with verbal SOPT performance in the comparison group, but not in the autism group, providing a further indication that participants with autism were not exploiting their verbal skills to enhance working memory in the verbal condition of the task. In contrast, the autism group evidenced a significant association between visual memory ability and non-verbal SOPT performance, whereas the comparison group did not. The differential pattern of associations among test measures for the two groups suggested the possibility of a greater dependence in the autism group on visual representations in working memory. One explanation for the relatively weak performance by the comparison group in the non-verbal condition and by the autism group in both conditions is that purely visual representations cannot be rehearsed and refreshed via the visuospatial sketchpad in working memory as effectively as verbally coded representations can be via the phonological loop.

Whereas children with autism performed significantly less well on the verbal SOPT, they performed as well as the comparison participants on the verbal span task, which was administered to assess verbal rehearsal skills in the two groups independently of the monitoring demands of the SOPT. Although superficially similar, the verbal span task and the verbal SOPT differed in at least two important ways. First, in the verbal span task, children were *given* the sequence of items to which they had to point. To do this, they needed to maintain a fixed sequence in working memory, presumably with the aid of verbal rehearsal, and simply keep their place in the sequence as they pointed to the successive items. In contrast, in the SOPT, children had to *generate* a sequence of novel choices by continuously comparing choices already made and represented in working memory with those yet to be made. The monitoring and updating requirements of the latter task were therefore much more taxing on executive capacities. Second, in the verbal span task, the sequence was spoken by the examiner and thus given to children in verbal auditory form. In contrast, in the verbal SOPT, children needed to spontaneously adopt the strategy of recoding the picture stimuli in verbal form so that they could rehearse and maintain the choices already made in working memory.

The results from the verbal span task indicated, consistent with Russell et al. (1996), that verbal rehearsal skills were unimpaired in participants with autism and that their relative weakness in verbally mediated self-monitoring on the SOPT did not result from an inability to maintain verbal information online via the phonological loop. Against this conclusion, it could be argued that the autism group's good performance on the verbal span task was potentially mediated more by visual than by phonological representations of the given word sequences. However, the strong association between verbal span and language level that was found for children with autism as well as comparison participants favors the conclusion that verbal rehearsal processes were key for both groups when the sequence was given in auditory form, as was the case in the verbal span task.

Verbal span was not associated with performance on the verbal SOPT in either group. This finding suggested that although verbal rehearsal skills may have been necessary for above-chance performance on the verbal SOPT, the SOPT measured abilities that were in excess of and different from verbal rehearsal capacities. This would be consistent with the large body of neuropsychological evidence indicating that the SOPT specifically taps, apart from other memory functions, the ability to monitor a self-ordered sequence of actions within working memory (Petrides & Milner, 1982; West et al., 1998) as well as more recent neuroimaging evidence supporting a distributed neural network of verbal working memory, including the central executive functions of dorsolateral and ventrolateral prefrontal cortex (Curtis & D'Esposito, 2003; Levy & Goldman-Rakic, 2000; Petrides, 2000) and the rehearsal functions of speech-related frontal brain regions such as Broca's area and supplementary motor cortex (Chein & Fiez, 2001; Smith, Jonides, Marshuetz, & Koeppe, 1998).

Evidence from this study of an autistic deficit in the self-monitoring functions of verbal working memory is inconsistent with the null findings of two prior studies (Ozonoff & Strayer, 2001; Russell et al., 1996). How might these inconsistencies be explained? Russell et al. (1996) administered classic processing and storage tasks in which children were required to complete a series of trials from a focal task, such as counting the dots on a card or completing a sentence, while simultaneously maintaining a mental record of all their responses in working memory. Russell et al. found that their low-IQ participants with autism performed as well as an IQ-matched control group. However, given the association between general intelligence and processing speed (Anderson, 1992), one possibility is that such tasks are more sensitive to deficits in speed of information processing than to working memory capacity, particularly in lower-IQ groups. The processing demands of the focal task in the SOPT—choosing a new stimulus by comparing those already selected to those not yet chosen—are relatively meagre and are more closely and naturally tied to the working memory and self-monitoring components of the task, arguably making the SOPT a more sensitive measure of the executive processes involved in working memory.

Nonetheless, Ozonoff and Strayer (2001) failed to find significant deficits among high-ability children with autism on a self-ordered "box search" task. In their computerized test, children searched for prizes hidden in three of the six different boxes that changed place on each trial, but which could be identified and verbally coded on the basis of the boxes' different colors. The goal of the task was to find all the prizes without selecting the same box more than once. A possible explanation for Ozonoff and Strayer's null finding comes from the present study. We found that a working memory load of 6 items was not sensitive to group differences in children with autism who were on average 3 years younger than in the Ozonoff and Strayer study, whereas larger loads of 9 and 12 items increasingly differentiated between the autism and comparison groups, at least in the verbal condition of the SOPT. Thus, ceiling effects may have obscured group differences in this earlier study.

In summary, whereas children with autism were unimpaired in their ability to use verbal rehearsal to maintain a given sequence of words in memory, they exhibited deficits in their capacity to spontaneously use verbal encoding and rehearsal strategies to monitor and regulate their actions via working memory. These findings provide further support for Russell's (1997) hypothesis that individuals with autism fail to use language in the service of self-monitoring, and they extend prior research by providing evidence of autistic deficits in verbal working memory that are independent of the need to inhibit prepotent responses (Hughes, 1996; Hughes & Russell, 1993). They also provide evidence of deficits in the self-regulatory functions of working memory that are independent of the complex problem-solving and planning requirements of the Tower of Hanoi and Tower of London, tests on which individuals with autism have consistently exhibited deficits. Unlike the tower tests, the SOPT did not require participants to plan a sequence of moves in advance, but only to keep track of their pointing choices as they were made, and to use this information to make subsequent choices.

The question still remains as to whether the SOPT deficit we observed in our autism group involves a failure of verbal mediation per se, or a broader weakness in self-monitoring that is not limited to an impairment in using inner speech and verbal representations to regulate and direct action. It is possible that a more general impairment of self-monitoring in autism is most readily reflected in a failure to use verbal mediation because it is the most effective strategy for maintaining goal-related information in working memory. The possibility of a more generalized impairment would also be consistent with evidence of autistic deficits in the episodic or self-conscious memory of personally experienced events (Bowler, Gardiner, & Grice, 2000; Gardiner, Bowler, & Grice, 2003; Milward, Powell, Messer, & Jordan, 2000; Toichi et al., 2002), which could arguably explain a weakened ability to monitor a pointing sequence in the SOPT.

This leads us finally to consider the possibility that our SOPT findings reflect, at least in part, a hippocampus-based impairment of episodic memory in autism. In Petrides and Milner's (1982) original study, patients with hippocampal lesions were as impaired as patients with frontal lesions on self-ordered pointing. There is well-known evidence of anatomical abnormalities of the hippocampus in autism from classic histopathology studies (Bauman & Kemper, 1985, 1994) as well as magnetic resonance research (Schumann et al., 2004; Sparks et al., 2002). Recent models of medial temporal lobe memory function have identified the recollection of context-specific episodic information, such as would be involved in remembering a self-ordered pointing sequence, as crucially dependent on the hippocampus. In contrast, the recognition of a stimulus as familiar has been argued to be less dependent on the hippocampus than on extra-hippocampal rhinal and temporal cortex (Aggleton & Brown, 1999; Rugg & Yonelinas; Vargha-Khadem et al., 1997). As such, hippocampal damage in autism would fit well with substantial prior evidence of intact recognition memory (Ameli, Courchesne, Lincoln, Kaufman, & Grillon, 1988; Barth, Fein, & Waterhouse, 1995; Minshew, Goldstein, Muenz, & Payton, 1992) in combination with deficits in episodic memory as well as in free recall. Although free recall deficits in autism have most often been attributed to executive or strategic impairments in encoding and retrieval (Minshew & Goldstein, 1993, 2001; Minshew, Goldstein, & Siegal, 1997; Renner, Klinger, & Klinger, 2000; Rumsey & Hamburger, 1988), some researchers have related them to disturbances in the self-reflective (Gardiner et al., 2003; Tager-Flusberg, 1991) or contextual (Toichi & Kamio, 2003) aspects of episodic memory.

A hippocampus-based impairment in episodic memory does not preclude the possibility that additional pathology of the prefrontal cortex also contributes to the autistic deficits we observed on the verbal SOPT. Prefrontal cortex is part of the distributed brain circuitry involved in the encoding and retrieval of episodic memories and, as noted above, also subserves the monitoring functions of the central executive of working memory. Recent functional neuroimaging studies have revealed that working and episodic memory tasks activate largely overlapping areas (e.g., dorsolateral and ventrolateral cortex) in the prefrontal lobes (Ranganath, Johnson, & D'Esposito, 2003). These frontal areas may serve similar functions across different kinds of memory, and may best be differentiated on the basis of their interactions with other brain regions (Ranganath et al., 2003). Of particular relevance to understanding the behavioral findings from the present study is the prefrontal–medial temporal lobe network subserving episodic memory as well as the neural circuitry connecting prefrontal and language association cortex for the integrated functioning of monitoring and rehearsal in verbal working memory. The possibility of disruption in either or both of these circuits is raised by a variety of findings from recent structural imaging studies of autism, including evidence of cerebral white matter overgrowth, particularly of the radiate white matter comprising short- and mid-range, intrahemispheric cortical connections (Herbert et al., 2004), and reversed structural asymmetry of the language association areas in the cerebral cortex (de Fossé et al., 2004; Herbert et al., 2002). Although subtle and not easily detectable on an individual basis, such evidence of systematic neurostructural abnormalities in autism suggest that deficits in memory and other higher cognitive functions may only be fully understood in terms of disturbances within distributed neural circuitry rather than simply in terms of the effects of localized lesions.

Future research into the nature of the self-monitoring impairment in autism will benefit not only from conceptual and methodological advances in the behavioral testing of memory's component processes, but also from advances in magnetic resonance techniques, such as those that combine functional activation with connectivity imaging (Olesen, Nagy, Westerberg, & Klingberg, 2003), and which will allow us to identify distributed as well as localized brain abnormalities in autism.

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