Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cognitive Psychology 46 (2003) 260–301
Cognitive Psychology
www.elsevier.com/locate/cogpsych

Spatial breakdown in spatial construction: Evidence from eye fixations in children with Williams syndrome

James E. Hoffman,[a,*] Barbara Landau,[b] and Barney Pagani[c]

[a] *Department of Psychology, University of Delaware, Newark, DE 19716, USA*
[b] *Johns Hopkins University, Baltimore, MD, USA*
[c] *University of Delaware, Newark, DE, USA*

Accepted 1 July 2002

Abstract

We investigated the role of executive and spatial representational processes in impaired performance of block construction tasks by children with Williams syndrome (WS), a rare genetic defect that results in severely impaired spatial cognition. In Experiment 1, we examined performance in two kinds of block construction tasks, Simple Puzzles, in which block faces contained a single color, and Complex, in which some block faces contained an arrangement of two colors. WS and control children were comparable in their ability to solve *simple* puzzles, and showed similar eye-fixation patterns, suggesting that basic executive processes were intact. However, WS children were severely impaired in their ability to solve *complex* puzzles. In these puzzles, WS children fixated the complex puzzle models and checked their partial solutions less often than normal children, but they were comparable in their ability to detect errors in their copies and almost exclusively made repairs to copies that were, in fact, incorrect. We conjecture that the abnormal fixation patterns were a *consequence* of impoverished spatial representations, rather than a cause of it. This conjecture was tested in Experiment 2, where we examined children's capacity to match and place individual blocks without engaging the complex executive processes required to carry out a complete puzzle solution. We found serious deficiency among WS children in both aspects of spatial representation. Moreover, estimates of the errors in representing the *identity* and *location* of model blocks derived from Experiment 2 provided a good account of the observed errors in the block construction task of Experiment 1.

* Corresponding author.
E-mail address: hoffman@udel.edu (J.E. Hoffman).

0010-0285/03/$ - see front matter
doi:10.1016/S0010-0285(02)00518-2

Keywords: Spatial cognition; Williams syndrome; Eye fixations; Block construction; Problem solving; Spatial representation

1. Introduction

Breakdown in human spatial organization can occur under a wide variety of pathological conditions, including lesions to the adult brain (Behrmann, 1999), fetal or environmental insult to the developing brain (Diamond, 1998; Stiles, 1998; Stiles-Davis, Kritchevsky, & Bellugi, 1988) and genetic deficit, such as Turner syndrome (Rovet & Buchanan, 1999) or Williams syndrome (Bellugi, Mills, Jernigan, Hickock, & Galaburda, 1999; Mervis, Morris, Bertrand, & Robinson, 1999). Although the circumstances of breakdown and the nature of ensuing impairment are clearly important in their own right, they can also shed light on the nature of normal cognitive architecture. One way this can occur is through observation of unusual *dissociations* between cognitive functions, which can shed light on the nature of cognitive architecture. Another way is through observation of unusual *interactions* between cognitive functions, which can shed light on the degree to which cognitive impairment can drive new solutions to cognitive tasks.

In this paper, we use this framework to examine spatial breakdown in children with Williams syndrome. We focus on a micro-analysis of one task that has been widely used to document spatial deficits in people with Williams syndrome, as well as those resulting from other kinds of brain damage in children (Vicari, Stiles, Stern, & Resca, 1998) and adults (Akshoomoff, Delis, & Kiefner, 1989; Caplan & Caffery, 1992; Ivry & Robertson, 1998). In this "block construction" task, people are shown a model pattern and are asked to create a replica of it in an adjacent "copy" space, using individual blocks that they can select from a larger set (see Fig. 1). Versions of the task can be found in a variety of intelligence tests, including the Wechsler Adult Intelligence Scale (WAIS-R; Wechsler, 1981) and the Differential Ability Scales (Elliott, 1990). Profoundly poor performance is diagnostic of a spatial deficit. Yet the detailed nature of the deficit that leads to poor performance in these tasks has eluded our understanding, largely because the task is quite complex, drawing on a number of possibly different capacities. These may include perception and representation of the spatial relationships within and between blocks in the model, spatial working memory, and executive processes, which guide activities such as the observers' search for information in the model, their search for individual blocks, and any attempts to correct their copy.

In our paper, we build on an analysis of this task that has been offered to explain the mechanisms of normal performance among adults who are **not** spatially impaired (Ballard, Hayhoe, Pook, & Rao, 1997). We argue that the block construction task is remarkably complex, and that consequently, breakdown in performance can occur at any of a number of steps along the way. Despite this complexity, we also argue that the spatial breakdown among children with Williams syndrome can be well understood by separately considering different requirements of the task. In particular, we present evidence showing that (a) the critical breakdown in WS occurs in the

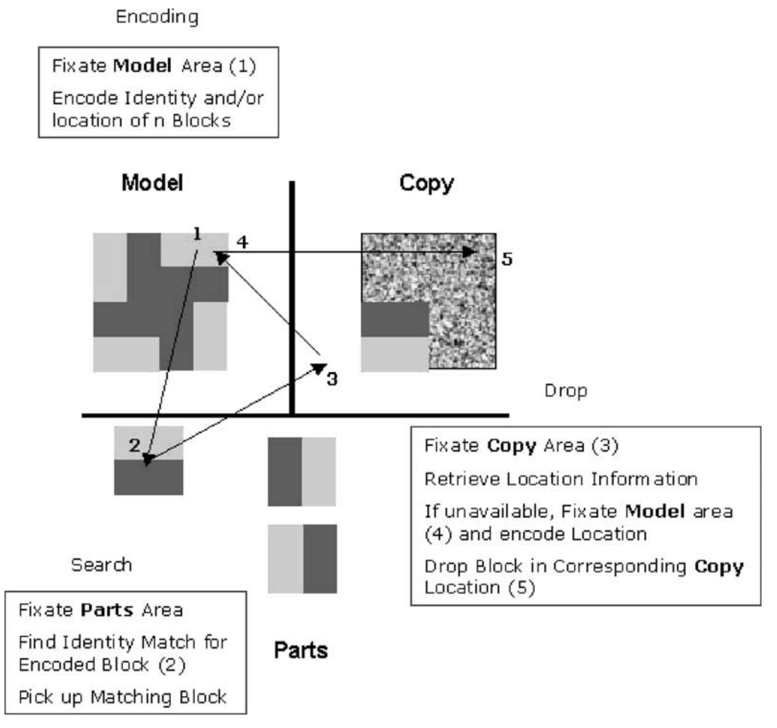

Fig. 1. (A) Task analysis of the block construction task showing the various processes involved in encoding information from the model, finding a matching part, and placing it in the copy area. The numbered arrows indicate the fixations associated with each processing operation. The parts area always contained just those parts required to reconstruct the model. (B) An example of a fixation sequence indicating that the subject was comparing the copy and model. This process plays an important role in detecting a mismatch between copy and model and initiating repairs.

spatial representations within and between individual blocks of the model, and that, by contrast, (b) the *executive processes* that guide problem solving are relatively intact. This evidence shows that the two processes are separable. However, we also show that (c) these two classes of capacity *interact* in such a way as to produce increasingly impoverished performance as the puzzles become more complex. The latter kind of interaction is consistent with theories of "cascading" processes (e.g., Thelen & Smith, 1994), in which one aspect of breakdown can set the stage for changes in other processes, both within a task and over the course of development. We suggest that our analysis provides an important framework for yielding insights about normal spatial representation, as well as the nature of spatial breakdown in Williams syndrome and other cases of spatial deficit.

2. Williams syndrome and spatial deficit in the block construction task

Williams syndrome (WS) is due to a rare genetic defect (1 in 20,000 births) whose unusual cognitive profile has recently attracted considerable attention from cognitive

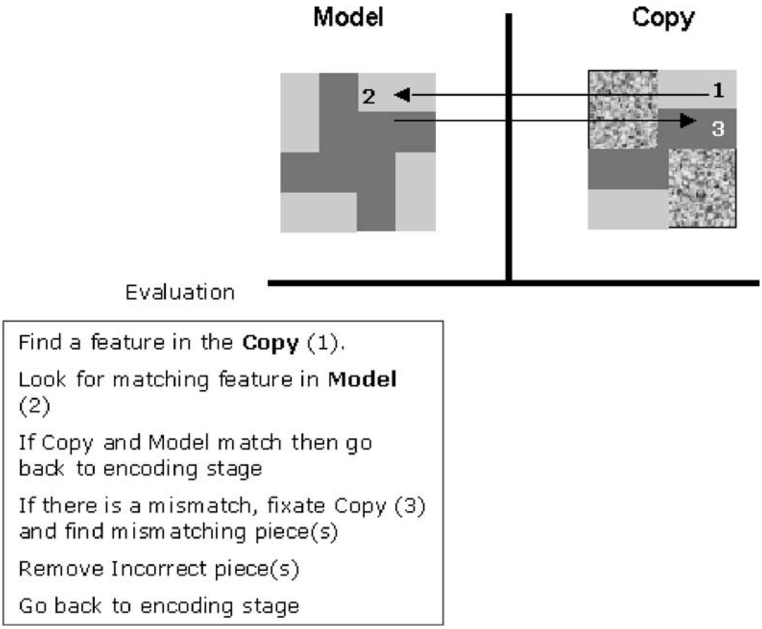

Fig. 1. (*continued*)

and neuroscientists: Individuals with WS have a unique profile of profound spatial deficit together with relatively spared language capacities (Bellugi, Bihrle, Neville, Doherty, & Jerigan, 1992; Bellugi, Wang, & Jernigan, 1994; Mervis et al., 1999). The syndrome is caused by a hemizygous submicroscopic deletion of chromosome 7q11.23; this region includes, roughly, 20 genes, including the gene for elastin (ELN) and the protein LIMK1 (Bellugi, Lichtenberger, Jones, Lai, & St George, 2000; Frangiskakis et al., 1996). The latter gene may be implicated in the spatial disorder, as it is strongly expressed pre- and post-natally in the brain, whereas ELN is not (Frangiskakis et al., 1996). Diagnosis is made through phenotypic characteristics and/or the FISH blood test, which can detect the relevant deletion (Morris et al., 1994).

The spatial deficit in Williams syndrome has been documented using a range of standardized visual–spatial construction tasks, in which people are given an existing pattern to replicate, either by drawing (e.g., the test of Visual-Motor Integration or VMI, Beery & Buktenica, 1967) or by assembling blocks (e.g., the Differential Ability Scales or DAS, Elliott, 1990; WAIS-R; Wechsler, 1981; see Fig. 1 for an example from the DAS). Children and adults with WS find these tasks very difficult to carry out correctly, as do children or adults with right hemisphere brain damage (Akshoomoff et al., 1989; Ivry & Robertson, 1998; Schatz, Ballantyne, & Trauner, 2000; Vicari et al., 1998). Adolescents with WS typically perform at a mean age equivalent of 4 years, 8 months, roughly in the first percentile for their age (Bellugi et al., 1992; Mervis et al., 1999). Poor performance by these individuals cannot be attributed solely to motor problems as they can successfully trace designs that they are unable to construct (Bellugi, Bihrle, Marks, & Filley, 1987). Moreover, comprehensive tests of visual functioning (including acuity, stereopsis, and visual field testing) suggest that low-level visual impairments cannot account for the impaired performance in spatial construction tasks (Braddick & Atkinson, 1995). Finally, although individuals with WS are mild to moderately retarded (Mean IQ = 55–60, Mervis et al., 1999), it seems unlikely that low IQ per se is responsible for the WS deficit. Comparably retarded individuals with Down syndrome perform poorly on the block construction task, but not as poorly as individuals with WS, and their pattern of errors is qualitatively different (Bellugi et al., 1992).

What underlies the spatial deficit? The most widely cited hypothesis regarding the cause of these visual construction deficits is that WS subjects are impaired in their ability to carry out "global processing" (Bellugi et al., 1994). This hypothesis is consistent with Bellugi et al.'s (1992) observation that children with WS made different types of errors in the block construction task from those with Down syndrome. They reported that children with WS generally chose the correct parts to use but failed to arrange them correctly such that the global (outline) shape of their solutions often failed to match that of the model. In contrast, children with Down syndrome generally reproduced the global shape of the model but often used incorrect parts. This hypothesis is also consistent with a study showing that individuals with WS tended to reproduce the local elements in "hierarchical" stimuli while failing to preserve the global structure (Bihrle, Bellugi, Delis, & Marks, 1989). For example, when asked to copy a large "D" composed of smaller "M"s, people with WS tended to reproduce the Ms but not the overall (global) shape of the D. This pattern of performance is reminiscent of that found among people with right hemisphere brain damage (Ivry & Robertson, 1998), and suggests the possibility that spatial breakdown in both cases might be due to impaired processing of the global aspects of shape.

However, as Pani, Mervis, and Robinson (1999) pointed out, carrying out construction tasks requires a good deal more than intact global perceptual processing. These tasks are intrinsically slow and sequential, and thus might be associated with impaired performance even if perceptual, "global" processing of the model is intact. Pani et al. provided direct evidence that some aspects of global perceptual processing may be intact in WS subjects by showing that visual grouping mechanisms facilitated search in adults with WS just as they do in normal adults. Moreover, Key, Pani, and Mervis (1998) analyzed error patterns in the block construction task, and showed that for both WS and normally developing children, the most common errors were incorrectly selecting individual parts (i.e., blocks) and placing them in the wrong location in the copy area. Errors in reproducing the "global shape" of the puzzle were rare for both groups of children. These latter two findings contradict those reported by Bellugi et al. (1992) and the reason for the discrepancy is not clear. The results reported here agree with the findings of Key et al. in showing that choosing an incorrect part is a common error for both normal and children.

These results suggest a straightforward hypothesis about spatial breakdown in the block construction task: WS individuals may fail because they have impaired *spatial representations*. Specifically, they may fail because they incorrectly encode: (a) the spatial structure of individual blocks (which typically have internal spatial structure, see Fig. 1) and/or (b) the spatial relationships among blocks, i.e., the relative locations of blocks in the whole pattern. Incorrectly encoding the spatial structure of a block would result in errors selecting candidate blocks to place; and incorrectly encoding the spatial relationships among parts could result in placing a block in the wrong location. Moreover, in most versions of the block task, subjects must segment the puzzle into separate parts that correspond to the kinds of parts available for constructing the copy. As can be seen in Fig. 2, complex puzzles often have a ''natural'' part structure that does not directly map onto the available parts. People must ignore these parts that span multiple blocks in favor of those dictated by the task. Failure to do so could also result in incorrect encoding of the identity and location of parts.

One further hypothesis should be considered, given that the task requires considerable planning and monitoring of one's progress. Poor performance could be due to deficits in the ''executive processes'' that are responsible for establishing subgoals during problem solution and sequencing the procedures to reach them (Anderson

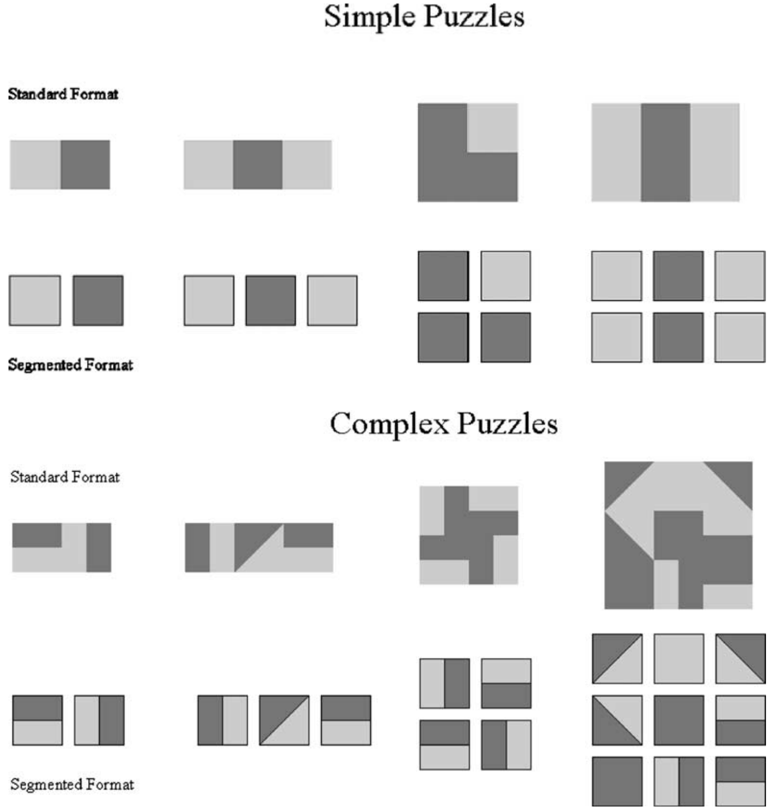

Fig. 2. Examples of simple and complex puzzles used in Experiment 1. Each puzzle was composed of 2, 3, 4, 6, or 9 pieces. Standard and segmented formats are illustrated.

& Lebiere, 1998). In the construction task, a person must: (a) *look* at the model to gain information about its spatial organization, (b) *search* in the parts space for a block that matches one component of that organization, and then (c) *reexamine* the model area to see where to place the block. After dropping the block, a person might also (d) *check* the model to verify that the copy matches it; if a discrepancy is detected, they might decide to (e) *correct* the copy by removing incorrect blocks, and then begin the entire sequence again (see Fig. 1). Successful solution of the puzzle depends on carrying out these procedures at the correct times and in the correct sequence as well as on the accuracy of the representations used in each step. Given that individuals with WS are mild to moderately retarded, it is possible that these executive processes are impaired. This alone could explain severely poor performance on the task.

In normal adults, the executive processes we describe interact with the spatial representations that are required by the task. Ballard et al. (1997) presented an extensive analysis of the subgoals and procedures used by normal adults to solve block construction tasks, based on computational considerations and eye-fixation data. They argued that people do not solve these puzzles by constructing an elaborate spatial representation of the entire model. Rather, they propose that adults solve the puzzle "one block at a time." An example is provided in Fig. 1A. An initial fixation on a block in the *model* results in a representation of the block's "identity"; that is, the person encodes the spatial arrangement of different colors on its face. The fixation also establishes a pointer or index to this block. This pointer does not, by itself, retain any information about the identity or relative location of the block to other blocks but only provides a mechanism for acquiring these properties by guiding fixations to its location. The identity information is then used to search the *parts area* for a match and the corresponding block is picked up. The subject then uses the pointer information to glance back to the same model block in order to retrieve its location relative to other blocks in the model. The part is then dropped into the corresponding location in the *copy area*.

This analysis suggests that normal adults may not need detailed information about the global configuration of the whole model because they have decomposed the copying task into a string of primitive operations concerned with the identity and location of individual parts. Working memory load is minimized through the use of pointers that allow the visual display to act as a kind of external memory or "blackboard," enabling subjects to retrieve relevant information just before it is needed. Ballard et al. confirmed that adults do not construct representations of the global shape of the model in a separate experiment in which they sometimes changed the color of one of the to-be-copied blocks in the model while the subject was fixating elsewhere. Despite having made repeated saccades to the model, subjects were not disrupted by these changes, suggesting that they had learned little about the model as a whole while they were solving the puzzle. However, Ballard et al. also showed that this single-block approach could change if the model and copy area were widely separated. In this case, people tended to store more complex spatial information about the model when examining it, selecting and placing several blocks after each fixation on the model. This kind of interaction between executive processes and spatial representations is probably based on something like a "cost-benefit" analysis of the relative effort in making fixations vs. retaining information in working memory.

Such interaction raises yet another possibility for the WS spatial deficit—faulty spatial representations and executive processes could interact in an unusual fashion. Following Ballard et al.'s analysis, errors in the block construction task could arise from several different sources, and then compound each other. Poor performance could reflect a deficit in the ability to represent the spatial identity and/or location of individual model blocks. Alternatively, poor performance could reflect a deficiency in the control processes that direct fixations to the model, parts, and copy areas. Deficiencies here could result, for example, in the subject placing blocks into the copy area without having gained adequate information from the model. Deficiencies in either process could result in poor performance, and even small deficiencies in both could result in cumulative errors that would result in downward spiraling of performance.

3. The role of eye fixations in separating causes of impairment

How might we separate the two possible sources of error? Adapting Ballard's analysis, we propose to do so by examining the sequence of eye fixations as children carry out the task. Suppose, for example, that WS and control children are comparable in the accuracy of their representations of the identity and location of individual model blocks but that WS children sometimes fail to look at the model prior to a drop. This could occur because of faulty executive processes, which would normally require that a person fixate the model to obtain missing information about the identity or location of a block that is currently being placed in the copy area. In this case, WS and control children should have comparable drop accuracy on those trials in which they have fixated the model prior to a drop. In addition, however, we should observe that the WS children show a lower rate of fixation on the model, and poor accuracy on those trials where they fail to fixate the model.

Faulty executive processes could also come into play after all of the blocks have been placed in the copy. Ballard et al. as well as Lagers-van Haselen, van der Steen, and Frens (2000) found that people sometimes looked back and forth between the model and copy (Fig. 1B), presumably comparing the two patterns. This comparison could proceed in several ways, ranging from a block by block comparison to the use of structural descriptions of emergent shapes in the pattern that span multiple blocks, such as the "L" shape visible in Fig. 1B. Once such a comparison has been completed, the detection of a mismatch between model and copy should be followed by attempts to remove the incorrect parts and replace them with the correct ones.

On the other hand, suppose that WS children have intact executive processes but faulty spatial representations (within blocks and/or between blocks). Then we should see comparable rates of fixation on the model for all groups but lower accuracy for WS subjects even on drops preceded by fixations on the model. That is, the WS children may guide fixations to the relevant regions at the right times, but faulty spatial representations would lead to inaccurate encoding of the spatial identity of individual blocks and/or their location. Such faulty representations would result in failure to either select the appropriate matched block or place it in the correct location in the copy area.

After all the blocks are placed, the child might initiate a check to see whether the model matches their copy. Having checked, the child must now determine whether to make a repair, and if so, how. It is possible that an accurate comparison between model and copy requires the same kinds of spatial representations as the initial process of selecting and placing blocks. If these are faulty, then we should sometimes observe attempted corrections (i.e., removing and/or replacing blocks) when the model and copy *do* match, as well as failure to attempt corrections when the model and copy do *not* match. In cases of attempted correction, the child must begin the process of solution again, by re-coding the identity and locations of individual blocks in the model. As in the first iteration of the solution, faulty spatial representations could again lead to flawed attempts at correction, ultimately resulting in repeatedly erroneous copies that do not improve.

3.1. Summary

A detailed analysis of the block construction task reveals considerable complexity, and therefore, the potential for errors at many steps along the way to solution. However, we have proposed that analyses of the children's eye fixations over the course of the task will allow us to separately examine the possible roles of impaired spatial representations and impaired executive processes. Moreover, it is possible that these will interact in some way, as found by Ballard et al. (1997). In the following experiments, we use this approach to understand how children with Williams syndrome carry out the block construction task and how this might differ from the performance of normally developing children and adults.

4. Experiment 1

In this experiment, we tested children and adults on a full, standard version of the Block Construction task, adapting materials from the Pattern Construction Sub-test of the DAS. We designed a computerized version of the task, in which children could use a mouse to move individual blocks from the parts area to the copy area. We examined their eye fixations while they carried out the task, as well as various key aspects of their performance.

Participants. Participants included 8 children with Williams syndrome (chronological age $M = 9.5$, range from 7.0 to 13.11), 8 normally developing control children (chronological age $M = 5.3$, range from 5.1 to 6.4), and 8 normal adults. Control children were chosen to match children with WS on the basis of mental age as determined by scores on the Kaufman Brief Intelligence Test (KBIT, Kaufman & Kaufman, 1990). The KBIT yields a composite score using two subtests: a Verbal and a

Matrices section. The Verbal section requires children to name line-drawn objects; the Matrices section requires them to solve simple matching and categorization problems, and is considered the "nonverbal" section. The Matrices component relies very little on spatial items, hence it does not penalize the children with WS for their spatial disorder. WS children were individually matched to the control children using the raw scores on the KBIT subtests (average scores for WS group: verbal $M = 31$, matrices $M = 19$ with a standardized IQ = 78; average scores for control children: verbal $M = 29$, matrices $M = 22$ with a standardized IQ = 114). In addition, both groups of children were given the Pattern Construction sub-test of the Differential Ability Scales (Elliott, 1990), which is the hallmark task used to diagnose their spatial disorder. Children with WS had a mean ability score of $M = 81.63$ (range = 55–101, $SE = 5.63$) and fell into the 2nd percentile on the block construction sub-task. For the digit span recall portion of the test, they had a mean score of $M = 104$ (range = 90–126, $SE = 3.72$) and fell into the 5th percentile. The control children's score on the block construction portion of the test was $M = 105.67$ (range = 88–117, $SE = 3.52$), which fell into the 47th percentile. On digit span recall, their score was $M = 115.33$ (range = 102–122, $SE = 5.40$), which fell into the 48th percentile. These scores are comparable to those reported in other studies of Williams syndrome (Bellugi et al., 1999; Mervis et al., 1999) and therefore show the documented severe spatial deficit.

Children with WS were recruited with the aid of the Williams Syndrome Association and control children were recruited from local preschools and mothers' groups. Adults were undergraduate students at the University of Delaware who received course credit in an introductory psychology class in the spring of 1999.

Apparatus and stimuli. Stimuli were simple and complex block patterns containing different numbers of blocks. Examples of each puzzle type are shown in Fig. 2. Simple puzzles were composed of blocks having a uniform face color chosen from a set of two colors. Complex puzzles contained a mixture of solid pieces and blocks with patterned faces. Patterned faces were of three types, differing in the orientation of the line dividing the two colors: vertical, horizontal, and diagonal. For each of these types, the position of the colors was reflected across the dividing feature resulting in a total of 10 block types: 2 solids, 2 verticals, 2 horizontals, and 4 diagonals. Examples can be seen in Fig. 2. Each block in the pattern subtended 2.45° visual angle. Puzzles were presented in two formats (shown in Fig. 2): standard and segmented in which blocks were separated by a small space and were surrounded by a border. We included this variable in order to evaluate whether spatial deficits in WS subjects were due to difficulty in segmenting the model (see Mervis et al., 1999).

Patterns were presented on a 19 in. color monitor under the control of a Quantex 350 MHz Pentium III computer. Head position was stabilized by means of a chin rest. Eye tracking was performed using an ISCAN table-mounted eye tracker, which has an average error of 1/2° visual angle. Eye position measures were collected at 60 Hz. These individual samples were subsequently grouped into fixations according to the following rule: three or more consecutive samples occurring within one degree of visual angle were averaged into a single fixation. All analyses of eye movement data were conducted on these fixation measures. A block was considered to be fixated if a fixation occurred within a radius of 1.5° visual angle from the center of the block. Fixations were then classified according to the *area* (Model (M), Parts (P), or Copy (C)) in which a block was fixated.

Procedure. Each session began with calibration of the eye-tracker. Subjects fixated five calibration points on the monitor while the eye tracker recorded their eye position. The experimenter continuously monitored eye tracking during the experiment and recalibrated the subject whenever necessary.

Each subject served in two sessions, each containing 36 trials. Each session used either the segmented or standard puzzles with the order of this variable counterbalanced across subjects. Trials occurred according to the following schedule of puzzle type–puzzle size (number of trials): Simple-2 (3), Complex-2 (5), Simple-3 (3), Complex-3 (5), Simple-4 (5), Complex-4 (5), Simple-6 (5), Complex-9 (5). Most (24/36) of the puzzles were direct copies of items from the DAS Pattern Construction Test. Additional Simple puzzles were created to provide a good sample of the children's ability in these contexts, as well as to allow them to experience a reasonable degree of success over the total range of problems. Examples of the various puzzle types are shown in Fig. 2.

Subjects initiated each trial by clicking on an icon at the center of the computer monitor. A model then appeared in the upper-left portion of the screen along with a set of parts on the bottom. A copy area with placeholders was located in the upper-right (see Fig. 1). All of the parts in the parts area were required to complete the copy and they were arranged in a random order in the parts area. Subjects used the mouse to choose a part and drag it into the copy. When the part was dropped, it automatically "snapped into place" if it was dropped close to the center of one of the placeholders. Subjects were free to remove pieces from the copy and replace them if they made a mistake. When the copy was finished, subjects were given a final opportunity to make any desired corrections. Subjects were given positive feedback after each trial regardless of the accuracy of their copy.

5. Results

5.1. Performance data

Performance on the puzzles was evaluated using two measures: (1) the percentage of individual block placements or "drops" that were correct and (2) percentage of correctly solved puzzles. These measures were entered into a mixed model analysis of variance with group (WS, control children, and adult) as the between-subjects factor and format (segmented vs. standard) as the within-subjects factor. Separate analyses were performed on simple and complex puzzles and included the relevant display sizes (2–6 for simple puzzles, 2–9 for complex puzzles) in each analysis.

5.1.1. Simple puzzles

First consider drop accuracy for the simple puzzles, shown in Table 1. All three groups were close to ceiling with these puzzles (with the possible exception of the

Table 1
Percent correct drops in simple puzzles

Group	Puzzle size			
	2	3	4	6
WS	94	96	89	94
CT	96	98	96	97
AD	100	100	100	100

WS group in puzzle size 4) resulting in no significant main effects or interactions. Obviously, if individual drops were highly accurate, so were completed puzzle solutions. The mean percents of correct puzzles were 94, 98, and 99 for the children with WS, control children, and adults, respectively, which were not significantly different. ($F(2,21) = 2.197$, $p > .13$). The excellent performance of WS subjects on these *simple* puzzles provides an important confirmation that they understood the nature of the task and were able to manipulate the "virtual" blocks on the screen using a mouse without difficulty. Adult controls were also accurate on the Complex puzzles (drop accuracy varied between 93 and 100% and puzzle accuracy was 100% in all conditions). Therefore, the remainder of the analyses of the performance data will concentrate on comparing WS and Control children on Complex puzzles.

5.1.2. Complex puzzles

Fig. 3 shows the percentage of correctly solved complex puzzles as a function of puzzle size for Williams syndrome (WS) and control subjects (CT). Data have been

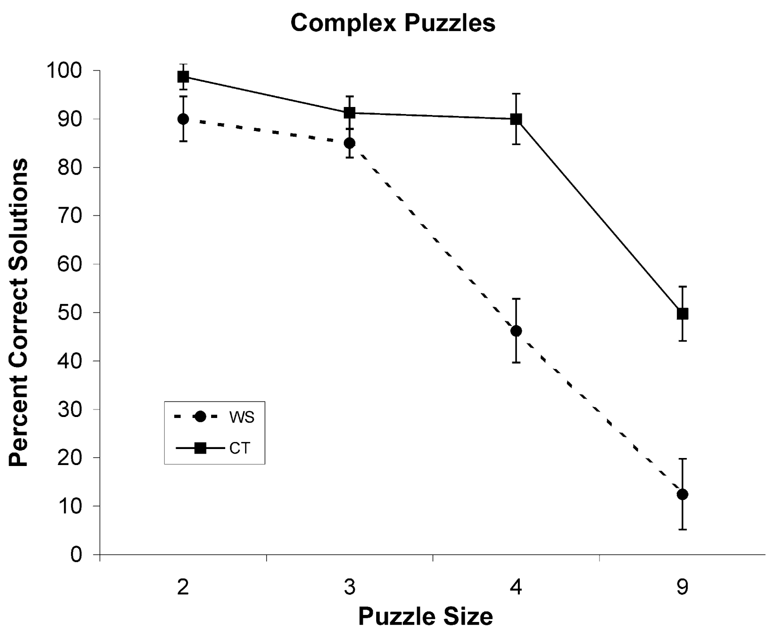

Fig. 3. Percent correct solutions of complex puzzles as a function of puzzle size and group.

averaged over puzzle format (segmented vs. standard). Both groups solved the small puzzles (2 and 3 pieces) accurately but showed a precipitous drop in performance when the number of pieces reached a critical number. For the WS subjects, this critical number occurred at puzzle size four and for controls it occurred with nine pieces in the puzzle, leading to a significant group × puzzle size interaction, $F(3, 42) = 4.33$, $p < .01$. This replicates previous findings showing that WS subjects are severely impaired in solving complex block puzzles containing as few as four pieces (Key et al., 1998).

Looking now at individual drops, Fig. 4 shows the percentage correct as a function of puzzle size for the two groups. Once again, control children are more accurate than children with WS ($F(1, 14) = 6.94$, $p < .02$) and accuracy is reduced with increasing numbers of pieces in the puzzle ($F(3, 42) = 53.3$, $p < .001$). However, the effect of number of pieces is the same for both groups (group × puzzle size interaction, $F < 1$). This contrasts with the significant interaction between group and puzzle size obtained for *puzzle accuracy* (Fig. 3). A comparison of Figs. 3 and 4 suggests that both groups suffer a sudden reduction in the accuracy of individual drops once the number of pieces reaches 4 but that control children are better able to recover from erroneous drops to correctly solve puzzles of this size. The nature of these error recovery processes is considered later in this section.

The children's performance on both the simple and complex puzzles is consistent with that reported by other investigators who have studied standardized tasks, such as the Pattern Construction sub-test of the DAS (e.g., Mervis et al., 1999). In order

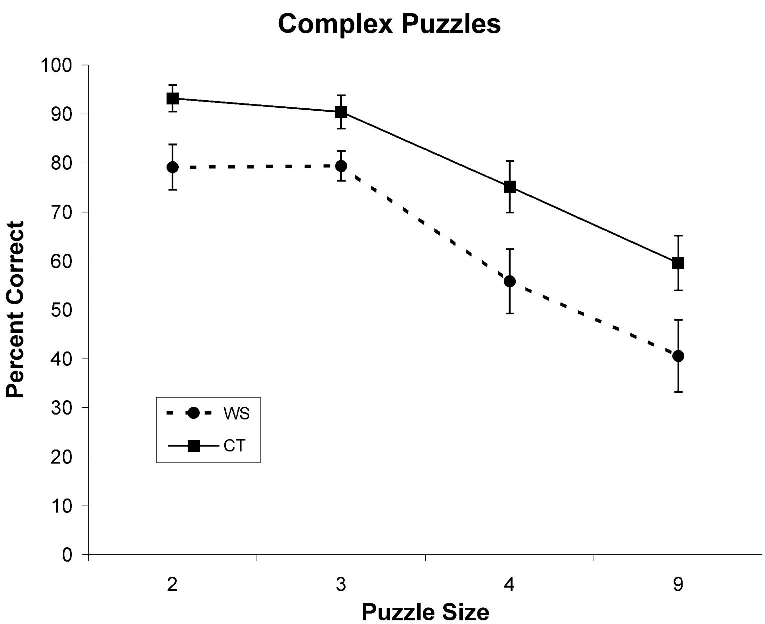

Fig. 4. Percent correctdrop accuracy for complex puzzles as a function of puzzle size and group.

to determine whether our task was tapping into the same deficit as seen in the DAS, we carried out correlations between the children's scores on the DAS and their average performance on complex puzzles in our computerized version of the task. The correlation was 0.70, showing that our version of the task accurately reflected the children's performance on more traditional measures.

5.1.3. Segmentation

We suggested earlier that one potential cause of errors on complex puzzles is a failure to correctly segment the puzzles into relevant pieces. Segmentation might be difficult if children have trouble ignoring the part structure provided by their visual systems in favor of an artificial segmentation demanded by the task. If so, then subjects should have an easier time with the *segmented puzzles* in which each piece is surrounded by a border and separated by a small space from its neighbors. Fig. 5 shows the effect of segmentation on drop accuracy for puzzle sizes 4 and 9. For children with WS, segmentation improved drop accuracy for puzzle size 4 but not 9. For control children, segmenting the model resulted in large accuracy improvements for both puzzle sizes. This pattern led to a significant interaction between group, segmentation, and puzzle size ($F(1, 14) = 7.01, p < .02$). These results suggest that both groups of children found it difficult to ignore the perceptual organization provided by their visual systems in favor of an artificial division into parts based on the design constraints of the puzzle. The lack of a segmentation advantage for WS subjects solving the nine-piece puzzle is surprising but may be due, at least partially, to their relatively low frequency of fixating the model in this condition, as we show below. Tentatively, we can conclude that part of the difficulty that young children (both normal and WS) face in solving block construction puzzles lies in their inability to

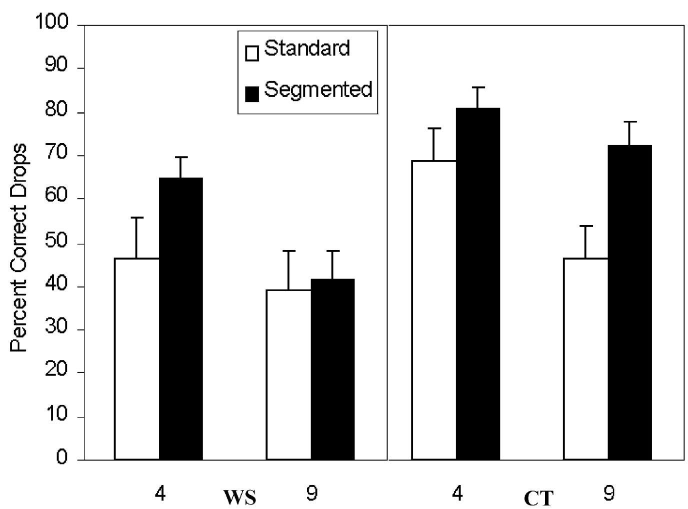

Fig. 5. Percent correct drops for complex puzzles as a function of segmentation style (standard vs. segmented), puzzle size, and group.

ignore the perceptual organization of the puzzle into parts that do not map onto the parts available for construction. This is not the only source of error, however, as both groups continue to make errors even when the model is segmented into appropriate parts.

5.1.4. Summary of performance data

The children with WS were comparable to the normally developing children on Simple puzzles, but substantially worse on Complex puzzles. Their rate of accuracy was lower than controls when they dropped each individual block; but this by itself did not account for their dramatically poorer performance on the complete puzzle solutions. This suggests that some process interacted with the accuracy of individual drops to allow control children to accurately complete more puzzles. This difference is likely to be in the process of error detection and repair, which we discuss more fully later.

5.2. Eye-fixation data

The performance data reviewed above showed that children with WS were less accurate than control children, both in placing individual pieces and in achieving a correct solution. Both groups of children were less accurate than adults. We now turn to an examination of the fixation data in an attempt to get a detailed look at the underlying mental processes that might account for the deficit in performance of WS subjects. Following Ballard et al. (1997), we divided each trial into separate *drop cycles*, defined as the sequence of areas (model, parts, and copy) that were fixated preceding each placement of a block in the copy area. An area was considered fixated if any of the blocks in that area were fixated. Consecutive fixations in the same area (e.g., on different model blocks) were combined into a single *area fixation*. Ballard et al. conducted a similar analysis and reported that the majority of drop cycles (about 90%) included at least one fixation on the model. The remaining drop cycles, which did not contain a model fixation, represent cases in which the identity and location of the block being dropped on cycle n were encoded into memory on drop cycle $n - 1$ or earlier (*memory-guided* drops). If children with WS fixate the model as frequently as controls, it would indicate that they have intact control or executive procedures for guiding the pickup of information required for correct performance. If their patterns of fixation differ from controls, then we will ask whether these differences can account for differences in performance.

5.2.1. Fixating the model

Simple puzzles. Ballard et al. found that the frequency of *memory-guided* drops increased when subjects solved puzzles in which several blocks of the same color could be grouped into a single "chunk" and encoded in a single model fixation. We first asked whether children with WS show similar chunking effects when solving "simple" puzzles. Fig. 6 shows the percentage of drop cycles containing at least one fixation on the model for each group as a function of puzzle complexity (simple or complex). Subjects made fewer model fixations for simple compared to complex puzzles (main effect of puzzle complexity, $F(1,21) = 147.4$, $p < .001$). There was no main effect of Group ($F < 1$) but the Group × Puzzle Complexity interaction ($F(2,21) = 3.43, p < .051$) was marginally significant. A separate analysis of the data from the simple puzzles revealed no main effect of group ($F(2,21) = 1.2$, $p > .3$), suggesting that the size of the "chunks" or clusters of blocks encoded by WS subjects was comparable to those of the other two groups.Thus for simple puzzles, WS children were capable of representing and storing roughly the same amount of spatial information as normal children, and both of these groups were comparable to normal adults.

Complex puzzles. A separate analysis of the complex puzzle data in Fig. 6 revealed no main effect of group ($F(2,21) = 1.38$, $p > .25$) showing that *overall*, the WS children fixated the model about as often as subjects in the other two groups. However, closer inspection of the complex puzzle data shows that the WS children's fixations varied substantially as a function of puzzle size. As can be seen in Fig. 7, for small puzzles (containing 2 or 3 pieces), all three groups fixated the model on between 60 and 70% of the drops. However, for larger (4 or 9 pieces) puzzles, the two control groups slightly increased their fixations on the model while the WS subjects show a precipitous drop in model fixations. This pattern resulted in a significant Group by Puzzle Size Interaction ($F(6,63) = 3.33$, $p < .01$). A separate analysis restricted to the Control and WS subjects also showed a significant interaction between Group and Puzzle Size ($F(3,42) = 5.04, p < .01$). A similar analysis comparing the two control groups (normal children and adults) revealed no main effect of group ($F < 1$) or the group by puzzle size interaction ($F < 1$) which replicates Lagers-van Haselen et al. (2000) who found that normally developing children and adults have similar fixation patterns during the solution of these puzzles.

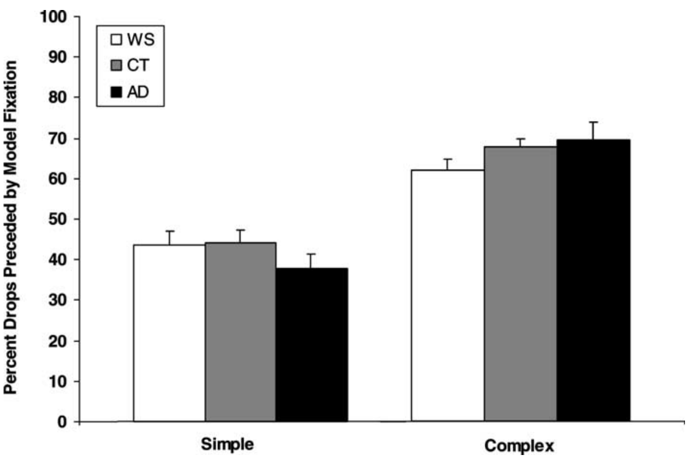

Fig. 6. Percent drop cycles containing at least one fixation on the model as a function of the Puzzle Complexity (Simple or Complex) for each of the three groups (Williams Syndrome children (WS), Control children (CT), and Control Adults (AD).

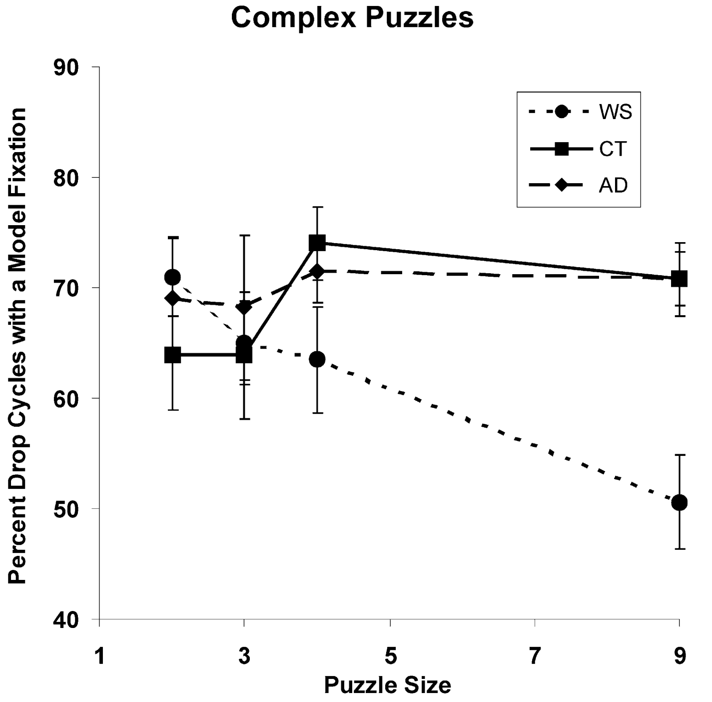

Fig. 7. Percent drop cycles containing at least one fixation on the model as a function of the number of pieces in the puzzle for each of the three groups. Puzzle type is Complex. Note the scales are different for Figs. 6 and 7.

Lower levels of fixation on the model by WS children could be the cause for their impaired performance, if they failed to adequately sample information from the model for difficult puzzles. We investigated this possibility by examining the relationship between drop accuracy and whether the subject fixated the model just prior to that drop. These data are shown in Table 2. There appears to be a relatively small benefit of model fixation on drop accuracy, mainly for the 9 block puzzles. An ANOVA showed a nonsignificant main effect of model fixation ($F(1,14) = 3.49$, $p > .08$) and a marginally significant interaction between model fixation and display size ($F(1,14) = 4.52$, $p < .051$). Separate analyses conducted on data for display sizes 4 and 9 showed a significant effect of model fixation for the 9 block puzzles ($F(1,14) = 8.15$, $p < .01$) but not for four block puzzles ($F < 1$). Apparently, for puzzles with fewer than nine pieces, subjects used information about the structure of the model that was stored in working memory to guide their construction efforts and this was true of WS subjects as well as controls. For nine-piece puzzles, subjects made more errors for drops that were not preceded by a model fixation suggesting that they sometimes placed pieces in the copy without any information in memory to guide them. This is supported by the finding that accuracy for WS subjects in the nine-piece condition was not significantly different than

Table 2
Percent correct drops for Complex puzzles as a function of puzzle size and whether the drop was preceded by a fixation on the model

	Group			
	WS		Controls	
	4	9	4	9
Model fixated	55	45	76	60
Model not fixated	57	35	75	57

chance[1] when they failed to fixate the model ($t(7) = 1.03$, $p > .33$). The relatively small number of model fixations (Fig. 7) coupled with chance performance on these drops suggests that WS subjects, faced with the complex nine-piece puzzles, frequently moved pieces into the copy randomly, without guidance from the model, in hopes of generating correct solutions by chance. This is not an unreasonable strategy when drop accuracy is as low as it is (45%) even with a model fixation.

In sum, the WS children had a normal frequency of model fixations for the simple puzzles and small complex puzzles, but a sharp reduction for larger, complex puzzles. This reduction in fixating the model, does not, however, account for their poorer performance. Even when we restricted our analysis to those trials in which a drop was preceded by a model fixation, WS subjects were still impaired relative to mental age-matched controls (see Table 2). These results suggest that impaired spatial representations are the underlying cause of poor performance by WS children in visuospatial construction tasks. This can be seen most clearly in the following comparison. Even though WS subjects generally fixated the nine-piece models less frequently than the controls, they almost always (95%) glanced at the model before making their first drop. Average drop accuracy on these initial drops was 47%, which is quite close to average drop accuracy on the next eight drop positions (41%) in which they fixated the model on only 48% of the trials. In other words, there does not appear to be a close relationship between a fixation on the model and the likelihood of a correct drop. Accuracy is still low for WS subjects even on those drops that were virtually always preceded by a model fixation. In the discussion, we will suggest that the reduction in model fixations observed for WS children may be a *response* to their low accuracy, rather than a *cause*.

5.2.2. Detecting and repairing errors

In the case of 4-block puzzles, drop accuracy was higher for control children than for WS children (19% advantage seen in Fig. 3), and the controls enjoyed an even

[1] Chance performance was determined by having a computer program randomly choose parts and place them in randomly chosen locations in the copy using the same puzzles and parts that were presented to "real subjects." The simulation was repeated 1000 times to provide stable estimates of chance probabilities. Chance drop accuracy was 31 and 29% correct for complex four- and nine-piece puzzles, respectively.

larger advantage (41% in Fig. 4) in the accuracy of final puzzle solutions. This difference between drop and puzzle accuracy may lie in the greater ability of control children to detect and repair their errors. In order to do these, children would have to: (a) *compare* their copy against the model, (b) *detect* any differences, and (c) *repair* the copy by replacing the incorrect parts with correct ones in order to achieve a correct solution. We analyzed fixation data in order to examine (a) and (b), and we analyzed the child's subsequent movement of pieces (after an error was detected) in order to examine (c).

Comparing copy and model. We estimated the rate at which children compared the model and copy by tabulating how often individual drops were followed by a pattern of fixations indicating that a "copy check" was in progress. We defined "copy check" sequences as any series of fixations between the model and copy areas that did not include a fixation on the part area. We excluded fixations that occurred while a subject was dragging a block from the parts area to the copy because fixations between model and copy during these times may reflect encoding of the part's location (Ballard et al.). An example of a copy check fixation sequence is shown in Fig. 1B.

First, we analyzed how often completed complex puzzles were followed by a copy check. Averaged over puzzle size, WS, MA-matched controls, and adults checked their solutions 61, 60, and 64% of the time, respectively, which were not significantly different ($F < 1$). In addition, there was no Group × Puzzle Size Interaction ($F < 1$). Therefore, it appears that all three groups inspected their final solutions at about the same rate for different size puzzles.

Next, we examined copy checks that occurred *during* the solution process (i.e., excluding those that followed the final drop) and these data are shown in Fig. 8. Note that both adults and control children increase the rate at which they check their partial solutions as puzzle size increases from 4 to 9. WS subjects, in contrast, show a slight decline in copy checks when faced with the most difficult puzzle. This pattern resulted in a significant Group by Puzzle Size interaction ($F(6, 63) = 4.32$, $p < .001$). Separate analyses showed that the significant Group × Puzzle Size interaction still held for each pair-wise comparison between groups—when comparing the WS and Control subjects ($F(3, 42) = 3.62$, $p < .02$), the WS and Adults ($F(3, 42) = 4.39$, $p < .01$), and the Controls and Adults ($F(3, 42) = 5.15$, $p < .01$).

Overall, these data indicate that both WS and control children check their intermediate puzzle solutions more often than adults, particularly as puzzle size increases. In a sense, this is not surprising, because the children are error prone in placing their blocks and must rely on frequent checks in order to detect and repair their errors. What *is* surprising is that the WS children check their puzzles *less* often than control children, even though they are considerably more likely to make incorrect drops. Together with the fact that they fixate the model less often than controls for four- and nine-piece puzzles (Fig. 7), these data reinforce our impression that the WS children often attempted to solve the 9-block puzzles by rapidly moving pieces into the copy and then checking to see if their solution matched the model.

Detecting differences between copy and model. Given that a person has checked his/her copy, how often were attempted repairs determined by the accuracy of the copy? This question speaks to the issue of whether subjects can accurately compare their

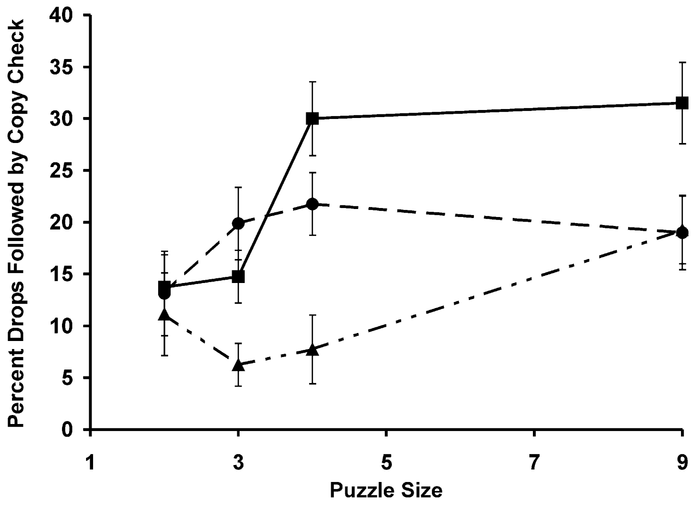

Fig. 8. Percent drop cycles followed by a copy check fixation sequence as a function of puzzle size for each of the three groups. Puzzle type is Complex.

solutions to the model. In order to answer this question, we examined the circumstances under which the children began a repair sequence. (Adults were excluded from this analysis because their rates of repair were too low to provide a meaningful analysis.) We examined the fixation data for "copy check" sequences and noted whether the copy was correct as well as whether subjects subsequently initiated error correction by removing blocks from the copy. If the children with WS were impaired in their basis for making a correction (due either to faulty executive processes, or impaired perceptual matching), then we would expect them to (incorrectly) make changes to correct copies and (incorrectly) fail to make changes to incorrect copies. In addition, children with WS might be impaired at the error correction process itself and thereby remove correct as well as incorrect pieces from the copy.

Table 3 shows how often a piece was removed from a copy that was correct or incorrect at the time of the copy-check. Both groups rarely attempted to repair correct copies and these small rates were not significantly different ($F(1,14) = 2.44$, $p > .13$). When the copy was incorrect at the time of the copy check, controls were more likely to begin a repair sequence although this difference was not quite significant ($F(1,14) = 4.09$, $p < .07$). If we consider the repair of an incorrect puzzle as a

Table 3
Percent of trials in which a repair was attempted after a comparison of model and copy contingent on whether the copy was correct or incorrect

	Group	
	WS	Controls
Copy correct	2	5
Copy incorrect	37	50

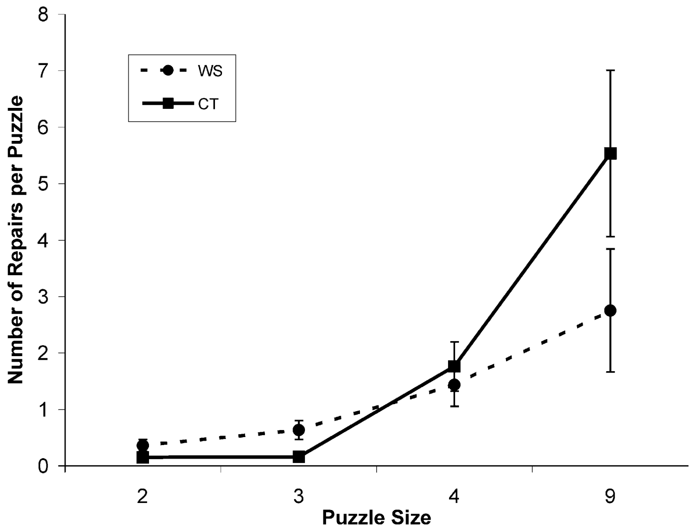

Fig. 9. Average number of pieces removed from the copy per trial as a function of Puzzle Size for Ws and CT groups. Puzzle type is Complex.

"hit" and the repair of a correct puzzle as a "false alarm" then we can apply signal detection theory to the average data in Table 3. These average values correspond to a d' of 1.66 for WS subjects vs. 1.65 for Controls, which is consistent with the claim that the two groups are similar in their ability to "detect" incorrect puzzles with controls having a lower criterion for initiating repairs.[2]

We also looked at *all* repairs of complex puzzles, regardless of whether they were preceded by a copy check (371 repairs for WS subjects and 520 for control children). For WS subjects, 96% of all repair attempts were directed at incorrect puzzles. The corresponding figure for controls was 92% and these values were not significantly different ($F(1,14) = 2.09$, $p > .16$), suggesting good and comparable discrimination of correct and incorrect copies for both groups. Tentatively, we conclude that both groups are comparable in their ability to determine the accuracy of their partial solutions and that controls may have a lower criterion for making repairs.

Repairing the copy by removing and replacing parts. Although the children were comparable in their *initiation* of error repairs, it is possible that they carried out the repairs quite differently. In our first analysis we looked at the average number of pieces per trial that were removed from the copy as a function of puzzle size and these data are shown in Fig. 9. Both groups are comparable for puzzle sizes 2, 3, and 4 but for puzzle size 9, the controls remove approximately twice as many

[2] Two caveats are in order regarding these conclusions. First, the small false alarm rates shown in Table 3 are difficult to estimate accurately, particularly with the small number of trials available here and second, these are measures of *repairs* and it is possible that a task requiring perceptual *judgements* would yield different results.

Table 4
Observed and corrected percentages of *correct* blocks removed from the copy area during repairs as a function of puzzle size and group

	Group	
	WS	Controls
Observed	21	24
Corrected for chance	66	50

pieces as WS children. This was confirmed by a significant Group × Puzzle Size interaction ($F(3,42) = 6.78$, $p < .001$).

Next, we asked how *selective* the children were when they made corrections. Did they ever erroneously remove *correct* pieces from their copies? Table 4 shows the percentage of removed pieces that were *correct*, averaged over puzzle size for each group (complex puzzles only). It appears that WS children are slightly less likely than controls to erroneously remove a correct piece. However, WS subjects are also less likely to have correct pieces in their puzzle because of their lower drop accuracy. In order to compare the selectivity of the two groups it is necessary to correct for these different a priori probabilities of errors. For each subject, we estimated the probability of removing correct pieces by chance alone, using a computer program that replaced each subject's actual correction with a random choice from the available pieces in the copy area at the time of the correction. This process was repeated 500 times for each repair to get stable estimates of chance performance. We found that WS subjects would remove correct pieces by chance with a probability of 0.35 while the corresponding value for controls was 0.51. These values were then inserted into the formula for guessing correction[3] to get the "true" probabilities of removing correct pieces, also shown in Table 4. An analysis of variance of these values indicated that the two groups were not significantly different ($F(1,14) = 1.93$, $p > .18$). In addition, both groups' scores were significantly above chance performance as indicated by single-sample t tests (WS: $t(7) = 4.79$, $p < .002$; Controls: $t(7) = 6.01$, $p < .001$). So it appears that both groups successfully removed incorrect pieces from their copies at about the same rate and this rate was greater than predicted by random removal of parts. However it is worth noting that although correction rates were above chance, they were also rather unselective as subjects in both groups were as least as likely to remove correct pieces as incorrect pieces, when corrected for guessing (i.e., the values in Table 4 are greater than or equal to 50%).

Once a part was removed from the copy, how often was it correctly placed back in the puzzle? Fig. 10 shows the percentages of pieces removed from the copy area that were later placed back into the copy in a correct location. For comparison, Fig. 10 also shows the percent correct for "regular drops." Controls were more accurate than WS children ($F(1,14) = 5.14$, $p < .05$). There is also a small advantage (4.4%) for regular drops relative to repairs ($F(1,14) = 9.64$, $p < .01$). However, this effect did not interact with puzzle size ($F < 1$) or Group ($F(1,14) = 1.11$, $p > .3$).

[3] $P_{\text{corrected}} = (P_{\text{observed}} - g)/(1 - g)$, where g is the probability of a correct guess.

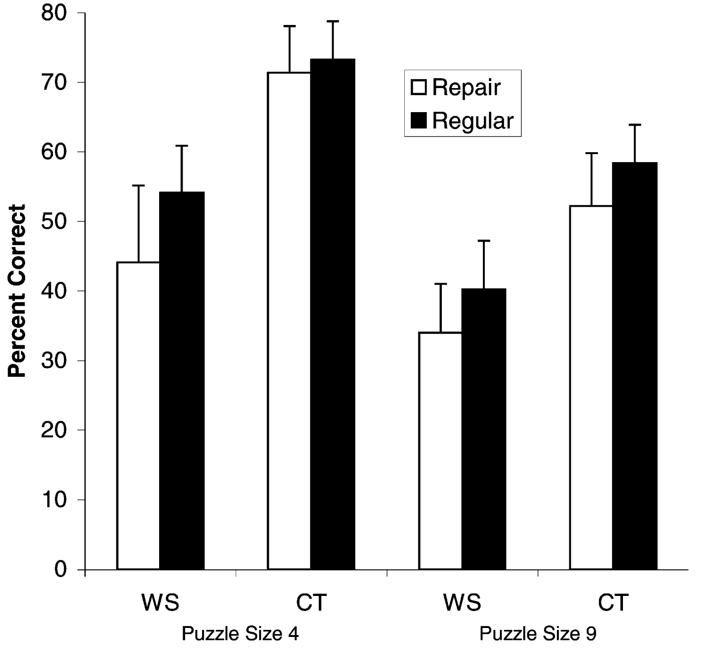

Fig. 10. Percent correct repairs and regular drops as a function of Puzzle Size and Group. Puzzle type is Complex.

The small disadvantage for repairs compared to regular drops may simply reflect the fact that errors, and their associated repairs, may be tied to particularly difficult parts of the puzzle.

The relatively small magnitude of the effect and its additivity with Puzzle Size and Group suggest that repairs are controlled by the same mechanisms as any other drop. Children do not appear to correct their puzzles using procedures that are tuned to transferring incorrect parts to their correct locations. Instead, once an incorrect copy is detected, subjects remove blocks somewhat unselectively, including about as many correct blocks as incorrect ones (when corrected for chance, see above). Once these blocks are out of the copy area, they are treated similarly to other parts that have not yet been placed in the copy. Notice that this is a strategy that appears to place minimum demands on working memory. Subjects do not need to keep track of which part was removed or its former location. Access to the model provides the necessary (albeit "noisy") information for placing the removed block back into the copy area.

5.2.3. Summary of eye-fixation data

Overall,children with WS fixated simple and small (less than four pieces) complex models as often as normally developing children and adults reflecting a similar approach to sampling data from the model to guide the selection and placement of parts. They also showed comparable "chunking" of pieces (evidenced by reduction in fixation for simple puzzles), indicating that that their perceptual organization of the model into parts was preserved. There were substantial similarities between the WS and control children on other measures as well. For example, both groups of children checked their finished copies at the same rate, were highly accurate in determining whether their copy was right or wrong (and hence required repairs), and reinserted pieces with roughly the same accuracy as they originally had. The main differences between the children appeared to be the WS children's: (a) reduced fixation of the model for complex puzzles with many pieces, (b) reduced numbers of checks of their copy against the model while they were carrying out their puzzle solution, and (c) lower number of repairs directed at the most difficult puzzles.

6. Discussion

We distinguished between two broad classes of processes that are important to success in block construction: *Executive processes*, which sequence the gathering of information from the model, the search of the parts area, the placing of parts in the copy, and the initiation of error–repair sequences, and *spatial representational processes* which extract and store the identity and locations of individual blocks. The bulk of the evidence suggests that the root of the WS deficit lies in faulty spatial representations, not faulty executive processes. However, it also appears that the deficits in representation influence how intact executive processes are deployed.

Intact executive processes are suggested by the following findings. First, children with WS were comparable to normally developing children in solving simple puzzles. Solving these simple puzzles requires many of the same executive processes as solving complex puzzles. However, they are simpler in their spatial representational requirements—segmenting the puzzle, and representing the identity and location of individual blocks should be easier than for complex puzzles. Second, an examination of eye fixations on different areas of the puzzle space revealed that for complex puzzles containing three or fewer blocks, children with WS fixated the model at about the same rate as control children and adults. In addition, all three groups were similar in the way in which they reduced their fixations on the model for simple puzzles, which allow blocks to be grouped into chunks. Thus, children with WS appear to be capable of grouping multiple model blocks into a single chunk and they can accurately "unpack" these chunks into a series of block placements based on a single model fixation.

These observations suggest that children with WS possess the "executive routines" required for solution of block puzzles in general, and that they approach the encoding, search, and drop processes illustrated in Fig. 1 in a manner similar to that of normal children. Further, it seems unlikely that their deficit is due to "motor" or "action" errors that would cause blocks to be accidentally dropped into incorrect copy locations, since these errors would be expected to lower accuracy for simple puzzles as well.

We did find a marked *decrease* in fixations on the model for WS children when complex puzzles contained more than three pieces and this was accompanied by a decrease in drop accuracy. These same puzzles elicited an *increase* in model fixations in the two control groups. However, it does not appear that these lower fixation rates are responsible for lower drop accuracy in WS subjects. Their drop accuracy was approximately the same regardless of whether or not they fixated the model and was near chance even on the first drop of each problem, which was preceded by a model fixation on 95% of the trials. Similarly, control children fixated the model at least as often as the adults but had much lower drop accuracy. We speculate that the cause of errors in both groups of children lies in faulty representations of the spatial arrangements of parts within blocks and the relative location of blocks within the puzzle (Key et al., 1998) and we evaluate this possibility more directly in Experiment 2. Our conjecture is that the different fixation patterns observed for the two groups of children represent different strategies designed to cope with these faulty representations. Normally developing children fixate the model repeatedly, presumably in a continual attempt to gather information to solve the puzzle. In the case of WS children, their generally low accuracy of drops may dictate a strategy of moving pieces into the copy area in a more or less random fashion in the hope of sometimes producing a correct solution.

Inaccuracy in dropping individual blocks does not, however, account for the striking impairment in *solving* puzzles that was observed in the children with WS. Mental age-matched controls achieved 90% accuracy in solving the Complex four-piece puzzles with a drop accuracy of 71%. In contrast, children with WS solved 45% of these puzzles with 53% drop accuracy. What accounts for this disproportionately large difference in the accuracy of final puzzle solutions? The answer appears to lie partly in the nature of correction procedures responsible for detecting and repairing errors. Both groups of children checked their *final* solutions at the same rate. However, controls were more likely than WS children to check their *partial* solutions and were more likely to initiate repairs, particularly for the largest puzzle (in which they made twice as many repair attempts). The two groups appeared to be roughly comparable in their ability to *detect* an error in their copy and both groups tended to remove both correct and incorrect pieces from their copies. Pieces removed from the copy were subsequently placed back into the copy with approximately the same accuracy as any other drop, which confers an advantage on the control group because of their higher drop accuracy. The greater puzzle accuracy obtained by control subjects then appears to be due to a combination of factors. Controls are more accurate in their drops, they check their partial solutions more often, and when they detect an error they are more likely to initiate a repair. Their repairs are more likely to be accurate because removed pieces are placed back into the copy with the same accuracy as other pieces.

In summary, we conjecture that the block construction deficit associated with Williams syndrome is due to several factors. The lower drop accuracy appears to be due to deficits in the spatial representations responsible for encoding the identity and/or location of individual blocks. In addition, WS children are less likely to check their copies against the model during the process of solution, and less likely to remove puzzle pieces in order to repair the puzzle. We emphasize that the differences in copy checking and error repair were observed for the complex puzzles only, suggesting that these executive processes change in response to the difficulty of the puzzle—i.e., its spatial structure.

7. Experiment 2

In this experiment, we tested children's capacity to represent identity and location while reducing the executive processes that would be required to solve the whole puzzle. If we are correct in assuming that faulty spatial representations are responsible for the WS spatial deficit, then similar deficits should be observed in these experiments. In Experiment 2A, we evaluated children's ability to encode the *identity* of a single cued block in the model and find the matching block in the parts area. In Experiment 2B, we evaluated the children's ability to move a single block in the parts area to a *location* in the copy corresponding to a cued block in the model. Finally, performance measures from these two experiments were combined to determine whether they could account for the drop accuracy observed in Experiment 1.

Participants. The same children that served in Experiment 1 also participated in Experiment 2. A new sample of adult control subjects was recruited from University of Delaware students enrolled in an introductory psychology class. Children participated in Experiment 2 within a several week period following Experiment 1.

7.1. Experiment 2A: Block matching

Design and materials. This experiment examined a factorial combination of the following factors: group (WS children, control children, and adult), segmentation type (standard vs. segmented), puzzle size (4 or 9), and type of cued block (solid, vertical, horizontal, or diagonal). Group was a between-subjects variable; all others were within-subject.

Each subject completed two blocks of 32 trials, one block for each of the two segmentation types. Blocks were administered on different days and their order was counterbalanced across subjects in each group. Within blocks, subjects received 16 four-piece puzzles followed by 16 nine-piece puzzles. Each model was a complex type (see Fig. 2) composed of blocks from the following categories: solid, horizontal, vertical, and diagonal. For each subject, all the models used the same pair of colors and the particular color pair was chosen from eight possible sets. Color sets were assigned randomly to subjects with the constraint that each of the color pairs was used once for the subjects in each group. Blocks were cued with a small (0.5° visual angle), opaque pink disk that appeared directly in the center of the block.

The models chosen were drawn from those used in Experiment 1. The subject was presented with a screen that had the same basic layout used in Experiment 1 with the following exceptions. One of the blocks in each model contained a solid pink disk (the cue) located in its center and the parts area contained all 10 of the blocks that could appear in any of the models.

Procedure. Subjects were instructed to initiate a trial by clicking on a start button located in the center of the screen. The model appeared (with one of the blocks cued) along with all 10 parts. The subject's task was to click on the block in the parts area that matched the cued block in the model. Positive feedback was provided at the end of each trial regardless of the accuracy of the subject's response.

Results. A $3 \times 2 \times 2 \times 4$ mixed-model ANOVA (Group by Segmentation type by Puzzle size by Cued Block-type) was conducted to analyze the data. There was a significant between-group effect ($F(2, 21) = 23.85$, $p < .001$). The adults were significantly better than the WS and control children, as determined by Tukey HSD tests ($p < .001$ and $p < .016$, respectively). In addition, control children were more accurate than WS children ($p < .003$). Adult performance was at ceiling and none of the independent variables had significant effects on their performance. Consequently, the remainder of the results section will only consider data from the two groups of children.

Consider first whether any of the independent variables in this experiment *should* have had an effect on matching accuracy. The single block to be matched was clearly marked by a cue that remained visible for the entire trial. If children were able to successfully attend to the cued block, their matching should have been independent of the number of pieces in the puzzle as well as whether the model appeared in a segmented format. On the other hand, if children had trouble attending to just the cued block, they might have made errors in matching, either because they incorrectly segmented the cued block or because they used a nearby block instead. This effect would be compounded by larger puzzle sizes because, on average, each block would have a greater number of immediate neighbors.

The data are shown in Fig. 11 in terms of average accuracy as a function of group (WS children vs. control children), puzzle size (4 or 9 pieces), and segmentation type (standard vs. segmented). Matching was more accurate for segmented puzzles, reflected in a main effect for segmentation, $F(1, 13) = 19.4$, $p < .001$. In addition, there

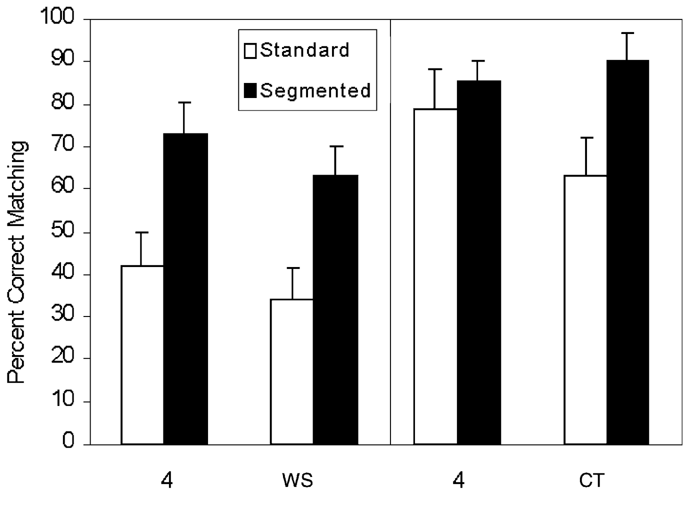

Fig. 11. Percent correct matching in Experiment 2A as a function of puzzle size (4 or 9 pieces), segmentation type (standard vs. segmented) and Group (WS and CT).

was a significant interaction of group, segmentation style, and puzzle size, $F(1,13) = 8.39$, $p < .012$. Separate analyses on the two groups showed that for children with WS, segmentation produced the same accuracy gain for both display sizes (Puzzle size $\times$ Segmentation Type interaction: $F < 1$) while for controls, the segmentation advantage was larger for the nine-piece puzzle ($F(1,7) = 7.99$, $p < .05$). This interaction, however, is probably an artifact of the high performance achieved by control children in the standard 4-block puzzles, which does not leave much room for improvement when the puzzles are segmented. Overall, the effects of segmentation appear to be quite substantial for both groups and indicate that children generally had difficulty restricting their attention to the cued block for the standard puzzles.

The type of block cued in the model also had an effect on performance. A repeated measures analysis of variance revealed a main effect of Block type, $F(3,42) = 14.6$, $p < .001$ showing that solids were the most accurate, horizontals and verticals were intermediate, and diagonals the worst. Block type did not interact with any other independent variables except for one uninterpretable three-way interaction.

In order to see whether children made systematic errors, we classified each error as either "within-category" (e.g., choosing an incorrect diagonal in response to a cued diagonal block) or "between-category" (e.g., choosing a vertical for a diagonal). This analysis excluded the solids because there were very few errors in this category. A pattern of predominantly within-category errors would suggest that the children could represent part of the spatial structure of the block, specifically, that it contained a vertical, diagonal, or horizontal split. A pattern of between-category errors would suggest that this aspect of spatial structure was not represented accurately.

Table 5 shows the percentage of errors, averaged over puzzle size, that were within-category as a function of standard vs. segmented puzzle format for the two groups of children. Note that the a priori probability of a within-category error is only 0.21, so the values in Table 5 indicate that in all conditions, subjects were more likely to make a within-category error than would be expected by chance. An analysis of variance revealed that there were significantly more within-category errors in the segmented format than the standard format ($F(1,14) = 28.5$, $p < .001$). There was no significant effect of Group ($F(1,14) = 2.70$, $p > .12$) or the Group by Format interaction ($F < 1$, n.s.). The increase in within-category errors with segmentation could be accounted for as follows. Suppose that for standard puzzles, subjects sometimes failed to correctly segment the cued block from its neighbors. This kind of error

Table 5
The percentage of errors that were in the same category as the cued item for the matching task of Experiment 2 for Williams Syndrome (WS) and Control (CT) children

Group	Format	
	Standard	Segmented
WS	51	79
CT	67	94

Puzzles were presented in standard or segmented format.

would often lead to between-category errors. For example, two neighboring verticals with mirror image arrangements of their face patterns could lead to a choice of a solid block if they were not segmented correctly. This kind of error becomes less likely when the puzzle is segmented, and consequently, the main source of confusion is other blocks within the same category.[4]

These results clearly indicate that both the children with WS and the normal controls do represent some aspect of the spatial structure of the patterned blocks. That is, they can represent the fact that a block is either solid, or patterned, and, within the patterned blocks, that it has a vertical, horizontal, or diagonal split. Errors principally occur when the representation does not further specify which color is on the top/bottom (for the horizontal blocks), which is on the left/right (for the vertical blocks), or which is on the top right/bottom left, etc. (for the diagonal blocks). The differences in accuracy between the WS and control children (Fig. 11) do not appear to reflect qualitatively different representations of the blocks' spatial structure. Rather, the representations of the WS children may be weaker or more susceptible to noise.

7.2. Experiment 2B: Location

Design, materials, and procedure. Subjects completed the Location Task after finishing the Matching task. The stimuli and equipment were the same as in Experiment 2A except for the following. The parts area contained just a single block that was identical to the cued block in the model. In addition, the copy area on the screen was now visible, showing the locations that could contain a block. Subjects were instructed to move the part into the copy location that corresponded to the cued location in the model.

Results. A $3 \times 2 \times 2 \times 4$ (Group by Segmentation type by Puzzle size by Cued-Block type) mixed-model analysis of variance was carried out to analyze the data. There was a significant main effect for Group ($F(2,21) = 8.318$, $p < .002$). Post hoc analyses (Tukey HSD) showed that children with WS ($M = 78\%$) performed significantly worse than the control children ($M = 97\%$) and the adults ($M = 97\%$). The adults and control children were not significantly different. The remaining analyses will compare the two groups of children.

Percent correct for these two groups on the location task as a function of segmentation type and puzzle size is shown in Fig. 12. Both groups were accurate in the segmented condition but performance fell sharply for the children with WS in the standard condition, particularly for the 9-block puzzles. This was confirmed by a significant three-way interaction of group, segmentation type, and puzzle size ($F(1,14) = 18.8$, $p < .001$). A separate analysis of the segmented condition revealed

[4] Two caveats are in order regarding these conclusions. First, the small false alarm rates shown in Table 5 are difficult to estimate accurately, particularly with the small number of trials available here and second, these are measures of *repairs* and it is possible that a task requiring perceptual *judgments* would yield different results.

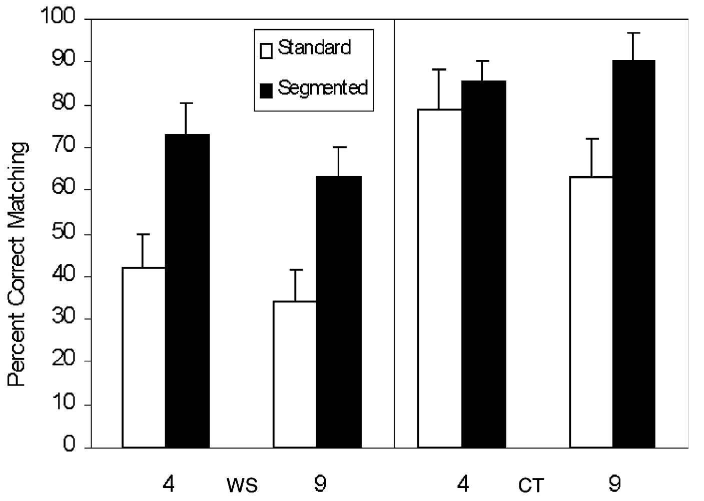

Fig. 12. Percent correct in the Location task as a function of segmentation style, puzzle size, and group.

no significant effects of group or puzzle size. These results suggest that children with WS have difficulty in localizing the cued block when it is presented in the midst of a large, unsegmented model, even when the relevant block is clearly marked by a cue. Experiments 2A and 2B together suggest that the large number of errors observed in Experiment 1 for WS children in the 9-block, standard puzzle is attributable to difficulty in representing both the identity and location of the attended block.

7.3. A simulation model

In Experiment 2, we attempted to separately measure the component processes of identifying and locating a block by studying these processes in isolation from the whole task of block construction. We found that WS subjects were impaired in their ability to represent the identity and location of individual blocks in the model. It is possible, however, that performance on these isolated tasks is considerably better than the corresponding processes when they are embedded in the block construction task. For example, if representing both identity and location information and holding them in working memory is more difficult than representing or holding a single feature, we would expect performance on the whole puzzle to be worse than expected based on performance of the two tasks in isolation.

We evaluated this possibility by attempting to predict group performance on the block construction task using estimates of the probabilities of accurately representing location and identity based on the results of Experiment 2. For each group, the location and identity probabilities for each combination of puzzle size (4 or 9) and segmentation style (standard and segmented) were corrected for guessing to get the probabilities of "knowing" the location and identity of the attended block. These estimates were then inserted into a modification of the computer program we used to estimate chance performance in Experiment 1.

On each trial, the simulated subject was assumed to be in one of two states: "know" or "guess." It was assumed that in the "know" state, location and/or identity were represented correctly. In the "guess" state, these features were chosen at random from the available choices. The probabilities of being in a "know" state for location and identity information were assumed to be independent with a probability given by the parameters estimated from Experiment 2. The program simulated 1000 trials with the actual puzzles used in Experiment 1.

The model predicted eight probabilities: drop accuracy in segmented and standard versions of four- and nine-piece puzzles for WS and control groups. The obtained data consisted of drop accuracies in the corresponding conditions of Experiment 1 restricted to those drop cycles that contained a model fixation. This restriction was employed because eye-tracking measures obtained during Experiment 2 indicated that subjects always fixated the model before making their response. Predicted vs. obtained values are shown in Fig. 13. The solid line represents perfect correspondence between predicted and observed values. Predicted values accounted for 90% of the variance in observed values, which is a reasonably good fit considering there were no free parameters estimated in fitting the model. We take the good fit as evidence that drop accuracy in the block construction task can be accounted for in terms

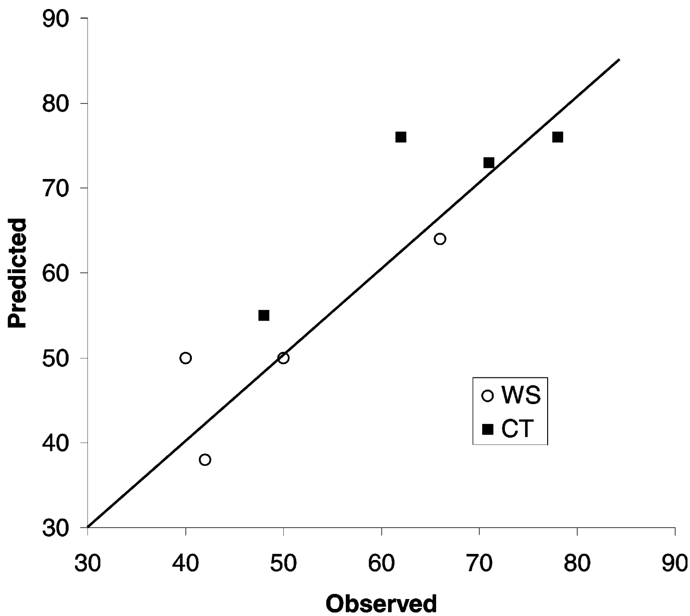

Fig. 13. Predicted and observed values for average performance of children with WS and control children. Each observed point represents group averaged drop accuracy for standard and segmented models containing four and nine pieces observed in Experiment 1. The predicted values are based on estimates of correctly representing the identity and location of individual blocks, obtained from Experiment 2. The diagonal line represents perfect correspondence between model predictions and observed performance. Predicted values accounted for 90% of the variance in observed values.

of independent location and identity processes operating on single blocks in each drop cycle. This conclusion is compatible with the analyses of eye-fixation data presented in this paper as well as that of Ballard et al. (1997).

8. General discussion

In the present set of experiments, we sought to use evidence from eye fixations to gain insight into the nature of spatial breakdown in children with Williams syndrome when they attempt to reconstruct visual patterns. We assumed that it should be possible to separate two distinct sources of breakdown: Impaired *spatial representations* (including the spatial structure of individual blocks and spatial relationships among blocks) and impaired *executive processes* (including sequencing of fixations on the model, and controlling, detecting, and repairing errors). Our findings suggest that these two components can indeed be distinguished using a combination of data from children's overall performance as well as their eye fixations as they carry out this complex task. As in many complex but natural tasks, the two components are intertwined as people solve each puzzle. Our evidence suggests that impaired spatial representations are the root of poor performance in WS. But they also suggest that such impairment interacts with executive processes—and that, in WS, this interaction can contribute to impaired performance. Ultimately, the performance among WS children—and possibly, other spatially impaired individuals—may be caused by the interaction of these two, reflecting the cumulative effects of one facet of spatial cognition on the next.

8.1. Overall performance in the block construction task

In Experiment 1, we examined eye fixations in children as they carried out block construction tasks that were similar to those used in standardized tests such as the DAS. We used simple puzzles in which individual blocks were solid colors arranged in a spatial pattern, and complex puzzles in which the blocks were multi-colored, creating additional internal spatial structure (division along the vertical, horizontal, or diagonal axis). We replicated previous findings showing that children with WS are, overall, impaired on this task relative to mental age-matched controls (see, e.g., Mervis et al., 1999). We also replicated previous findings showing that segmentation of the model–in which each block is surrounded by a border and separated from neighboring blocks—benefited both groups of children. However, the two groups benefited by approximately the same amount, suggesting that segmentation itself does not account for the large difference between groups.

In addition, we found that children with WS were as accurate as controls on the simple puzzles. In Ballard et al.'s (1997) study, normal adults solved puzzles like these by organizing them into a small number of "chunks," selecting and placing multiple blocks at a time, and therefore dramatically reducing the number of model fixations required to move each block (0.7 fixations per drop for simple ones vs. 1.3 for complex ones). In our study, children with WS and normal controls alike fixated the simple models prior to block drops about 33% of the time, compared to 60–70% of the time for the complex puzzles, showing the same reduction in model fixations found by Ballard et al. These results show that children with WS form perceptual groups of similar size to those of control children. In addition, they show that at least under some circumstances, the children with WS are able to code the relative location of pieces and they can make the necessary motor movements required for successful placement of blocks in the copy area. The conclusion that at least some aspects of perceptual organization are intact in WS is consistent with the results of Pani et al. (1999) who found that grouping of display elements had the same effect on visual search in WS and control adults. Importantly for the present study, our results show that many of the basic mechanisms required for solving the block construction puzzle are intact, at least for these simple puzzles.

The story for complex puzzles was quite different. Children with WS were much less accurate than normal controls, both in terms of the accuracy of placing individual blocks and in producing correct puzzle solutions. However, the deficit in *solution accuracy* was particularly dramatic, especially for the larger puzzles. Since neither group of children was at ceiling in their accuracy of placing individual blocks, this dramatic difference in ultimate performance suggests that the control children were more successful at correcting their erroneous puzzles.

8.2. Executive processes: Search for information, detection of errors, and repair

Deficient performance by children with WS was not due to impaired executive processes, at least those that we could evaluate with our methods. First, the deficit was not caused by a failure to fixate the model. For complex puzzles containing two or three pieces, the number of fixations on the model was comparable across both groups of children. Children with WS did make fewer fixations on the model for the two largest complex puzzles (4 and 9 pieces)—a fact we discuss further below—but their accuracy in dropping each block was similar regardless of whether the drop was preceded by a fixation on the model area. This shows that it was not frequency of fixation on the model itself that caused their poorer performance.

Nor was the deficit caused by failures in the other executive processes we considered—either detecting an error, or initiating and carrying out a repair. Both groups were similar in their ability to detect a discrepancy between their copy and the model. This was shown by the fact that children overwhelmingly initiated corrections in cases where there actually were errors in their copies. We could not determine exactly how the children detected these discrepancies. However, recent work by Caplan and Caffery (1992) showed that the capacity to detect a difference between two completed block puzzles was only partially related to the capacity to accurately construct a block puzzle. Given Pani et al.'s (1999) finding of intact global perception among individuals with WS, it seems plausible that the process of successfully detecting errors could be carried out by perceptual mechanisms that differ from those used to select or place individual blocks in the copy.

Both groups were also similar in the nature of their attempts to correct their copies. A surprising pattern emerged here. Children in both groups had approximately the same accuracy in terms of removing correct and incorrect pieces. The process of correction did not appear to be a detailed search for what made the two puzzles different, followed by a thoughtful removal of offenders, but rather, a quasi-random attempt to make the repair. Furthermore, children in both groups placed the removed pieces back into the copy with the same accuracy that they placed other pieces. This meant that, although the WS children were as capable as normal children at detecting an error and initiating a repair by removing blocks, they were less likely to succeed in replacing a block in the correct location. Repeated attempts at correction were therefore repeated failures for the WS children—a fact that they seemed to understand, as they often spontaneously commented that they were "not good at these puzzles."

One difference did emerge. Although both groups of children checked their *final solutions* with the same frequency, the controls checked their *partial solutions* more frequently and were more likely to initiate repairs, particularly for 9-block puzzles. The greater frequency of checking their partial solutions, larger number of repairs, and greater drop accuracy appear sufficient to account for the superior puzzle solving ability of controls.

It could be argued that the WS children's failure to check their partial solutions reflects deficits in the executive processes that should be guiding these attempts. We believe, however, that this is a choice based on a cost-benefit evaluation of the likelihood of success in adopting such a strategy. Given their low drop accuracies and the unselective nature of their repairs (which removed correct blocks as often as incorrect blocks), checking would often reveal that the copy was incorrect with little chance of improvement through repair. WS children often seemed to adopt a strategy of rapidly moving parts into the copy and then checking to see if their completed puzzle matched the model.

These results, obtained from observation of eye fixations during block construction, serve to eliminate several possible explanations for deficits in block construction observed in Williams syndrome. In particular, the following processes appear to be unimpaired in WS relative to controls: "executive processes" responsible for controlling the sampling of information from the various areas of the puzzle, motor processes responsible for placing blocks in the copy, grouping processes that chunk neighboring blocks into higher-level units, and perceptual matching of the copy and model. The main differences between controls and WS subjects appear to lie in the greater accuracy of individual block placements for controls, their greater frequency of checking partial copies, and greater frequency of repair attempts. Of course, given that their drop accuracy for repairs was higher than the WS children's, the controls would naturally make more accurate repairs. The frequency and persistence of repairs helps explain why controls are ultimately able to achieve high accuracy in their final solutions despite the relatively low accuracy of their individual drops.

8.3. Spatial representations: The spatial structure of blocks and their locations

Having found much intact in the executive processes, we can now turn to the possibility that poor performance in the task is due to impaired spatial representations. The lower level of accuracy in block placement in Experiment 1 is consistent with this possibility. Experiments 2A and 2B followed up on this possibility by independently examining the children's capacity to accurately represent: (a) *identity* and (b) *location* of individual blocks. Children with WS were impaired in choosing a part that had the same face design as a cued block in the model. However, all subjects tended to make "within-category" errors; for example, choosing a block with red above green for a cued block that had the opposite arrangement. This suggests that WS subjects generally perceived the orientation of the patterns (horizontal, vertical, or diagonal) but had trouble representing the spatial arrangement of the parts—for example, which colors on the horizontally split block were on the top vs. bottom, or which colors on the vertically split block were right vs. left. Control children, although less error-prone than WS subjects overall, were also more likely to make within-category errors than between-category errors. This finding suggests a similarity in the spatial representations of the WS and control children: They both could represent the *axial* structure of the block (i.e., horizontal, vertical, and diagonal). The difference was in the degree to which the children could also represent *direction* within this structure. Evidence from other studies of spatially impaired individuals suggests that axes (vertical, horizontal) may be encoded separately from direction within an axis (McCloskey & Rapp, 2000). Part of the spatial impairment in WS may reflect less accurate representation of direction, in particular. Errors in the matching task also depended on whether or not the blocks in the model were clearly separated from each other. Segmentation improved performance for both groups, even though the block to-be-matched was clearly indicated by a visual cue, suggesting that subjects were not completely successful in focusing attention on the cued block. Children with WS continued to show failures of attention even in the segmented condition as shown by their poorer performance with increases in the number of model blocks. Like the representation of spatial arrangement of parts, there appears to be a developmental increase in the ability to focus attention on one object among many (Shepp & Barrett, 1991).

Our results do not reveal the reason why children with WS—or normal children—have difficulty in representing the spatial arrangement of parts within an object. One possibility is that WS children have weaker, or noisier representations of direction within an axis. Landau (in press, 2002) reported results consistent with this proposal. They asked WS and normal children to place a dot in locations either "above," "below," "to the left" or "to the right" of a square, and found that both groups of children respected the correct axis for the term (i.e., vertical for above/below, horizontal for left/right) but WS children made more errors in the direction within each axis. Such errors, in which the correct axis is preserved, but the direction within axis is not preserved, have also been reported in the early lexical acquisition of spatial terms by normally developing children (Clark, 1972). Hence fragile representation of direction may be characteristic of very early spatial development, and people with WS may never overcome this fragility.

Another possibility is that the arrangements of color and shape in our blocks may represent an arbitrary conjunction of features, which cannot be easily encoded in the visual–spatial system (Wolfe & Bennett, 1996). Encoding such conjunctions may depend on representational systems, such as language, that can construct propositions composed of symbols and relations. Hermer-Vazquez, Spelke, and Katsnelson (1999) reviewed evidence showing that young children and adult rats are good at reorienting themselves using information about the shape of their environment ("the long wall should be on the left") but have difficulty in conjoining shape and color ("the long wall on the left should be blue"). They suggest that a "geometric module" that only represents shape is responsible for orienting oneself in the environment. In this scheme, children must learn to reliably attach terms such as "left" and "right" to the output of modular systems that compute these relations. Once this mapping has been learned, the child can construct more complex representations such as "the block with red on the left and green on the right". It is precisely this conjoining of shape and color that is required in matching blocks with patterned faces. WS subjects may be developmentally delayed—or permanently impaired—in learning this mapping, and hence perform at developmentally earlier levels than their mental age-matched controls.

In addition to deficits in representing the arrangement of parts within a block, children with WS also made errors in representing the *location* of a cued block in the model, a task that control subjects found easy. This was only the case for large, unsegmented puzzles, however. Separating the puzzle pieces in the model resulted in comparable and accurate performance for both groups. Why does segmentation have such a dramatic impact on the ability of WS subjects to derive a spatial code? One possibility is that segmenting the puzzle makes its row and column structure more apparent (Akshoomoff & Stiles, 1996) leading to a discrete code for each position ("upper left," "lower right," etc). Non-segmented puzzles may lead to a continuous representation of location that can be ambiguous, particularly if the boundaries of the cued block are not apparent. Note that coding the location of the block in the model (which WS subjects can clearly do, at least for segmented puzzles) may appear to be similar to the coding of parts within a block, which poses difficulty for WS subjects, even when the model is segmented. A critical difference, however, may be that coding of block identity involves a *conjunction* of shape and color.

8.4. Williams syndrome and the perception of global structure

We have suggested that WS subjects are similar to controls in their ability to perceptually organize models into component chunks as well as in their ability to detect a mismatch between copy and model. This conclusion is at odds with other research claiming that WS subjects may have impaired representation of configuration causing them to correctly see "parts" but not "wholes" (Bellugi et al., 1992; Deruelle, Mancini, Livel, Casse-Perot, & de Schoon, 1999). For example, Bellugi et al. reported that WS subjects often chose the correct parts but arranged them incorrectly resulting in "broken configurations" in which the outline shape of the copy failed to match that of the model.

We could not evaluate the frequency of these errors in the present experiments because subjects were required to place their parts in a copy area that already contained the correct outline shape of the model. Nonetheless, as we pointed out earlier, Key et al. (1998) carried out a detailed analysis of error types in block construction, and reported that errors involving broken configurations were rare in both the WS and normally developing children in their study. The most common errors involved choosing an incorrect part and placing it in an incorrect location. As Experiment 2 of the present report showed, WS subjects are impaired at both of these operations and their impairments were sufficient to account for their poor performance in block construction.

Following Ballard et al. (1997), we have emphasized that subjects appear to construct their copies by encoding the identity and location of individual parts, not by perceiving and remembering the global shape of the model. This does not mean, however, that there is no role played by "global perceptual processes" (i.e., those that operate on units larger than a single block) in the block construction task. One possibility is that normal people can keep track of those "global" areas of the model that have already been completed, thus making their solution process more efficient. This type of process was evaluated by Hayhoe, Bensinger, and Ballard (1997), who changed the color of selected blocks in the model area during adults' saccades toward the model. When a single block in the model was changed immediately after a drop in the copy area and while the eye was in motion toward the model area, the duration of a subsequent fixation on the model was not significantly different from a no-change control condition. However when several model blocks were changed, the subsequent model fixation was significantly lengthened, indicating that subjects retained and used information about model blocks that were not immediately relevant. Hayhoe et al. suggested that people were using global information about the model to keep track of which areas of the model were already completed, which in turn helped to guide their saccades to the next relevant block. At present, we do not know whether WS subjects are impaired in using this kind of global information to guide their solution progress.

A second possibility is that global information about the model is important in evaluating the accuracy of one's copy. Recall that both WS and control children rarely attempted to modify an accurate copy, suggesting that they were capable of detecting discrepancies between the copy and model even though their correction attempts removed as many correct as incorrect pieces. This suggests that this type of global information is used normally by WS children, and is consistent with other evidence that individuals with WS often appear normal in their sensitivity to configural information in perceptual tasks. For example, Pani et al. (1999) found that adults with Williams syndrome, who remain impaired at construction tasks, show normal sensitivity to configuration in visual search tasks. Similarly, Jordan, Reiss, Hoffman, and Landau (2002) showed that children with WS were as good or better than control children in perceiving biological motion in point light walker displays, a task that requires integration of individual lights into a configuration. These results suggest that individuals with Williams syndrome may be unimpaired in their *perception* of global structure in visual displays and that the spatial deficit revealed in construction tasks may lie elsewhere, perhaps in visual memory (Bellugi et al., 1994). In any case, there remain discrepancies in the literature concerning the ability of WS children to perceptually match global patterns (e.g., Deruelle et al., 1999) and this must remain an open issue at present.

8.5. Interactions of impaired spatial representations with executive processes

Although we have argued that impaired spatial representations are the root of the problem for WS children, we also believe that this impairment has repercussions for the kinds of executive processes that are used. Any impairment we observed in executive processes occurred for the puzzles of greatest complexity: primarily the complex puzzles, and within these, the puzzles with a larger number of pieces. This suggests that the change in executive processes (fewer fixations on the model, reduced checking of partial solutions) was a response to the added complexity of the puzzles. The WS children in our study were painfully aware of their own shortcomings in solving these puzzles. When they were given the more complex puzzles, they frequently (and accurately) predicted that they would fail. This did not stop them from trying, or from initiating and carrying out repairs. But it did appear to alter their strategy. With the simple puzzles, we observed careful checking of their copy against the model, and explicit (and accurate) assessment that they had correctly solved the puzzle. With the complex puzzles, we often observed the children beginning with a fixation or two on the model, followed by rapid placement of the pieces, followed by a check on the model. This was usually followed by explicit (and accurate) assessment that they had failed to solve the puzzle, and initiation of repairs. Thus, the overall strategy of puzzle solution changed rather significantly as the children evaluated their own prospects for success. We observed this same pattern among normal children, although in a much milder form—usually only for the most complex puzzles.

Thus we suggest that executive processes do interact with spatial representations in a quite significant way, with the latter forcing alterations in the former. The combination of impaired spatial representations with altered executive strategies ultimately compound each other: The child has difficulty in encoding the identity and location of blocks in the model and resorts to a quasi-random process of assembling blocks into the copy area, without bothering to check on interim solutions and avoiding fixations on the model which might provide marginal increases in drop accuracy. Thus a spatial impairment leads to a change in executive strategy, which may compound the likelihood of failure.

We are not the first to suggest that such an interaction can be produced by spatial impairment. Walker, Findlay, Young, and Lincoln (1996) reported the case of a man who showed left-sided object-based neglect following a stroke. This neglect was echoed in his eye-movements, as he showed normal saccades to the left of midline, but tended to fixate only the right side of individual objects, including chimaeric objects. However, Walker et al. present evidence that the patient's neglect could not be *explained* by his failure to fixate the left sides of objects. For example, he sometimes fixated the left sides of chimaerics but did not accurately recognize that side; and he did accurately recognize left half faces when they were presented very briefly, showing that his failures could not be accounted for by inadequate fixation of the left side. Walker et al. argued that the patient's tendency to fixate the right side of objects was not a cause of his neglect, but a consequence of it. Impaired spatial representations, at some level in the brain, may result in different patterns of fixation, but these fixation patterns are not themselves the *cause* of the impairment.

Note that the executive processes we have studied correspond to the sequence of eye fixations used to gather information from the model, search the parts area, and check for errors. Obviously, this is not the only kind of executive process that exists, and there are likely other ways in which executive processes and spatial representations can be said to interact—ways which might more directly implicate certain aspects of the spatial impairment in WS.

One such example concerns the executive processes required for visualization and transformation of visual images. Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) found that tests of executive function, such as the Tower of Hanoi puzzle and random number generation, were highly correlated with tests of spatial ability that involve visualization and transformation of visual images. In contrast, the "identical pictures" test, which requires subjects to match a target picture to one of five similar alternatives, had much smaller correlations with tests of executive functioning.

This kind of executive function would appear to entail the controlled activation, maintenance, and transformation of visual–spatial information together with the inhibition of inappropriate automated routines (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kane, Bleckley, Conway, & Engle, 2001). Many of these spatial processes are believed to be carried out in the posterior parietal lobe under control of executive processes operating in prefrontal cortex (Haberecht et al., 2001), and could be responsible for some aspects of the WS deficit—such as the inability to copy figures—which would seem to involve spatial visualization and transformation (Atkinson et al., 2000). At the same time, such processes are not likely to be involved in more automatic perceptual processes, which might explain why WS children are comparable to controls in tasks involving perceptual grouping (Pani et al., 1999), perception of biological motion (Jordan et al., 2002), and the recognition of faces (Wang, Doherty, Rourke, & Bellugi, 1995) and objects (Landau, Hoffman, & Kurz, submitted).

Whatever the complete story of interactions between executive functions and spatial representations, the notion of alterations in one cognitive mechanism dependent upon changes in another mechanism is consistent with current theories of development that emphasize the high degree of interactivity present in the course of development. Several theorists have argued that development consists of a series of cascading processes, in which changes in one system can have major repercussions on the development of other systems (Johnson, 1997; Karmiloff-Smith, 1998; Thelen & Smith, 1994). For example, Thelen and Smith (1994) have shown that changes in body size and weight have major repercussions for the development of motor control, with the former enabling change in the latter. Accepting interactivity does not, of course, mean rejecting the idea that fundamental components of cognition are separable, distinct, and highly structured in their own right (Spelke & Newport, 1998). We have argued that the true root of the problem for individuals with WS is their failure to represent the spatial structure of individual blocks and their locations relative to each other. But this failure—of which they are painfully aware—leads in turn to significant changes in the way they approach the block construction task as it becomes more complex. Therefore, we believe that our findings are an illustration of how specific impairments in one such cognitive system—spatial representation—can lead to changes in the deployment of another cognitive system, ultimately leading to very significant changes in a child's performance.

Acknowledgments

This work was supported in part by Research Grant No. 12-FY-99-670 from the March of Dimes Birth Defects Foundation, SBR-9808585 and SBR-0196314 from the National Science Foundation, and 1 R55 NS37923 from the National Institutes of Neurological Disorders and Stroke. The authors thank Laura Carlson for comments on an earlier draft of this paper and Andrea Zukowski for help with all aspects of this work. We are also grateful to the children who participated in these studies, their parents, and the National Williams Syndrome Association and the Mom's Club of Delaware, who were helpful in identifying participating families.

References

Akshoomoff, N. A., Delis, D. C., & Kiefner, M. G. (1989). Block constructions of chronic alcoholic and unilateral brain-damaged patients: A test of the right hemisphere vulnerability hypothesis of alcoholism. *Archives of Clinical Neuropsychology, 4*(3), 275–281.

Akshoomoff, N. A., & Stiles, J. (1996). The influence of pattern type on children's block design performance. *Journal of the International Neuropsychology Society, 2*(5), 392–402.

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. Mahwah, NJ: Lawrence Erlbaum.

Atkinson, J., Braddick, O., Anker, S., Curran, W., Andrew, R., Braddick, F., & cWattam-Bell, J. (2000). Neurobiological models of visuo-spatial cognition in children with Williams Syndrome: Measures of dorsal-stream and frontal function. Unpublished manuscript.

Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. N. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences, 20*, 723–767.

Beery, K. E., & Buktenica, N. A. (1967). *Developmental test of visual-motor integration*. Cleveland: Modern Curriculum Press.

Behrmann, M. (1999). Spatial reference frames and hemispatial neglect. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (2nd ed., pp. 651–666). Cambridge, MA: MIT Press.

Bellugi, U., Bihrle, A., Marks, S., & Filley, D. (1987). *A dramatic dissociation between language and cognition*. Paper presented at the California Psychological Association, San Diego.

Bellugi, U., Bihrle, A., Neville, H., Doherty, S., & Jerigan, T. L. (1992). Language, cognition, and brain organization in a neurodevelopmental disorder. In M. Gunnar & C. Nelson (Eds.), *Developmental behavioral neuroscience: The Minnesota symposia on child psychology*. Hillside NJ: LEA.

Bellugi, U., Lichtenberger, L., Jones, W., Lai, Z., & St George, M. (2000). The neurocognitive profile of Williams syndrome: A complex pattern of strengths and weaknesses. *Journal of Cognitive Neuroscience, 12*(Suppl. 1), 7–292000.

Bellugi, U., Mills, D., Jernigan, T., Hickock, G., & Galaburda, A. (1999). Linking cognition, brain structure, and brain function in Williams Syndrome. In H. Tager-Flusberg (Ed.), *Neurodevelopmental disorders*, *Developmental cognitive neuroscience* (pp. 111–136). Cambridge, MA: MIT Press.

Bellugi, U., Wang, P. P., & Jernigan, T. L. (1994). Williams Syndrome: An unusual neuropsychological profile. In S. H. Broman & J. Grafman (Eds.), *A typical cognitive deficits in development disorders* (pp. 23–56). Hillside, NJ: Lawrence Erlbaum.

Bihrle, A. M., Bellugi, U., Delis, D., & Marks, S. (1989). Seeing either the forest or the trees: Dissociation in visuospatial processing. *Brain and Cognition, 11*, 37–49.

Braddick, O. J., & Atkinson, J. (1995). Visual and visuo-spatial development in young Williams Syndrome children. *Investigative Ophthalmology and Visual Science, 36*(Suppl.), S954.

Caplan, B., & Caffery, D. (1992). Fractionating block design: Development of a test of visuospatial analysis. *Neuropsychology, 6*(4), 385–394.

Clark, E. (1972). On the child's acquisition of antonyms in two semantic fields. *Journal of Verbal Learning and Verbal Behavior, 11*, 750–758.

Deruelle, J., Mancini, M. O., Livel, M., Casse-Perot, C., & de Schoon, S. (1999). Configural and local processing of faces in children with Williams Syndrome. *Brain and Cognition, 41*, 276–298.

Diamond, A. (1998). Evidence for the importance of dopamine for prefrontal cortex functions early in life. In A. C. Roberts, T. W. Robbins, & L. Weiskrantz (Eds.), *The prefrontal cortex : Executive and cognitive functions* (pp. 144–164). New York: Oxford University Press.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30*(3), 257–303.

Elliott, C. D. (1990). *Differential ability scales*. San Diego, CA: Harcourt, Brace and Jovanovich.

Frangiskakis, J. M., Ewart, A. K., Morris, C. A., Mervis, C. B., Bertrand, J., Robinson, B. F., Klein, B. P., Ensing, G. J., Everett, L. A., Green, E. D., Proeschel, C., Gutkowski, N. J., Noble, M., Atkinson, D. L., Odelberg, S. J., & Keating, M. T. (1996). LIM-kinase1 hemizygosity implicated in impared visuospatial constructive cognition. *Cell, 86*, 59–69.

Haberecht, M. F., Menon, V., Warsofsky, I. S., White, C. D., Dyer-Friedman, J., Glover, G. H., Neely, E. K., & Reiss, A. L. (2001). Functional neuroanatomy of visuo-spatial working memory in Turner syndrome. *Human Brain Mapping, 14*(2), 96–107.

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. S. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive Psychology, 39*, 3–36.

Hayhoe, M. M., Bensinger, D. G., & Ballard, D. H. (1997). Task constraints in visual working memory. *Vision Research, 38*, 125–137.

Ivry, R. B., & Robertson, L. C. (1998). *The two sides of perception*. Cambridge, MA: MIT Press.

Johnson, M. (1997). *Developmental cognitive neuroscience*. Cambridge, MA: Blackwell.

Jordan, H., Reiss, J. E., Hoffman, J. E., & Landau, B. (2002). Intact perception of biological motion in the face of profound spatial deficits: Williams syndrome. *Psychological Science, 13*(2), 162–167.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology. General, 130*(2), 169–183.

Karmiloff-Smith, (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences, 2*(10), 389–398.

Kaufman, A. S., & Kaufman, N. L. (1990). *Kaufman brief intelligence test*. Circle Pines, MN: American Guidance Service.

Key, A. F., Pani, J. R., & Mervis, C. B. (1998). *Visuospatial constructive ability of people with Williams Syndrome*. Paper presented at the Sixth Annual Workshop on Object Perception and Memory, Dallas, TX.

Lagers-van Haselen, G. C., van der Steen, J., & Frens, M. A. (2000). Copying strategies for patterns by children and adults. *Perceptual and Motor Skills, 91*, 603–615.

Landau, B. (in press). Axes and direction in spatial language and spatial cognition. In E. vander Zee, & J. Slack (Eds.), *Representing direction in language and space*. Oxford: Oxford University Press.

Landau, B. (2002). Axial representations in language and cognition: Evidence from children with Williams Syndrome (in preparation).

Landau, B., Hoffman, J. E., Kurz, N. (submitted). Spared object recognition with profound spatial deficits in a genetic disorder.

McCloskey, M., & Rapp, B. (2000). A visually based developmental reading deficit. *Journal of Memory and Language, 43*(2), 157–181.

Mervis, C. B., Morris, C. A., Bertrand, J., & Robinson, B. F. (1999). Williams Syndrome: Findings from an integrated program of research. In H. Tager-Flusberg (Ed.), *Neurodevelopmental disorders. Developmental cognitive neuroscience* (pp. 65–110). Cambridge, MA: MIT Press.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, P. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology. General, 130*(4), 621–640.

Morris, C. A., Ewart, A. K., Sternes, K., Spallone, P., Stock, A. D., Leppert, M., & Keating, M. T. (1994). Williams syndrome: Elastin gene deletions. *American Journal of Human Genetics, 55*(Suppl.), A89.

Pani, J. R., Mervis, C. B., & Robinson, B. F. (1999). Global spatial organization by individuals with Williams syndrome. *Psychological Science, 10*, 453–458.

Rovet, J., & Buchanan, L. (1999). Turner Syndrome: A cognitive neuroscience approach. In H. Tager-Flusberg (Ed.), *Neurodevelopmental disorders: Developmental cognitive neuroscience* (pp. 223–250). Cambridge, MA: MIT Press.

Schatz, A. M., Ballantyne, A. O., & Trauner, D. A. (2000). A hierarchical analysis of block design errors in children with early focal brain damage. *Developmental Neuropsychology, 17*(1), 75–83.

Shepp, B. E., & Barrett, S. E. (1991). The development of perceived structure and attention: Evidence from divided and selective attention tasks. *Journal of Experimental Child Psychology, 51*, 434–458.

Spelke, E. S. & Newport, E. L. (1998). Nativism, empiricism, and the development of knowledge. In R. M. Lerner (Ed.), *Theoretical models of human development* (Vol. 1), W. Damon (Ed.), *Handbook of child psychology* (5th ed.). New York: Wiley.

Stiles, (1998). The effects of early focal brain injury on lateralization of cognitive function. *Current Directions in Psychological Science, 7*(1), 21–25.

Stiles-Davis, J., Kritchevsky, M., & Bellugi, U. (1988). *Spatial cognition: Brain bases and development*. Hillsdale, NJ: Erlbaum.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Vicari, S., Stiles, J., Stern, C., & Resca, A. (1998). Spatial grouping activity in children with early cortical and subcortical lesions. *Developmental Medicine and Child Neurology, 40*, 90–94.

Walker, R., Findlay, J. M., Young, A. W., & Lincoln, N. B. (1996). Saccadic eye movements in object-based neglect. *Cognitive Neuropsychology, 13*, 569–615.

Wang, P., Doherty, S., Rourke, S. B., & Bellugi, U. (1995). Unique profile of visuo-perceptual skills in a genetic syndrome. *Brain and Cognition, 29*, 54–65.

Wechsler, D. (1981). *Weschler adult intelligence—revised*. New York: Psychological Corporation.

Wolfe, J. M., & Bennett, S. C. (1996). Preattentive object files: Shapeless bundles of basic features. *Vision Research, 37*(1), 25–44.