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Implicit Learning in Children and Adults With Williams Syndrome

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In comparison to explicit learning, implicit learning is hypothesized to be a phylogenetically older form of learning that is important in early developmental processes (e.g., natural language acquisition, socialization) and relatively impervious to individual differences in age and IQ. We examined implicit learning in a group of children and adults (9–49 years of age) with Williams syndrome (WS) and in a comparison group of typically developing individuals matched for chronological age. Participants were tested in an artificial-grammar learning paradigm and in a rotor-pursuit task. For both groups, implicit learning was largely independent of age. Both groups showed evidence of implicit learning but the comparison group outperformed the WS group on both tasks. Performance advantages for the comparison group were no longer significant when group differences in working memory or nonverbal intelligence were held constant.

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Williams syndrome (WS) is a genetic disorder caused by a submicroscopic deletion on chromosome 7 (Ewart et al., 1993). WS is typically manifest in mild to moderate retardation with an unusual cognitive profile, which includes relatively preserved language and music skills, which contrast markedly with extremely weak visuospatial and visuomotor skills (Bellugi, Wang, & Jernigan, 1994; Dilts, Morris, & Leonard, 1990; Don, Schellenberg, & Rourke, 1999; Mervis, Morris, Bertrand, & Robinson, 1999; Udwin & Yule, 1990, 1991). Individuals with WS also tend to be extremely sociable and outgoing (Udwin & Yule, 1990).

Researchers have suggested that implicit learning plays a crucial role in the acquisition of linguistic, social, and motor skills, and possibly other skills as well (Gomez & Gerkin, 1999; A. S. Reber, 1992, 1993). In contrast to explicit learning, implicit learning occurs without conscious awareness and is thought to be a phylogenetically older form of learning, which predates consciousness (A. S. Reber, 1992; P. J. Reber & Squire, 1994). Based on this line of reasoning, A. S. Reber (1992; Abrams & Reber, 1988) proposed that implicit learning should show relatively small variations as a function of individual differences in age and maturity and be relatively unaffected by neurological or psychological disorder. Moreover, in contrast to explicit learning, implicit learning should be relatively independent of measures of higher cognitive functioning (i.e., IQ; A. S. Reber, Walkenfeld, & Hernstadt, 1991). If implicit-learning processes are indeed largely invariant to individual differences in age and IQ, then such processes may be relatively preserved in individuals with WS and underlie their relative strengths in language and social skills.

In this study, we assessed implicit learning in individuals with WS and in a comparison group of typically developing individuals matched for chronological age. Our measures were a language-based artificial grammar learning (AGL) task and a visuomotor rotor pursuit (RP) task. The contrast between relatively strong language abilities and weak visuomotor skills in WS invited comparison among the abstract, nonmotor skills assessed by the AGL task, and the visuomotor skills measured in the RP task.

IMPLICIT-LEARNING PARADIGMS

A large variety of testing paradigms, including AGL and RP, have been used to study implicit learning (A. S. Reber, 1993). The ability of individuals with amnesia to perform successfully on these tasks is often considered evidence of their implicit nature (Abrams & Reber, 1988; Corkin, 1968; Sagar, Gabrielli, Sullivan, & Corkin, 1990). Nonetheless, a few tasks thought to assess implicit learning in normal individuals, such as the Hebb supraspan digits tasks, cannot be learned by patients with amnesia (Charness, Milberg, & Alexander, 1988).

Additional discrepancies among tasks suggest that the processes assessed in the various implicit-learning paradigms may be related but dissociable (Kosslyn & Koenig, 1992; Seger, 1994; Squire, Knowlton, & Mussen, 1993).

The AGL task is one of the most widely used measures of implicit learning (for a descriptive summary, see A. S. Reber, 1993). In the typical paradigm, individuals are presented with strings of letters generated from a finite-state grammar such as the one illustrated in Figure 1. In an initial learning phase, participants are familiarized with a set of strings generated from the grammar. In a subsequent testing phase, participants are asked to distinguish between novel strings that follow the rules of the grammar and those that violate the rules. Ability to distinguish grammatical from ungrammatical strings is taken as evidence that participants have learned the rules of the grammar.

Early studies of AGL focused primarily on participants' ability to distinguish grammatical from ungrammatical strings, whereas recent research has focused more on the nature of the learning and the representational form of the information learned (e.g., Altmann, Dienes, & Goode, 1995; Knowlton & Squire, 1994; Manza & Reber, 1997; Servan-Schreiber & Anderson, 1990; Vokey & Brooks, 1992). Some investigators argue that participants' success on AGL tasks does not reflect an implicit abstraction of the underlying grammatical rules, but, rather, explicit knowledge of permissible bigrams and trigrams (referred to as *chunks*) in

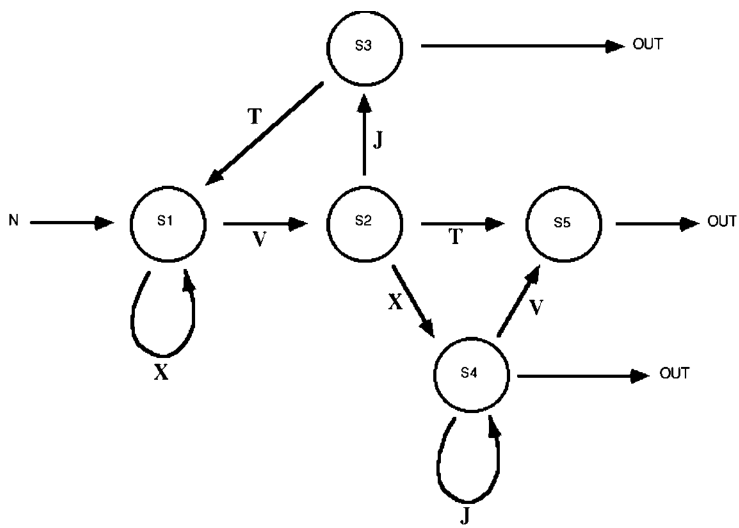

FIGURE 1 Finite-state grammar used by Abrams and Reber (1988). Strings were generated for this experiment by following the arrows from one node to another. Thus, XXVJ and XVTVJ are grammatical strings; XVTJ is ungrammatical.

the test stimuli (Perruchet & Pacteau, 1990). Such knowledge of permissible chunks would be stimulus-specific rather than abstract. Nonetheless, patients with amnesia who were studied by Knowlton, Ramus, and Squire (1992) performed as well as controls on AGL tasks. Because the amnesics had impaired declarative memory for the chunks, explicit knowledge of chunking patterns is unlikely to account for their performance. Moreover, the same patients showed positive transfer to a second AGL task that used an identical grammar instantiated in a new letter set. Again, these findings indicate that the participants' knowledge was not stimulus-specific (Knowlton & Squire, 1994). Normal controls can also transfer a learned artificial grammar across modalities (Altmann et al., 1995) and from one letter set to additional sets (Matthews et al., 1989). This combination of findings provides rather strong support for the proposal that abstract structures (i.e., grammars) are learned implicitly in AGL paradigms.

As with AGL tasks, the RP task has a long history as an implicit-learning paradigm (e.g., Heindel, Butters, & Salmon, 1988). This task requires fine motor and visuomotor skills. Participants are asked to maintain contact between a stylus (a metal pointer) and a target, which is placed near the edge of a horizontally rotating disk. An electric current is established when the stylus is in contact with the rotating target and accumulated contact time is recorded. Over time, performance improves, indicating that learning has occurred. Patients with amnesia demonstrate normal learning on the RP task, which is retained over a delay (e.g., Brooks & Baddeley, 1976; Milner, Corkin, & Teuber, 1968). By contrast, patients with damage to the basal ganglia, such as individuals with Huntington's disease, show impaired learning even after controlling for their baseline motor dysfunction (Heindel et al., 1988). Patients with Parkinson's disease also have basal ganglia pathology and exhibit similar impairment on the RP task (Harrington, Haaland, Yeo, & Marder, 1990), but patients with multiple sclerosis—who have motor impairments not attributable to the basal ganglia—perform normally (Beatty, Goodkin, Monson, & Beatty, 1990). A single neuroimaging study using positron emission tomography also suggests that skilled performance on the RP task depends on the integrity of the basal ganglia (Grafton et al., 1992).

Findings of relatively intact AGL abilities in patients with Parkinson's disease raise the possibility that AGL and RP performance may be dissociable. For example, Meulemans and Van der Linden (1998) reported that immediately after the training phase of their AGL procedure, patients with Parkinson's disease performed as well as controls, although their performance deteriorated to chance levels during the second half of the testing phase. P. J. Reber and Squire (1997) reported more compelling evidence for preserved AGL skills in Parkinson's disease. In their study, participants with Parkinson's disease performed similarly to controls and demonstrated positive transfer to a novel letter set (a new instantiation of the same grammar).

IMPLICIT LEARNING ACROSS DEVELOPMENT AND IN INDIVIDUALS WITH MENTAL RETARDATION

Most studies of implicit learning have been conducted with adults. Although a slight decline in performance is noted in very old adults, implicit learning appears to be remarkably stable across most of adulthood (Curran, 1997; Howard & Howard, 1997; for a review, see A. S. Reber & Allen, 2000). Studies of implicit learning in younger participants indicate that children can learn artificial grammars, but it is uncertain whether their performance matches that of adults. In one study, good AGL performance was evident in children 9 to 11 years of age (Fischer, 1997). In another study, Gomez and Gerkin (1999) used a head-turn preference procedure to assess whether 1-year-old infants could distinguish strings that conformed to an artificial grammar from strings that violated the grammar. Testing was conducted after less than 2 min of exposure to examples of grammatical auditory strings (sequences of nonsense syllables). Infants successfully distinguished between grammatical and ungrammatical strings, and they also transferred their knowledge to a second task in which the same grammar was instantiated in a new vocabulary. Performance could have been influenced, however, by explicit as well as implicit strategies, and the authors did not make any claim about the cognitive strategy used by their infant participants. Nonetheless, other studies with younger infants provide converging evidence of implicit learning in infancy. For example, when presented with structured sequences of nonsense syllables for brief periods of time, 7- and 8-month-old infants subsequently exhibit knowledge of the transitional probabilities between consecutive syllables (Saffran, Aslin, & Newport, 1996) and the grammatical rules that were used to construct the stimulus sequences (Marcus, Vijayan, Rao, & Vishton, 1999). Presumably, such learning in young infants is implicit rather than explicit.

Other studies provide additional support for the idea that implicit-learning abilities are well developed in early childhood and do not vary significantly with increased age. For example, Mecklenbraeuker, Wippich, and Schulz (1998) assessed memory for picture puzzles and found no difference in performance between younger (6–7 years of age) and older (9–10 years of age) children. Meulemans and Van der Linden (1998) found that sequence learning on a serial reaction-time task was equivalent for children (age 6–10) and young adults (age 18–27) and remained equivalent at follow-up 1 week later.

By contrast, Maybery, Taylor, and O'Brien-Malone (1995) observed that performance on an implicit contextual-learning task varied with age but not with IQ. Participants were children from two age groups (5–7 years and 10–12 years) subdivided into three IQ subgroups ranging from the borderline to the superior range. The older children performed at above-chance levels regardless of IQ, whereas the younger groups performed at chance. Another study from the same laboratory examined implicit-learning abilities across an even wider range of IQ (Fletcher, Maybery, & Bennett, 2000). Participants who were diagnosed with mental retardation performed less well on the contextual learning task than did participants with IQ scores in the normal range.

Other studies of individuals with mental retardation have used visual-priming paradigms to assess implicit memory rather than implicit learning. In priming tasks, participants are exposed to stimuli without explicit instructions to memorize the stimuli. Priming is inferred if subsequent identification of the same stimuli (often degraded) is facilitated. Priming can result from a single prior presentation, whereas implicit-learning paradigms involve multiple presentations of the information that is to be learned.

Results from priming studies of individuals with mental retardation are equivocal. In a large-sample study, Wyatt and Connors (1998) found that 6- to 17-year-olds with mental retardation performed similarly to a control group (matched for age) on a visual priming task (picture-fragment completion). In other words, performance on this task appeared to be independent of IQ. Nonetheless, age-related increases in performance were observed for both groups. Similarly, Vicari, Bellucci, and Carlesimo (2000) reported that repetition priming was preserved in 14 individuals with Down syndrome (*M* age = 21 years), who were compared to a control group matched for mental age (*M* chronological age = 5 years). These investigators also administered a simplified version of Nissen's serial reaction-time test (Nissen, Willingham, & Hartman, 1989) and found preserved performance on that task as well. By contrast, Mattson and Reilly (1999) found that mentally retarded children with Down syndrome showed significantly less priming than two control groups (both with higher mean IQ scores), who performed equivalently.

In sum, the existing literature leads to competing hypotheses about the implicit-learning abilities of individuals with WS. On the one hand, A. S. Reber (1992) contended that implicit learning should be robust in the face of neurological disorder. The findings of some investigators that implicit learning is preserved in populations with mental retardation are consistent with this proposal. On the other hand, the basal ganglia appear to subserve some forms of implicit learning, and MRI findings indicate that basal ganglia volumes are diminished in WS (Jernigan, Bellugi, Sowell, Doherty, & Hesselink, 1993). Moreover, other investigations have reported implicit-learning and priming deficits in samples of mentally retarded individuals. In other words, predictions about implicit learning in WS were unclear. Nonetheless, because explicit learning is impaired in WS, we predicted that the comparison group would attend more than the WS group to the chunk strength of the stimuli in the AGL task. Moreover, marked visuospatial and motor impairments in WS led us to expect that implicit learning would be better preserved in the AGL task than in the RP task.

METHOD

Participants

The WS group consisted of 27 individuals (14 male, 13 female) between 9 and 49 years of age (*M* = 23 years, 7 months; *SD* = 13 years, 6 months). The age-matched comparison group consisted of 27 normally developing adolescents and adults (11 male, 16 female), who ranged in age from 9 to 50 years (*M* = 23 years, 7 months; *SD* = 13 years, 4 months). Matching was within 6 months for participants 9 to 13 years of age, within 1 year for 14- to 29-year-olds, and within 2 years for those 30 years and over. Participants with WS were recruited through the local chapter of the Williams Syndrome Association and through national and regional meetings of the same organization. The comparison group consisted of siblings of the WS participants, employees of the institution where the research was conducted, and others recruited by word of mouth. All participants spoke English as their primary language and were without significant sensory or physical handicaps.

Measures

Implicit learning was assessed with an AGL task and an RP task. Short-term memory, working memory, receptive vocabulary, and nonverbal reasoning were also assessed to investigate the relationship between these variables and the implicit-learning measures.

Implicit-learning tasks. For the AGL test, we generated 36 letter strings from the finite-state grammar shown in Figure 1 (Abrams & Reber, 1988). This grammar was used to create 16 training strings and 20 test strings, each of which was two to five letters in length. In addition, 20 ungrammatical letter strings of two to five letters were created. Each ungrammatical string violated the rules of the grammar at only one position in the string, and such violations occurred at all positions. The 20 grammatical and ungrammatical strings were paired by length. Grammatical strings and foils were also paired on the basis of *chunk strength*, a term that refers to the presence of potentially familiar fragments within the strings.

Chunk strength was calculated in the manner of Knowlton and Squire (1996). The 16 training stimuli were examined to determine the frequency with which each possible bigram and trigram appeared across the training set. This frequency parameter has been termed the associative strength of each chunk. Each test stimulus was then examined to determine the number of bigrams and trigrams that appeared in each stimulus. For example, in the stimulus string XXVJ, the bigrams

XX, XV, and VJ appear, as do the trigrams XXV and XVJ. The chunk strength of each stimulus was calculated by averaging the associative strength of all the bigrams and trigrams that it contained. Half of the targets and half of the foil strings were created as high-chunk-strength strings. The other half had low chunk strength. The grammatical high-chunk-strength stimuli had a mean chunk strength of 6.81 (*SD* = 1.13); the low-chunk-strength stimuli averaged 3.60 (*SD* = 0.74). The ungrammatical, high-chunk-strength strength stimuli averaged 6.14 (*SD* = 1.26); the ungrammatical, low-chunk-strength strength stimuli averaged 3.42 (*SD* = .58).

Five pairs of each possible combination of high-chunk-strength and low-chunk-strength targets and foils were included in the set of 20 grammatical/ungrammatical test pairs (i.e., five sets each of high/high, low/low, high/low, or low/high target-foil combinations). The number of letters per string was matched in each pair.

The 16 training strings were printed in large bold letters on 3 × 5-in. cards and decorated with dinosaur stickers to create interest. Participants were shown the complete deck of training stimuli three times (48 training trials in total) in standard order and asked to spell the stimuli (called "dinosaur words") out loud each time. Testing immediately followed training. Test items consisted of 20 pairs of target–foil strings printed the same size as the training stimuli and placed one pair per page. One string was placed at the top of the page; the other was placed at the bottom. The placement of the target and the foil on the page was pseudorandom, with the target never appearing more than four times consecutively in one position. Participants were shown the new words, in pairs, and asked to spell both words out loud. They were then asked to identify the dinosaur word in each pair. This "forced-choice" design is a departure from the more typical classification task that has been used in other AGL studies. The method was modified to minimize yes or no response biases that might occur for individually presented stimuli. The entire block of 20 pairs was repeated immediately after the first block with string placement reversed and page sequence randomized. Thus, participants identified dinosaur words in a total of 40 string pairs. The outcome measure was the number of items answered correctly.

The motor-learning task was a standard RP task. Participants were asked to maintain contact between a stylus and a target on a rotating disk. On each trial, the disk rotated at 30 RPM for 20 sec. Trials were presented in blocks of four, with a rest period of 20 sec between trials. Duration of contact was recorded for each block. Six blocks were completed in a single testing session with a rest of approximately 1 min after blocks 1, 3, and 5 and a rest of about 3 min after blocks 2 and 4. The primary outcome measure was duration-of-contact on the sixth (final) block. We also examined participants' improvement in performance across the six blocks.

Supplementary measures. The Peabody Picture Vocabulary Test–Revised (PPVT–R; Dunn & Dunn, 1981) was used to assess receptive vocabulary. The

Matrices subtest of the Kaufman Brief Intelligence Test (K–BIT; Kaufman & Kaufman, 1990) was used to estimate nonverbal intelligence.

The Number Recall subtest of the Kaufman Assessment Battery for Children (K–ABC; Kaufman & Kaufman, 1983) provided a measure of short-term verbal memory. This subtest requires participants to repeat increasingly longer sequences of digits presented at a rate of one digit per sec. The Spatial Memory subtest from the K–ABC was also included in the testing protocol but the comparison group performed at ceiling levels. Thus, it was excluded from further consideration.

Working memory was assessed with the Counting Span Test, an experimental measure adapted from Case, Kurland, and Goldberg (1982). Participants were shown an array of large blue and yellow dots arranged randomly on a page and asked to touch and count all of the blue dots on a page (e.g., 5). They were then shown another page of blue and yellow dots and again asked to count (beginning at 1) all of the blue dots on the page (e.g., 3). Finally, the participant was shown a page with a question mark and asked to recall the number of blue dots on each page in the order they were presented (e.g., 5, 3). Testing began with a block of five two-page trials. Additional pages were added for subsequent blocks until trials included a maximum of five pages. Testing was terminated when participants failed two or more trials within a block.

Procedure

Participants were tested at their convenience, either in the research laboratory of a children's hospital, at meetings of the Williams Syndrome Association, or at home. Testing took place in a quiet room that was free from distractions. Tasks were administered in a fixed order. Matrices and the RP task were administered first. Number Recall and Spatial Memory were tested during rest periods of the RP task. The final three tests were Counting Span, the AGL task, and PPVT–R. Testing took approximately 75 min to complete. For 1 participant with WS, results from the second half of the AGL task were unavailable because he became fatigued and refused to complete the second half of the task. For 1 participant in the comparison group, RP scores were excluded because of technical difficulties.

RESULTS

Preliminary Analyses

A set of preliminary analyses examined differences between the WS and comparison groups on the raw scores obtained on the supplementary measures.

Descriptive statistics are provided in Table 1. The comparison group performed better than the WS group on each measure, PPVT–R: $t(52) = 3.26$, $p = .002$; Matrices: $t(51) = 10.31$, $p < .001$; Number Recall: $t(52) = 5.41$, $p < .001$; Counting Span: $t(51) = 8.16$, $p < .001$. Whereas group membership accounted for only 17% of the variance (i.e., eta-squared) in PPVT–R scores, it explained at least 36% of the variance in each of the other three measures (Number Recall 36%; Counting Span 57%; Matrices 68%). This pattern is consistent with other results showing that the vocabulary knowledge of individuals with WS is relatively spared compared to their marked impairments in other domains. Indeed, the WS group had higher standard scores on our test of receptive vocabulary (PPVT–R) than on our test of nonverbal reasoning (Matrices), $t(22) = 2.10$, $p = .048$. By contrast, the comparison group performed better on Matrices than on PPVT–R, $t(26) = 2.19$, $p = .038$.

Implicit Learning: Artificial Grammar

Scores on the AGL task represent the total number of correct responses (maximum = 40). Descriptive statistics are provided in Table 2. One-sample *t* tests (one-tailed) were used to compare performance with chance levels (20 correct). The comparison group performed significantly better than chance, $t(26) = 8.39$, $p < .001$, with performance levels (66% correct) similar to that reported in other AGL studies with normal individuals (Knowlton et al., 1992; McAndrews & Moscovitch, 1985; A. S. Reber & Allen, 2000). The WS group was only marginally better than chance, $t(25) = 1.36$, $p = .093$. Whereas 56% of participants in the comparison group (15 of 27) performed significantly better than chance as individuals (binomial test), only 15% did so in the WS group (4 of 26). An independent-samples *t* test confirmed that the difference among groups was reliable,

TABLE 1
Descriptive Statistics for Scores on the Supplementary Measures

	Williams Syndrome Group		*Comparison Group*	
	M	*SD*	*M*	*SD*
PPVT–R: raw score	111.9	28.2	135.8	25.8*
PPVT–R: standard score	73.6	16.0	97.3	18.6*
Matrices: raw score	19.5	4.3	34.0	5.8*
Matrices: standard score	66.2	13.2	103.8	11.5*
Number Recall: raw score	9.3	2.5	13.3	2.9*
Counting Span: raw score	6.4	3.8	14.1	3.0*

Note. PPVT–R = Peabody Picture Vocabulary Test–Revised.
*Williams syndrome and comparison groups significantly different, *p*s < .005.

$t(51) = 4.46$, $p < .001$, accounting for 28% of the variance in the data. This between-group effect size is similar in magnitude to the effect size for PPVT–R and for Number Recall, but significantly smaller than the effect size for Matrices, $z = 3.28$, $p = .001$, and for Counting Span, $z = 2.36$, $p = .018$.

AGL performance in the WS group was investigated further by comparing the first block of 20 trials with the second block. During the first block, 26% of individuals in the WS group (7 of 27) performed significantly better than chance. As a group, performance was better than chance (10 correct) on the first block, $t(25) = 2.87$, $p = .004$, but not on the second block. The decrement in performance from the first to the second block was significant, $t(25) = 2.71$, $p = .012$. In other words, implicit learning was evident among the WS group only for the first half of the AGL procedure. The comparison group exceeded chance levels for the first and second blocks, ts(26) = 8.28 and 5.51, respectively, ps < .001, and outperformed the WS group in both cases, $t(52) = 3.80$ and $t(51) = 3.65$, respectively, ps < .001. The difference among groups accounted for 22% of the variance in the first-block data and for 21% in the second block. Nonetheless, the comparison group also exhibited a significant decrement in performance over time, $t(26) = 2.85$, $p = .008$. Moreover, a 2 × 2 mixed-design analysis of variance (ANOVA) with one within-subjects variable (first vs. second block) and one between-subjects variable (group) did not uncover a two-way interaction, $F < 1$. In short, the comparison group performed better than the WS group throughout the procedure, and the performance of the two groups deteriorated similarly from the first to the second half of the testing protocol.

The next set of analyses investigated the effects of age on AGL performance. Scatterplots are provided in Figure 2. A general linear model with one dichotomous variable (group), one continuous variable (age), and an interaction term (Group × Age) yielded no significant results (Figure 2, top panel); identical null findings were observed when the analysis was limited to the first block (Figure 2, bottom panel). Indeed, tests of simple associations between age and AGL performance revealed correlations that were unlikely to be significant even with much larger samples of participants (WS group: $r = -.091$; comparison group: $r = .118$; groups combined: $r = -.007$; ps > .5). Again, separate analysis of the first block yielded identical results. Because many of the participants in both groups were adults, associations between age and AGL performance could be curvilinear. A rigorous set of tests failed, however, to uncover any nonlinear associations.[1]

The next set of analyses tested whether the comparison group was more sensitive than the WS group to the presence of chunks (i.e., specific reoccurring

[1]Tests of nonlinearity were twofold: (a) We used nonparametric tests (Spearman correlations) to test for monotonic associations of any type and (b) we successively added more and more higher order nonlinear terms to regression equations that were used to analyze the implicit-learning measures (i.e., age, age + age^2, age + age^2 + age^3, and age + age^2 + age^3 + age^4).

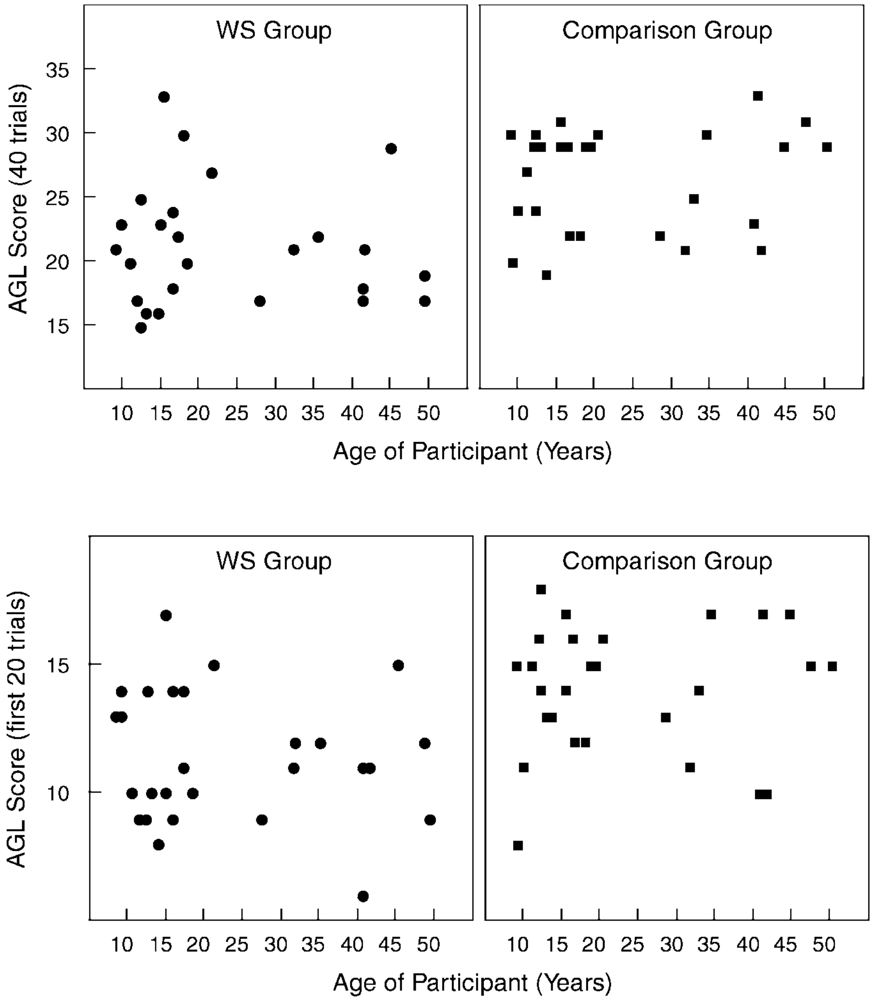

FIGURE 2 Scatterplots illustrating scores on the artificial grammar learning (AGL) task (number correct) as a function of age. The upper panel shows total scores derived from the first and second blocks of trials (maximum score = 40, chance = 20). The lower panel shows scores from the first block (maximum score = 20, chance = 10).

strings of letters) in the AGL targets and foils. A mixed-design 2 × 2 × 2 ANOVA had one between-subjects variable (group) and two within-subjects variables, which represented the chunk strength of the targets (high or low) and the chunk strength of the foils (high or low). In addition to the reported overall advantage for the comparison group, the analysis revealed a significant main effect of the chunk strength of the targets, $F(1, 52) = 10.97$, $p = .002$, with better performance for high-chunk-strength compared to low-chunk-strength targets. By contrast, the decrement in performance for high-chunk-strength compared to low-chunk-strength foils was only marginally significant, $F(1, 52) = 8.96$, $p = .096$. Our prediction of a larger effect of chunk strength for the comparison group over the WS group received partial support. Specifically, the two-way interaction between group and the chunk strength of the targets approached conventional levels of significance, $F(1, 52) = 3.16$, $p = .081$. Moreover, separate analysis of the comparison and WS groups revealed that performance was reliably better with high-chunk-strength compared to low-chunk-strength targets for the comparison group, $F(1, 26) = 15.58$, $p < .001$, but not for the WS group.

To confirm that overall responding on the AGL task did not rely on recognizing familiar strings of letters, we conducted additional analyses of the 20 trials in which the target and the foil items had equal chunk strength. The comparison group performed better than chance (10 correct) in these conditions ($M = 13.52$), $t(26) = 9.68$, $p < .001$ (one-tailed), but the WS group did not ($M = 10.33$). The difference among groups was significant, $t(52) = 4.64$, $p < .001$, and accounted for 29% of the variance in the data. When we examined the 10 equal-chunk trials that occurred during the first block of trials, however, we found that the WS group did indeed perform better than chance (5 correct; $M = 5.67$), $t(26) = 1.88$, $p = .035$.

Additional analyses explored in more detail the differences among groups that we observed on the AGL task. Specifically, a series of four analyses of covariance (ANCOVAs) was conducted, one for each of the supplementary measures. In each case, the independent variable was the group (WS or comparison), the dependent variable was the total number of correct responses, and the covariate was one of the supplementary measures. Because the main effect of group was tested multiple (four) times, we used the Bonferroni multistage procedure (Howell, 1997) to ensure that the alpha level for this family of tests did not rise above .05. Differences among groups on the AGL task remained significant when group differences in receptive vocabulary (as measured by the PPVT–R) were partialed out, $F(1, 50) = 12.80$, corrected $p = .003$, and when differences in Number Recall were held constant, $F(1, 50) = 7.64$, corrected $p = .024$. Between-group differences on the AGL task were no longer significant, however, when Counting Span or Matrices scores were included as covariates.

Implicit Learning: Rotor Pursuit

Scores on the RP task are illustrated in Figure 3 and summarized in Table 2. Initial analysis of our main outcome measure (duration of contact on the final block) uncovered a finding consistent with analyses of the AGL data: The WS group's

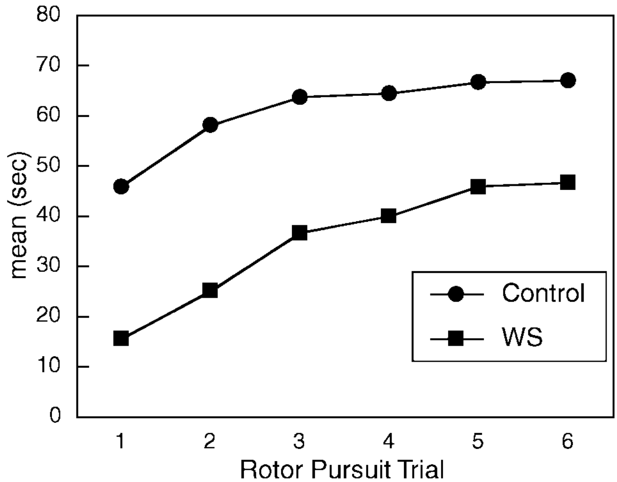

FIGURE 3 Scores (duration of contact) on the six trials of the rotor pursuit task.

TABLE 2
Descriptive Statistics for Scores on the Implicit-Learning Measures

	Williams Syndrome Group			*Comparison Group*		
	M	*SD*	*Range*	*M*	*SD*	*Range*
Artificial grammar learning						
All 40 trials	21.23	4.62	15–33	26.56	4.06	19–33
First block	11.41	2.55	6–17	14.04	2.53	8–18
Second block	9.96	2.72	6–16	12.52	2.38	6–16
Rotor pursuit						
Final (sixth) block (sec)	46.69	17.69	1.46–72.02	66.97	6.56	40.02–75.17
Change (block 6–block 1)	32.29	12.61	–1.69–48.33	21.28	7.52	11.65–38.27

performance was significantly below that of the comparison group, $t(51) = 5.49$, $p < .001$. Between-group differences accounted for 37% of the variance in the data. In contrast to our predictions, this effect size was similar in magnitude to the effect size observed on the AGL task. It was significantly smaller, however, than the between-group effect size reported for our measure of nonverbal intelligence (Matrices), $z = 2.27$, $p = .023$, but no different from the effect sizes reported for our three other supplementary measures.

Improvement in performance across the six RP blocks was examined with a multivariate repeated-measures ANOVA that included one within-subjects factor (blocks 1–6) and one between-subjects factor (group). As shown in the figure, the comparison group outperformed the WS group throughout the procedure, $F(1, 50) = 63.51$,

$p < .001$. Performance also improved across blocks, $F(5, 46) = 66.78, p < .001$, and a significant interaction indicated that the pattern of change differed across groups, $F(5, 46) = 7.58, p < .001$. To investigate the interaction in more detail, a rotor change score was calculated for each participant by subtracting their score on the first block from their score on the final (sixth) block. Whereas duration of contact for the WS group increased, on average, by 32.29 sec from the first to the sixth block ($SD = 12.61$ sec), the comparison group increased by 21.28 sec ($SD = 7.52$ sec). The between-group difference in rotor-change scores was statistically significant, $t(40.8) = 3.82, p < .001$ (separate variances test). As can be seen in the figure, however, the comparison group reached their plateau (near ceiling levels for the test) by the third block, whereas the WS group began their plateau on the fifth block. Moreover, the performance of the WS group plateaued at a level approximately equivalent to the initial level witnessed for the comparison group.

To investigate the association between age and implicit learning on the RP task, we calculated correlations between age and duration of contact on the final RP block (see Figure 4, upper panel). The correlation was not significant for the WS group, the comparison group, or for the groups combined, rs = .122, .165, and .095, respectively, ps > .4.

Analyses of rotor-change scores yielded a slightly different pattern (see Figure 4, lower panel). Whereas change scores of the groups combined and the WS group analyzed separately did not have a reliable association with age, rs = –.177 and .001, respectively, ps > .2, the comparison group exhibited a significant negative correlation, $r = -.586, p = .002$. In other words, younger participants in the comparison group tended to have larger improvements over the six RP blocks than did their older counterparts. Rotor-change scores for younger participants in the comparison group (median split) were still relatively low ($M = 26.60$), however, compared to those of the WS group (see Figure 4, lower panel). Indeed, Figure 4 makes it clear that individual differences in change scores for the comparison group—due to age as well as to other factors—were smaller than they were for the WS group, $F(25, 25) = 2.81, p = .012$ (test of equal variance). Moreover, a linear association between age and performance on the RP task was evident for the comparison group during the first RP block, $r = .487$, $p = .012$, but not for any subsequent blocks. Rigorous investigation of the possibility of nonlinear associations based on age yielded no additional findings (see footnote 1). In sum, the RP data provided partial support for A. S. Reber's (1992) hypothesis that implicit learning is independent of age. The only exception was that the comparison group showed a significant positive association with age on the first of six blocks, and, thus, relatively large improvement from the first to the final block for younger participants.

As with the AGL analyses, the next set of analyses explored further the between-group differences in performance evident on the RP task. Specifically, a series of four ANCOVAs was conducted (Bonferroni-corrected for four tests),

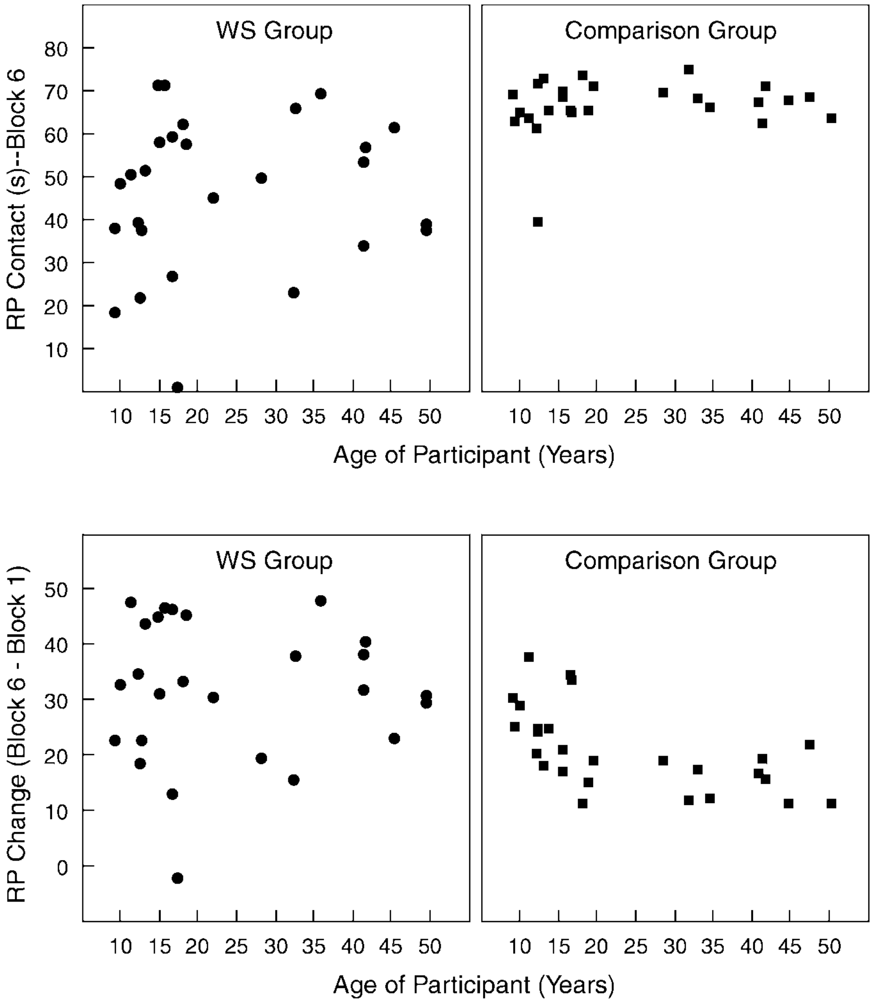

FIGURE 4 Scatterplots illustrating scores (duration of contact) on the rotor pursuit (RP) task as a function of age. The upper panel shows scores on the final (sixth) block. The lower panel shows RP-change scores, which represent improvement from the first to the final block.

with group (WS or comparison) as a between-subjects factor and one of the supplementary measures as a covariate. The outcome variable was the score on the final (sixth) block. In each analysis, our goal was to determine whether the advantage for the comparison group over the WS group would still be evident when group differences on the particular covariate were held constant. As with the AGL task, the advantage for the comparison group remained significant when differences in PPVT–R scores, $F(1, 50) = 20.74$, corrected $p < .001$, and Number Recall scores, $F(1, 50) = 7.58$, corrected $p = .025$, were held constant, but not when Counting Span or Matrices scores were partialled out.

Associations Between the Implicit-Learning Tasks and the Supplementary Measures

Partial correlations for all pairwise combinations of the two implicit-learning measures and the four supplementary measures are provided in Table 3. In each case, variance due to differences in age is held constant. Because negative correlations were unexpected and uninterpretable, tests of statistical significance were one-tailed. As shown in the table, the correlation between the two implicit-learning tasks was significant for the WS group but essentially zero for the comparison group. Correlations between implicit-learning measures in the comparison group may have been depressed, however, because performance on the RP task was near ceiling levels for this group.

In general, the 15 partial correlations were higher for the WS group than for the comparison group, $p = .007$ (sign test). Moreover, the eight correlations among the implicit-learning and supplementary measures were lower than the six correlations

TABLE 3
Partial Correlations Between Measures (Raw Scores) With Chronological Age Held Constant

	AGL	*RP*	*PPVT–R*	*Matrices*	*Number Recall*
Williams syndrome group (*n*s = 25–27)					
RP	.359**				
PPVT–R	.448**	.148			
Matrices	.085	.287***	.591*		
Number Recall	.288***	.576*	.538*	.350**	
Counting Span	.395**	.431**	.706*	.721*	.553*
Comparison group (*n*s = 26–27)					
RP	.012				
PPVT–R	.163	.055			
Matrices	.252	–.041	.683*		
Number Recall	.209	.432**	.380**	.265***	
Counting Span	.112	.250	.455*	.481*	.220

Note. AGL = Artificial grammar learning; RP = rotor pursuit; PPVT–R = Peabody Picture Vocabulary Test–Revised.
*$p < .01$. **$p < .05$. ***$p < .1$ (one-tailed).

among all possible pairwise combinations of supplementary measures, a pattern evident for both groups of participants (WS group: p = .020; comparison group: p = .014; Mann–Whitney tests). In other words, despite the weak (i.e., in the WS group) or null (i.e., in the comparison group) association between the implicit-learning measures, the two measures were somewhat dissociated from the four supplementary measures, which, by contrast, exhibited relatively strong and consistent pairwise associations.

DISCUSSION

We examined implicit learning in a group of individuals with WS and in a comparison group of normal individuals matched for chronological age. The results indicated that individuals with WS are capable of implicit learning in at least two contexts: (a) a categorization task in which stimulus grammaticality depends on a complex, probabilistic, and unstated set of rules (artificial grammar learning, AGL), and (b) a simple, repetitive motor-learning task (RP). On both tasks, however, performance of participants with WS was well below performance of the comparison group. The results speak not only to the issue of age and IQ independence of implicit learning, but more generally to the issue of cognitive dissociations and preservations in mental retardation. At the outset, however, it is important to acknowledge that our study did not include a comparison group matched for mental age (IQ) to the WS group. As such, it is impossible to determine whether the patterns we observed are specific to WS or more generally applicable to other populations with mental retardation.

Both groups of our participants spanned a wide range of age, which allowed for adequate tests of whether implicit learning varies as a function of age. In general, our results supported A. S. Reber's (1992) contention that implicit learning is relatively invariant across differences in age and maturity. Specifically, the age of the participants in the WS group did not affect their performance on either of our implicit-learning measures. Moreover, for the comparison group, there was no association between age and performance on the AGL task. On the RP task, however, younger participants in the comparison group tended to perform relatively poorly on the very first block of trials, but there were no age effects on subsequent blocks. Because age differences were noted for the initial block only, it is problematic to interpret our finding as evidence of a deficit in implicit learning in younger participants because learning may have not yet begun. Moreover, this initial decrement in performance may be attributable to age differences in attending, fine motor skills, or understanding the experimental instructions. Nonetheless, the decrement in performance on the first block of trials meant that younger participants tended to show greater improvement across the six blocks, which could be interpreted as an advantage in implicit learning.

More importantly, the relative lack of variability in implicit learning as a function of age appears to generalize across a broad range of intellectual abilities. Specifically, our WS group showed marked impairments on measures of vocabulary (PPVT–R) and nonverbal reasoning (K–BIT matrices), whereas our comparison group performed well within the normal range on both tasks. Our results also extend the age range for previously reported findings of age invariance on AGL tasks. Although the results for the RP are slightly less clear, it seems that for individuals 9 years of age and older, effects of age and maturity on implicit learning are very weak if they exist. Of course, our data do not address whether performance on other tests of implicit learning could vary reliably with age, or whether children younger than 9 years of age would show age-related differences in performance on the AGL and RP tasks.

By examining differences between the WS and comparison groups, we tested the hypothesis that implicit learning is independent of individual differences in intellectual functioning. Although previous studies yielded conflicting results, our findings revealed no ambiguity in this regard. Rather, the performance of the WS group was inferior to that of the comparison group on both implicit-learning measures. Moreover, because previous findings make it clear that individuals with WS have better grammar than individuals with Down syndrome (Bellugi, Lichtenberger, Jones, Lai, & St. George, 2000), we expect that deficits on the AGL task would be at least as great in the latter group as they are in the former.

The difference in performance between the WS and comparison groups on both implicit-learning measures was eliminated when the groups were equated by including either K–BIT Matrices (a measure of nonverbal intelligence) or Counting Span (a measure of working memory) as a covariate in the analyses. By contrast, partialing out group differences in vocabulary and short-term memory (as measured by PPVT–R and Number Recall, respectively) did not eliminate the effect. Preliminary analyses showed that our two groups of participants differed more in nonverbal intelligence and working memory than they did in receptive vocabulary and short-term verbal memory. In other words, statistically equating groups on the measures that best distinguish them eliminated the WS deficit in implicit learning.

Previous research makes it clear that cognitive deficits in WS are widespread, yet it is equally clear that the cognitive profile associated with WS is markedly uneven, with some abilities (e.g., language and music) better preserved than others (e.g., Don et al., 1999). Although deficits in implicit learning were apparent for the WS group, the effect size for between-group differences on our AGL task was similar in magnitude to those for vocabulary (PPVT–R) and short-term memory (Number Span) and much smaller than the effect size for nonverbal reasoning (Matrices) and working memory (Counting Span). Similar findings were obtained for effect sizes on the RP task, except that the difference in magnitude between the RP task and Counting Span was not significant. In other words, implicit learning may be an area of *relative* strength in WS, which is consistent with the spirit of A. S. Reber's (1992) proposals.

Interestingly, individual differences in nonverbal intelligence were not significantly correlated with performance on either implicit-learning measure for the comparison group (see Table 3; effects of age held constant). For the WS group, the partial association was not significant for the AGL task and very small and only marginally significant for the RP task. (The association of nonverbal intelligence with working memory was reliable for both groups.) In other words, our results suggest that large between-group differences in nonverbal intelligence are predictive of implicit-learning abilities, whereas relatively small individual differences within groups are not. This hypothesis is consistent with the results of Fletcher et al. (2000). On a contextual-learning task, these researchers (Maybery et al., 1995) found no evidence of an association between performance and IQ when their sample was restricted to children in the borderline to normal range (i.e., a narrow range of IQ). When they included participants with mental retardation (i.e., a large range of IQ), however, a reliable association with IQ was evident.

By contrast, our measure of working-memory capacity (Counting Span) was associated with individual differences in implicit learning among participants in the WS group as well as with differences among groups. For the comparison group, however, working memory was not associated with either of our measures of implicit learning. This result differs from that reported by P. J. Reber and Kotovsky (1997), who suggested that working memory serves as a necessary resource for implicit learning in the normal population. This discrepancy may be explained, however, by the different experimental design (dual task interference) and the different implicit-learning task used by those researchers. Our results suggest that large between-group differences in working-memory abilities are predictive of implicit learning, whereas individual differences within groups are predictive for some populations but not for others. Whether these findings extend to other groups with mental retardation could be addressed in future research.

Although the WS group showed deficits relative to the comparison group on the RP task, they also demonstrated greater improvement over the course of the six RP trials (Figure 3). The very poor performance of the WS participants on the initial trials is likely to be the primary reason for this finding; the WS group simply had more room to improve. Moreover, the comparison group improved rapidly to ceiling levels of task performance. Nonetheless, our findings make it clear that individuals with WS can implicitly acquire some motor skills over time. It seems unlikely, however, that their skills in this domain would ever catch up to those of normally developing individuals.

Our study is the first to use a two-alternative forced-choice response format for AGL tasks (i.e., which of two strings is grammatical?). Nonetheless, levels of performance for our comparison group (approximately 65% correct) were similar to those reported in studies that used a stimulus-categorization task (i.e., is a specific string grammatical or ungrammatical?). A higher proportion of correct responses might have been expected for our forced-choice method, but our task was unique in limiting our stimulus strings to five letters and presenting a smaller number of training stimuli. Both of these factors may have hindered performance (A. S. Reber, 1992, 1993) and offset potential gains from our choice of response format. Our comparison group also demonstrated expected effects of stimulus chunk strength, with superior performance for high-chunk-strength than for low-chunk-strength targets. As predicted, such effects, which rely on explicit memory, were nonexistent in the WS group. It is important to note, however, that the comparison group performed better than chance when targets and foils were matched for chunk strength, as did the WS group during the first block of trials. In short, patterns of responding on our forced-choice AGL task were very similar to patterns reported with other versions of the task (Knowlton & Squire, 1994).

Differences between the AGL and RP results raise the possibility that the various tests of implicit learning do not make up a homogeneous set. Indeed, our two measures showed no association in the comparison group, although they were correlated in the WS group. Different implicit-learning tasks may have distinct processing demands, or they may rely on distinct neurobiological substrates, which means that they could be differentially impaired in different disorders. For example, participants with WS showed a deterioration in performance over time on the AGL task but not on the RP task. In a previous study (Beatty et al., 1990), response patterns for adults with Parkinson's disease on an AGL task were similar to those observed for participants with WS in this study. Specifically, both groups performed at above-chance levels in the first half of AGL testing but deteriorated to chance levels as testing continued. Note, however, that our comparison group also deteriorated from the first to the second block of trials, and the WS and comparison groups did not differ in this regard. In short, chance levels of performance for the WS cohort in the second half of AGL testing may reflect a general deterioration of performance over time, starting from a level that was only slightly above chance. It may be premature, therefore, to relate the WS pattern of performance to the neuropathologic condition of the basal ganglia that is found in both WS and Parkinson's disease.

Indeed, decrements in performance for both of our participant groups on the AGL task may stem from proactive interference. Meulemans and Van der Linden (1998) speculated that the decrements in performance in their Parkinson patients were a consequence of attentional difficulties, yet deteriorations in performance were evident in both of our groups, and our comparison group appeared to be attentive throughout the task. Hence, a simpler explanation is that proactive interference caused the general decrement in performance that we observed. This hypothesis could be tested in the future by adding a third set of trials containing the foils and grammatical items of the original series as well as novel foils. If proactive interference plays a role in the performance decrement, foils from the prior set should be chosen more frequently than novel foils.

Despite the deterioration in performance over time, our data suggest that individuals with WS are capable of implicit learning on the AGL task. In the first half of testing, their performance was above chance levels even when targets and foils were matched for chunk strength. Obviously, this study is an initial and preliminary exploration of implicit learning in WS. Further investigation is required to determine whether other cognitive factors may contribute to the implicit-learning deficits in WS and whether such deficits are specific to WS or generalizable to other groups of individuals with mental retardation. Additional investigation could confirm whether implicit learning in WS is sufficient to be useful in other developmental tasks and whether other implicit-learning skills are better preserved or more severely impaired in WS.

Initial accounts of WS made claims of "islands of preservation" for specific cognitive skills (Bellugi et al., 1994). By contrast, recent reports tend to emphasize (a) the need for closer scrutiny of cognitive processes to avoid overinterpreting performance on specific tasks (Karmiloff-Smith, 1997) and (b) the need to study developmental changes in the deficits and relative assets associated with WS (Paterson, Brown, Gsödl, Johnson, & Karmiloff-Smith, 1999). It is now generally accepted that many of the apparently preserved skills of individuals with WS are accomplished by nonstandard processing mechanisms. Nevertheless, our findings provide additional evidence that individuals with WS have a very "unusual neuropsychological profile" (Bellugi et al., 1994). On the one hand, cognitive deficits in WS are widespread, and individuals who do relatively well (or particularly poorly) on one task tend to perform similarly on other tasks. Indeed, correlations among the measures we administered were higher in the WS group than they were in the comparison group. Other investigators have reported similarly high intertask correlations in WS (Mervis et al., 1999), and Detterman and Daniel (1989) suggested that low-IQ groups will typically show higher intertask correlations than their high-IQ counterparts. On the other hand, group deficits for individuals with WS are much smaller on some tasks (language, music, short-term memory, implicit learning) than they are on others (nonverbal reasoning, spatial abilities). In other words, our results provide support for islands of relative preservation. Moreover, our finding that implicit learning is relatively dissociated from other abilities implies that the various islands are not necessarily subserved by a common mechanism. More detailed examination of the relative strengths and weaknesses associated with WS could improve our understanding of WS in particular and of cognitive functioning in general.

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