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Working Memory Functioning in Developmental Dyslexia

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Abstract

Working memory impairments in dyslexia are well documented. However, research has mostly been limited to the phonological domain, a modality in which dyslexics have a range of problems. In this paper, 22 adult student dyslexics and 22 age- and IQ-matched controls were presented with both verbal and visuospatial working memory tasks. Performance was compared on measures of simple span, complex span (requiring both storage and processing), and dynamic memory updating in the two domains. The dyslexic group had significantly lower spans than the controls on all the verbal tasks, both simple and complex, and also on the spatial complex span measure. Impairments remained on the complex span measures after controlling statistically for simple span performance, suggesting a central executive impairment in dyslexia. The novelty of task demands on the initial trials of the spatial updating task also proved more problematic for the dyslexic than control participants. The results are interpreted in terms of extant theories of dyslexia. The possibility of a Supervisory Attentional System deficit in dyslexia is also raised. It seems clear that working memory difficulties in dyslexia extend into adulthood, can affect performance in both the phonological *and* visuospatial modalities, and implicate central executive dysfunction, in addition to problems with storage.

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Central Executive Functioning in Developmental Dyslexia

Dyslexia is the most prevalent developmental disorder, affecting some 5% of the population of the western world (Badian, 1984), despite adequate intelligence, education, and socioeconomic status. It is most commonly defined as a problem with the decoding of the written word, with such processing difficulties leading to the formulation of the phonological core deficit hypothesis of dyslexia (e.g., Frith, 1985; Ramus, 2003; Ramus, Pidgeon, & Frith, 2003; Snowling, 2000; Snowling & Griffiths, 2003; Stanovich, 1988; Vellutino, 1979; Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, impairments in a number of other domains have been reported in both the laboratory and in everyday life. These wide ranging problems have led to the formulation of rival explanations of dyslexia that, whilst consistent with phonological deficits, view the condition from a broader theoretical perspective (e.g., Goswami, 2002; Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 1995, 2001; Stein & Walsh, 1997; Tallal, Miller, & Fitch, 1993; Wolf & Bowers, 1999; for a review of these theories and the genetic basis of dyslexia, see Démonet, Taylor, & Chaix, 2004). What is without doubt is that dyslexia is a condition that impinges strongly on cognitive functioning, affecting performance across a wide range of domains.

Impairments in working memory have been described as one of the major defining characteristics of dyslexia and memory difficulties will have a significant impact on a dyslexic individual throughout life (McLoughlin, Fitzgibbon, & Young, 1994). It is, thus, important to understand more precisely the influence of dyslexia on working memory, charting the performance of dyslexics beyond childhood and adolescence into adulthood. Moreover, given that the UK Disability Discrimination Act 1995 (c.50) requires employers to make suitable accommodations to help dyslexic adults cope with their working environments, it is crucial to characterise the problems that they are likely to face. In the experiment reported in this paper, working memory tasks were administered to university students. An estimated 0.42% of students at UK higher education institutions are dyslexic (Richardson & Wydell, 2003), so it is similarly important to uncover the full range of their deficits. It seems plausible to argue that if dyslexic deficits are found in high-achieving and university-educated adults, then they should generalise to the wider population of young adults and be at the least of a similar magnitude.

Working memory is a limited-capacity memory system that is involved in the temporary storage and processing of information, maintaining, integrating, and manipulating information from a variety of sources (both external and internal to the individual). According to the multi-component perspective (Baddeley, 1986; Baddeley & Hitch, 1974), working memory consists of at least two modality-specific slave systems, the phonological loop (which deals with phonologically-based information) and the visuospatial sketchpad (dealing with visual and spatial information), overseen by a modality-free attentional controller, the central executive. A fourth component, the episodic buffer, has recently been added to the model (Baddeley, 2000). This is a limited capacity temporary storage component controlled by the central executive and able to integrate information from different subsystems, using a multi-dimensional code (although see Loisy & Roulin, 2003). Evidence has begun to emerge that the central executive is fractionable and that its different functions are independent of each other (Baddeley, 1996, 1998, 2002; Collette & Van der Linden, 2002; Fisk & Sharp, 2004; Handley, Capon, Copp, & Harper, 2002; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; Palladino, Mammarella, & Vecchi, 2003; however, a more radical approach is suggested by Towse & Houston-Price, 2001).

Dyslexic deficits in simple verbal memory span, a task that taps the phonological loop’s storage capacity, are reported extensively in the literature (e.g., Ackerman & Dykman, 1993; Cohen, Netley, & Clarke, 1984; Gould & Glencross, 1990; Helland & Asbjørnsen, 2004; Jorm, 1983; Miles, 1993; Palmer, 2000; Roodenrys & Stokes, 2001; Rose, Feldman, Jankowski, & Futterweit, 1999; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003). However, there remain questions over whether the impairments uncovered on working memory tasks are the result of phonological processing difficulties or working memory deficits per se. This has led to debate concerning the amount of group variance attributable to deficits in phonological or memory processes (e.g., Gathercole, 1994; Gathercole, Willis, Emslie, & Baddeley, 1991; Snowling, Chiat, & Hulme, 1991). For example, it has been suggested that memory span differences between dyslexics and controls can be accounted for in terms of phonological processes, such as slow articulation rate (Avons & Hanna, 1995; Hulme, Roodenrys, Brown, & Mercer, 1995; McDougall & Donohoe, 2002) or deficits in learning, encoding, or using phonological representations (Carroll & Snowling, 2004; Kramer, Knee, & Delis, 2000; Rack, 1994; Tijms, 2004).

Interesting differences between dyslexics and non-dyslexics have also emerged on working memory span tasks (e.g., Ransby & Swanson, 2004; Swanson, Ashbaker, & Lee, 1996; Wolff & Lundberg, 2003). In contrast to the passive storage requirement of simple span tasks, working memory span tasks involve the simultaneous processing of information. There is, thus, a dynamic processing demand to such tasks, drawing on the central executive as well as the relevant slave system for successful performance. By controlling for simple span capacities, it is possible to determine whether dyslexic working memory deficits are simply due to problems of maintenance or whether problems in processing are also in evidence. A number of different span tasks have been developed, including reading span (Daneman & Carpenter, 1980), computation span (Salthouse & Babcock, 1991), operation span (Turner & Engle, 1989), and spatial span (Shah & Miyake, 1996). Conway, Kane, and Engle (2003) summarise the literature in stating that working memory span tasks load on a factor that is independent of simple span performance.

Reading or sentence span tasks have been argued to provide a good overall measure of working memory function (Swanson, Mink, & Bocian, 1999). Baddeley (1990) has stated that the sentence span task requires phonological processing from the phonological loop and also strategy selection from the central executive. Research using the computation span task has indicated that working memory is involved in different aspects of mental arithmetic, which draw on phonological loop and central executive resources (de Rammelaere, Stuyven, & Vandierendonck, 2001; Logie, Gilhooly, & Wynn, 1994; Passolunghi, Cornoldi, & De Liberto, 1999). In a meta-analysis of 77 studies, Daneman and Merikle (1996) assert that computation span and reading span measures tap the same limited-capacity working memory system. Thus, comparing performance between simple and complex tasks in the phonological domain provides a means of establishing whether dyslexic deficits are confined to phonological processes or whether the working memory system is also implicated. Evidence in favour of a dyslexic working memory processing deficit has emerged recently, with central executive impairments being uncovered in both the laboratory (e.g., Jeffries & Everatt, 2004; Palmer, 2000; Smith-Spark et al., 2003; Swanson, 1999; Swanson & Sachse-Lee, 2001) and self-reported in everyday life (Smith-Spark, Fawcett, Nicolson, & Fisk, 2004).

A second means of determining whether working memory problems in dyslexia are restricted to the phonological loop is addressed in this paper. By administering visuospatial tasks, it is possible to eliminate many, if not all, of the concerns surrounding the contribution of phonological processing deficits to dyslexic working memory impairments. If impairments were to be found on non-phonological tasks, it would seem to be a convincing argument in favour of central executive problems in dyslexia.

There is conflicting evidence as to whether dyslexics are better, the same, or worse at visuospatial processing tasks, with many of the differences being the result of task demands. A series of experiments carried out in Vellutino's (1979) laboratory failed to uncover any dyslexic impairments in visuospatial tasks. Several other researchers have argued that visuospatial memory deficits are only apparent when verbal mediation is required by the task in question (e.g., Gould & Glencross, 1990; Thomson, 1982). Such findings were to prove highly influential in restricting research largely to the phonological domain for the following fifteen to twenty years. More recently, researchers have begun to explore visuospatial performance in dyslexia once more. For example, a study by Winner, von Károlyi, Malinsky, French, Seliger, Ross, and Weber (2001) found that dyslexics were poorer on the Rey-Osterrieth test. On the basis of their findings, they concluded that the impairment was a result of the working memory demands of the task and not due to global visuospatial processing. Indeed, the same team of researchers have also found evidence for an advantage in visuospatial processing conferred on dyslexics by their condition. von Károlyi, Winner, Gray, and Sherman (2003) have found that dyslexic children were significantly faster to recognise impossible figures as being impossible than controls, with there being no evidence of a speed-accuracy trade-off in their performance. On the other hand, Helland and Asbjørnsen (2003) reported a visuospatial sketchpad impairment in a particular subgroup of dyslexic children on the Rey-Osterrieth Test, with this group showing a memory difficulty on the task as well as problems with on-line processing.

Whilst some recent studies (e.g., Jeffries & Everatt, 2003, 2004; Kibby, Marks, Morgan, & Long, 2004) have failed to find any significant difference between dyslexics and non-dyslexics on a range of spatial *working memory* tasks, there is also some evidence in support of a deficit in this domain (e.g., Smith-Spark et al., 2003; Swanson, 1992). Swanson (1999) used a matrix task to uncover central executive impairments in dyslexia that were independent of the phonological system. Olson and Datta (2002) also found visuospatial memory impairments in dyslexic children on a task that required both visual processing and short-term memory for complex patterns. A dyslexic deficit in spatial updating, a central executive task, was uncovered by Smith-Spark et al., whilst performance on the simple visual and spatial span tasks did not significantly differ from that of non-dyslexics. Whilst the magnitude of many of these reported deficits was not as great as in the case of phonological working memory, their presence alone is sufficient argument for further investigation and potentially of much relevance for existing theoretical accounts of dyslexia.

It could be suggested that the participants used verbal recoding strategies to facilitate their recall and that the dyslexic deficits simply reflect their poorer phonological working memory abilities. However, this explanation seems unlikely, given that the phonological processing impairments in dyslexia would make it less likely that dyslexic individuals would elect to recode information verbally. Moreover, Gould and Glencross (1990) have argued that there is no opportunity for verbal mediation at a presentation rate of 1 item per second on the Corsi block span task. Despite this, some concerns regarding the use of such a phonological strategy on visuospatial tasks may remain (Morris, 1987). To further assuage such doubts, a Corsi block-type layout (Corsi, 1973) was chosen in the present experiment to replace the 5x5 grid used previously by Smith-Spark et al. (2003). This design eliminates any verbal re-labelling that may still occur with a matrix presentation and the task layout has a strong pedigree as being non-verbal in nature.

There have been several recent reviews and examinations of the Corsi block span task (e.g., Berch, Krikorian, & Huha, 1998; De Lillo, 2004; Fischer, 2001; Kessels, Postma, Kappelle, & De Haan, 2000; Vandierendonck, Kemps, Chiara Fastame, & Szmalec, 2004). In general terms, the task is regarded as being a measure of serial spatial short-term memory (Baddeley, 2001; Berch et al., 1998). More specifically, De Lillo (2004) has argued that the task probes the functioning of the inner scribe of the visuospatial sketchpad. In a large-scale study of memory span, Groeger, Field, and Hammond (1999) found that Corsi block recall is more reliant on general cognitive functioning than is digit span and that performance is more or less independent of level of recall on the digit span task. Dyslexic performance on the Corsi block span task has been documented previously, with there being no significant difference in recall compared to controls (e.g., Gould & Glencross, 1990; Jeffries & Everatt, 2004; Palmer, 2000).

To further probe the existence of executive deficits among dyslexic individuals, two memory updating tasks were also presented to the participants. These tasks involve the presentation of varying numbers of stimuli, with the participants being requested to recall the x most recent items. Successful task performance required the participants to hold the first x items in memory and then, if there were more than x items in a list, to update the contents of memory by dropping the least recent item and adding the new item to the string. However, Palladino et al. (2001) argue against the updating process being a simple process of inclusion or exclusion. Instead of being dropped from working memory once they are no longer relevant targets, they argue that a large number of items can be held active in memory, with levels of activation being adjusted continuously. In any event, the participants needed to repeat the updating process for each additional item in a list over x items. The participants were then asked to recall the last x items in the order that they were presented.

It is well known that updating tasks load on prefrontal executive resources. For example, Van der Linden, Bredart, and Beerten (1994) found that older persons were impaired in consonant updating citing this as evidence of an age-related decline in central executive capacity. Furthermore, Miyake et al. (2000) found that their letter memory task which is similar to the consonant updating task used in the present study shared variance with random generation and with complex memory span both of which are acknowledged to have an executive component. From a neuropsychological perspective, Kiss, Pisio, Francios, and Schopflocher (1998) examined event-related brain potentials (ERPs) under conditions where memory updating was occurring. Their results revealed that the ERP wave forms generated were similar to those evident when individuals engage in other tasks which involve managing the contents of working memory. Also utilising the ERP technique, Kusak, Grune, Hagendorf and Metz (2000) demonstrated that the pattern of ERP activity was most prominent in fronto-central regions consistent with increased prefrontal activity during updating. More recently, strong evidence linking the consonant updating task with executive processes has emerged in research using the MRI approach. This has directly implicated both the dorsolateral prefrontal cortex (DLPFC) and the ventrolateral prefrontal cortex (VLPFC) in the consonant updating task (Postle, Berger, Goldstein, Curtis, and D'Esposito, 2001).

Dyslexic deficits on phonological updating tasks have previously been reported by Ackerman and Dykman (1993) and Smith-Spark et al. (2003), with the latter also finding impairments in performance on an analogue task in the spatial domain. A modified version of the latter test will be presented in this paper and, for the sake of completeness, a phonological analogue, the consonant updating task, was also administered.

The purpose of this paper is, thus, to compare dyslexic and non-dyslexic performance on short-term memory tasks in both the phonological and visuospatial domains. Performance on tasks requiring storage alone (digit, letter, word, and Corsi block span) will be compared with that on working memory span tasks demanding an additional central executive or processing component (computation span, reading span, consonant and spatial updating, spatial working memory span).

On the basis of the existing literature, it is expected that the dyslexic group will show significant impairments on all of the verbal span measures. The existence of a central executive impairment in dyslexia should result in significant differences remaining on the working memory span tasks after controlling for simple verbal span. Previous work suggests that the dyslexic group will perform at a similar level to the controls on the simple spatial span task and in overall score on the spatial updating task. However, it is predicted that significant group differences will emerge on the spatial working memory conditions that draw most heavily on central executive functioning, with the dyslexic group showing poorer recall scores than the control group. Previous research (Smith-Spark et al., 2003) suggests that such differences will occur on items presented early in the spatial sequences and that significant interactions will emerge between group and other factors (list length and serial position).

Method

Participants

Two groups of university students, one group of 22 dyslexics (16 females, 6 males) and the other 22 non-dyslexics (15 females, 7 males), were employed in the experiment. In the light of potential gender differences in spatial processing (e.g., De Luca, Wood, Anderson, Buchanan, Proffitt, Mahony, & Pantelis, 2003; Vecchi, Phillips, & Cornoldi, 2001), the ratio of males to females was kept approximately equal across the two groups. All participants were native English speakers. The participants with dyslexia were recruited via the University of Kent Disability Support Unit and had been previously (and independently) diagnosed as dyslexic by educational psychologists. In addition to the independent diagnosis of the dyslexic group, two screening tasks were administered to all the participants in order to provide a further validation of the participant groupings. The first of these was a nonsense word reading passage taken from Fawcett and Nicolson’s (1998) Dyslexic Adult Screening Test (DAST). The speed and accuracy of reading such passages is known to identify deficits even in compensated dyslexics (Brachacki, Fawcett, & Nicolson, 1994; Finucci et al., 1976). Secondly, the WORD spelling task was used to determine the spelling age of the participants (Wechsler Objective Reading Dimensions; Wechsler, 1993).

The non-dyslexic control group was obtained through campus-wide advertising at the University of Kent. All the control participants obtained a ceiling spelling age of greater than

17 years and did not have any difficulties with the nonsense word reading passage, either in terms of speed or accuracy of performance. Furthermore, all the control participants reported that they were not dyslexic and that they had no problems with reading or spelling. Self-reports of being non-dyslexic have been found to be highly accurate by Nicolson and Fawcett (1997). Together with their scores on the literacy screening tasks (see Table 1), this provides convincing evidence that the control group was made up of non-dyslexics.

Due to the importance of IQ-matching in dyslexia research (e.g., Goswami, 2003), an IQ score was obtained for each participant. A combination of time constraints and the well-known ACID performance profile (which would result in shortfalls in the dyslexic group and would, thus, not be a reflection of their real cognitive ability) meant that a short-form IQ measure (Turner, 1997) was used rather than the full WAIS-III UK battery. To this end, the Similarities, Comprehension, Block Design, and Picture Completion subtests of the WAIS-III UK Edition (Wechsler, 1998) were administered. As Table 1 shows, the groups were well matched for age and short-form IQ, differing significantly only on the measures sensitive to dyslexia.

TABLE 1 ABOUT HERE.

The participants were paid for taking part in the study, which took one and a half hours to complete.

Materials

The experimental tasks were presented on an IBM-compatible PC. Answer booklets and writing materials were provided for each of the tasks.

Design and Procedure

The experiment followed a mixed measures design, with participant group (levels: dyslexic and control) being the between-participants variable on each task. There were 4 simple span, 3 complex working memory span, and 2 updating measures. To ensure that the order of presentation was fully counterbalanced, each participant was randomly assigned to one of the nine different orders of presentation. This procedure was followed with both participant groups. The dependent variables are reported below for each task. The participants gave informed consent to take part and received a verbal debrief after the experiment.

The simple span measures

Simple verbal span (digit, letter, and word span)

The participants were informed that they would see a sequence of stimuli, presented one at a time on the computer screen. They were asked to speak the name of each stimulus out loud and to remember it. At the end of each trial, the participants were requested to verbally report the stimuli in the order in which they appeared, with the experimenter recording their responses on an answer sheet. Verbal reports were used instead of written responses in order to avoid spurious results arising from the writing and spelling difficulties associated with dyslexia. The participants were warned that the number of stimuli presented would increase gradually during the experiment. There were three trials at each list length. The presentation of the stimuli alternated between two positions on the computer screen. The participants were required to recall at least two out of three lists correctly at any given span level to progress to the next level. There were three variants of the task, namely digit span, letter span, and word span. The dependent variable for each measure was span length. One-way ANOVAs were performed on each of the simple span measures.

Corsi block span

The participants were informed that they would be presented with a pattern consisting of blank squares and were told that some of the squares would be filled one a time with Xs. They were asked to remember the position of each of the cells so highlighted and to write down the positions of all the cells in the order in which they were filled. There were twelve positions that could be filled with Xs and these were set out on the computer screen in a

Corsi-type fashion (Corsi, 1973). The number of positions highlighted increased gradually over the course of the experiment, up to a maximum of six. There were three trials at each level of the task. The participants were requested to continue until the end of the task even if they could not manage to recall all the items. Two dependent variables were recorded, span level (being the last level of the task at which at least 2/3 trials were correctly recalled) and overall score (being the total number of blocks correctly remembered over the course of the experiment, out of a maximum of 63). Group span size and overall score were compared using one-way ANOVAs.

The complex working memory span measures

The three complex span tasks assessed verbal and visuospatial working memory. Both verbal tests (computation span and reading span) were based on ones run by Salthouse and Babcock (1991) and used the same timings. The participants were seated in front of the computer and asked to read either an arithmetic problem (computation span) or sentence (reading span) and then to solve the problem or answer a comprehension question about the sentence in either case by choosing the correct answer from a list of three alternatives, whilst retaining the last digit or word of the problem for later recall. During the first three trials only a single problem (sentence) was presented, this increased to two problems for the next three trials, and then three problems, and so on. At the end of the designated series of problems, the participant was requested to speak the last digit or word of each problem *in the order* that it appeared in the test. The participants were told to attach as much importance to giving the correct solution to the problem as recalling the last digit or word of the problem(s). The participants were allowed as long as they wanted to recall the last digit or word of each problem. Performance was self-paced, with the participant pressing any key on the keyboard to initiate the next trial. A practice session of three trials at the one item (sentence or problem) level and two trials at the two item level was given to familiarise the participants with the experimental procedure. On the main tests, three trials were presented at each level. Span level was designated as the highest level of the tests at which the participant was able to answer correctly two of the three test items. Testing was terminated at the first level at which performance fell below this level. For a test item to be deemed ‘correct’, the participants were required to perform 100% correctly on both the processing and the storage phase.

Specific details of the two tests are given below. In both cases, the span lengths of the two groups were compared using one-way ANOVAs.

Computation span

The participants were presented with a series of arithmetic problems. They were required to solve these problems, whilst remembering the last digit from each one. The number of arithmetic problems increased successively from one to a ceiling of ten. All problems took the form of ‘X+Y= ?’ or ‘X-Y= ?’. The following restrictions were in place: a) X and Y were single digit numbers between 1 and 9; b) answers to the problems could not be negative; c) the final number (Y) could not be the same for two adjacent problems in a trial; and d) the answer to the problem could not equal Y. The two incorrect response alternatives for the problem were randomly selected numbers between 1 and 20.

Reading span

The reading span task followed the same design as the computation span task, except that sentence stimuli were used. The number of sentences at any one level increased from one to a ceiling of seven. The sentences were the same as those used in Fisk and Warr’s (1996) reading span test.

Spatial working memory span

This task was based on one developed by Fisk (2004). A Corsi-type arrangement of cells appeared on the computer screen, five of which were highlighted (four filled with ‘X’s and one with ‘O’s), and the participants were requested to indicate whether there were more cells highlighted above or below a centrally placed dividing line on the screen. They did this by pointing to one of two boxes positioned in the top and bottom right hand corners of the computer screen. In addition, they were asked to remember the position of the cell highlighted with 'O's. A sample stimulus is shown in Figure 1.

FIGURE 1 ABOUT HERE.

In the first three trials, just a single display was presented. In the second three trials, two consecutive displays occurred, and subsequently the number increased by one display every three trials up to a maximum of six. At the end of each trial, after all of the displays had been presented, participants were asked to recall the positions of the cells marked with 'O's in the order in which they appeared. An answer sheet with the blank Corsi-type arrangement was provided for participants to record their responses. In order to familiarise the participants with the task demands, a practice session preceded the main experiment. There were 6 levels to the main experiment, with three trials at each level. A span score was calculated, with this being the last level at which 2 out of the 3 trials were answered correctly (both the recall and processing components). In order to provide additional serial position data, the experiment was run through to the end of the sixth level for each participant to give a maximum score of 63 on the task. Thus, similarly to the Corsi block span task, two dependent variables were measured, span length and overall score. Group performance on both measures was again compared using one-way ANOVAs.

The updating measures

Consonant updating

The participants were requested to recall in serial order the last six consonants of a sequence shown one at a time on the computer screen, writing these down in an answer booklet. Sequences of letters, varying in length, were presented, selected from lists of 6, 8, 10, and 12 letters. The participants were not informed of the number of consonants that would be displayed on any given trial (i.e. the number of updating operations required was unknown to the participant). The consonants were selected at random, subject to the requirement that no letter appeared in the same list more than once. The timings of the presentations were based on those used by Morris and Jones (1990). In total, the task consisted of twenty-four letter sequences, with there being six trials at each list length. The test was self-paced, with the next set of letters appearing only after the participant hit a key to continue. The version of the task reported in this paper is the same as that employed by Smith-Spark et al. (2003). A schematic of the task requirements is presented in Figure 2.

FIGURE 2 ABOUT HERE.

The dependent variable was the number of letters successfully recalled. A repeated measures ANOVA was performed on the data, with group (dyslexic, control) being the between-participants factor and the within-participants variables being condition (6, 8, 10, 12 letters) and serial position (1-6).

Spatial updating

The participants were told that they would be presented with a pattern consisting of blank squares and were told that some of the squares would be filled one at a time with ‘X’s. The timings of the presentation of stimuli were the same as those used by Morris and Jones (1990) in their letter updating task and by Smith-Spark et al. (2003). The participants were asked to remember the position of each of the cells so highlighted and to write down the position of the last four cells in order at the end of each trial. The number of positions filled varied between trials but on each trial only the last four were required for recall. There were 12 positions that could be filled with ‘X’s and these were set out on the computer screen in the same format as reported in the spatial span task. On some trials, participants were warned that *only* four cells would be highlighted. On the other trials, four, six, eight, or ten positions were highlighted with the participant being unaware of the number to be presented. Each list length was presented six times with the order randomised. Thus, there were thirty trials in total (24 updating, 6 known). A schematic of the task is presented in Figure 3.

FIGURE 3 ABOUT HERE

The dependent variable was the number of cells correctly recalled. A repeated measures ANOVA was performed on the data, with group (dyslexic, control) being the between-participants variable. Condition (unknown 4, known 4, 6, 8, 10 cells presented) and serial position (1-4) were the within-participants variables.

Results

Span measures. One-way ANOVAs carried out on the span measures showed that the dyslexic group had significantly lower scores on all the phonological tasks and also the spatial working memory span task. Furthermore, their poorer performance on the Corsi block span task also approached significance. The mean scores and analyses are shown in Table 2.

TABLE 2 ABOUT HERE.

Simple span vs. working memory span. The ANOVA results for this comparison and all subsequent analyses are presented in Table 3. The reading span and computation span tasks were standardised and averaged to yield a single measure of verbal working memory span. Similarly, the word and digit span scores were standardised and averaged to produce a single simple verbal memory span score. In order to determine whether impairments were present on the working memory span tasks after controlling for simple span, a one-way ANCOVA was performed with the composite standardised verbal working memory span scores as the dependent variable, group as the between-participants factor, and the standardised simple span composite score entered as a covariate. The results indicated that the significant group difference remained on the verbal working memory span measure after controlling for simple verbal memory span. With regard to the spatial working memory span measure, the significant group difference also remained after controlling for Corsi block span.

TABLE 3 ABOUT HERE.

Corsi block span vs. spatial working memory span. Group differences in performance at different span lengths were then subjected to statistical analysis. For each span length, the number of correct responses over all three trials was calculated for each serial position. These data were then averaged over serial positions to yield a single score for each presented span length for both tasks (maximum score = 3). These scores were then included in a repeated mixed-measures ANOVA design, with task (spatial working memory span task versus Corsi block span task) and presented span length (lengths 1 to 6) as the within-participants factors and group as the between-participants factor. This analysis yielded a significant overall group effect, with the dyslexic group recalling significantly fewer positions correctly. There were also significant main effects of task, with performance being more accurate on the Corsi block span task, and length, with fewer positions being recalled correctly at longer trial lengths. The group effect was qualified by a significant group x task interaction, with the dyslexic group being significantly more impaired on the spatial working memory task (mean difference = 2.45) relative to the Corsi block span task (mean difference = 6.23) than the control group. The mean scores on the two tasks are displayed in Table 4. No significant group x length interaction was evident, nor was there a significant group x task x length interaction.

TABLE 4 ABOUT HERE.

Consonant updating. There was a significant main effect of group on the consonant updating task, with the control participants scoring at a higher level overall than the dyslexics (although when letter span was added as a covariate, the group difference was reduced to below significance, $F(1, 41) = 1.25$, $MSE = 9.10$, $p = .269$). List length also had a significant effect upon recall, with more items being correctly recalled on the lowest levels of the task. A significant group x list length interaction also emerged from the analysis, indicating that the group difference was most apparent on the lower levels of the task (6 and 8 letter conditions). The mean recall of both groups for each list length, collapsed across serial position, are displayed in Table 5.

TABLE 5 ABOUT HERE.

Serial position was also found to have a significant influence on recall, such that more recently presented consonants were recalled significantly more successfully than items presented earlier in the sequence. In addition, there was a significant group x serial position interaction, with the dyslexics recalling significantly fewer of the earliest presented consonants correctly but performing at a similar level to the controls on the final two items to be shown. Figure 4 shows the mean recall of the control and dyslexic groups for each serial position, collapsed across list length.

FIGURE 4 ABOUT HERE.

A significant list length x serial position interaction was also uncovered, with the pattern of recall differentiating between the 6 letter level and later levels of the task. However, the three-way interaction between group, list length, and serial position was not significant.

Spatial updating. There was no significant effect of group, with dyslexics and controls performing at similar levels overall. While there was a main effect of list length on recall, with significantly better recall of items under less taxing loads, no significant group by list length interaction was found. However, there was a significant group by serial position interaction. Later positions were remembered more accurately than positions presented early on in a sequence and this tendency was especially evident among the dyslexic group. The results of a further ANCOVA showed that this interaction remained significant after controlling for Corsi block span, $F(2.57, 105.50) = 5.25$, $MSE = 0.723$, $p = .003$. There was a significant list length by serial position interaction (with performance on the two 4 cell conditions being different from that on the unknown conditions with a higher memory load) but this was qualified by a significant group by list length by serial position interaction. Further investigation of the interaction indicated that the dyslexic group were significantly poorer at recalling the first item to be recalled on the Unknown 4 condition, $F(1, 42) = 10.35$, $MSE = 1.06$, $p = .002$, and the Unknown 6 condition, $F(1, 42) = 4.72$, $MSE = 2.12$, $p = .035$. In addition, the dyslexic group showed a significantly poorer recall of the final item to be presented on the Unknown 8 condition, $F(1, 42) = 5.67$, $MSE = 0.90$, $p = .022$. The group mean recall scores by serial position collapsed across the levels of the spatial updating task are shown in Figure 5.

FIGURE 5 ABOUT HERE.

It became apparent during scoring of the data that dyslexic participants were experiencing difficulties during the early stages of the updating task. For this reason, it was decided to conduct supplementary analyses. To avoid undue repetition, only the main effects and interactions of interest to this observed difficulty are reported here. Table 6 shows the group means for the first and second halves of the spatial updating task.

TABLE 6 ABOUT HERE.

There proved to be a significant main effect of test-half on performance, with recall on the first half of the test being less accurate than on the second half. In addition, a significant test-half x condition interaction was found, with recall on the Unknown 6 and Unknown 8 conditions showing the most improvement in recall from the first half to second half, whilst performance on the remaining conditions remained relatively stable over testing. While, there was no significant test-half x group interaction, there was a significant three-way interaction between test-half, condition, and group,. Within-group comparisons indicated that the dyslexic group improved markedly from the first half to the second half of the test on the Unknown 6, $t(21) = -4.11$, $SEM = 0.431$, $p < .001$, and Unknown 8 conditions, $t(21) = -3.32$, $SEM = 0.615$, $p = .003$, whilst the performance of the control group remained at a similar level throughout, except for an improvement on the Unknown 4 condition over testing, $t(21) = -2.58$, $SEM = 0.565$, $p = .018$. The group mean recall by condition for the two halves of the test is displayed in Figure 6.

FIGURE 6 ABOUT HERE

Effect size analyses are shown in Figure 7. The performance of the dyslexic group was poorest relative to the control group on the simple span measures (mean = -.86), followed by the complex span tasks (mean = -.96), and then the updating tasks (mean = -.26). Using the method set out in Nicolson and Fawcett (2000), if an individual dyslexic participant's effect size was -1 or greater on the task, then he or she was deemed to show a significant deficit on the task. Further to this, control participants with abnormally high or low scores on a measure (deemed as ±1.50 SDs from the mean of the control group) were removed before calculating the z-score for that particular task, following a similar method to that of Ramus, Rosen, Dakin, Day, Castellote, White, and Frith (2003). The percentage of dyslexic participants showing a significant deficit on each task is also given in Figure 7.

FIGURE 7 ABOUT HERE

Discussion

It is apparent that the working memory deficits associated with dyslexia extend into adulthood, in accordance with previous research (e.g., McLoughlin, Fitzgibbon, & Young, 1994; Smith-Spark et al., 2003). Importantly, the working memory deficits in adult dyslexic students were not confined to the phonological domain but, instead, extended to the visuospatial domain. Group differences were found on both the simple and complex span tasks and also on the updating measures. Whilst the effect size analysis indicated that dyslexic working memory problems were greatest on the simple span measures (followed by the complex span tasks and then the updating tasks), significant shortfalls in performance on the complex span tasks remained after controlling for simple span. It would seem that the working memory problems evident in dyslexia are not limited solely to the maintenance of information in short-term memory; instead, the results argue in favour of a central executive impairment in dyslexia that is independent of either the phonological loop or visuospatial sketchpad slave systems.

It could perhaps be argued that the dyslexic sample may have had co-morbid AD(H)D and that this led to the attention and central executive difficulties evident on the working memory tasks (Barkley, 1997; Pennington & Ozonoff, 1996; Karatekin, 2004). This seems unlikely, however, as the dyslexia assessment reports were checked prior to testing and these made no mention of any such co-morbidity, nor was the behaviour of the participants with dyslexia during the experiment consistent with the presence of AD(H)D. This conclusion is also supported by there being no significant group difference in scores on the Picture Completion subtest of the WAIS-III (Wechsler, 1998), a measure sensitive to the presence of AD(H)D (Brown, 1996).

The participants with dyslexia showed impairments in their performance on the simple verbal span measures (the digit, letter, and word span tasks), obtaining significantly lower span levels than the control group. Such findings are entirely consistent with the existing literature (e.g., Jorm, 1983). However, the dyslexic group also showed some signs of difficulty on the Corsi block span spatial measure, with the group effect falling just short of significance. This finding was not expected on the basis of the results of previous studies (e.g., Jeffries & Everatt, 2003, 2004; Kibby et al., 2004). It has been argued that greater complexity within spatial arrays may require additional central executive or attentional resources and lead to variable performance at different levels of the task (e.g., Berch et al., 1998; Kemps, 1999, 2001; Smirni, Villardita, & Zappala, 1983). This explanation is supported by the work of Miyake, Friedman, Rettinger, Shah, and Hegarty (2001), who argue that performance on the Corsi block span task requires more involvement of executive processes than does the digit span task. Kessels, Kappelle, de Haan, and Postma (2002) have used a total score measure on the Corsi task, arguing that it provides a more reliable estimate of performance than span level on its own. The overall score measure in the present study indicates that there was no significant difference between the two groups.

A comparison of performance on the Corsi block and spatial working memory span tasks yielded an overall group effect which was qualified by a group x task interaction. The dyslexic participants were more impaired on the spatial working memory task relative to the Corsi block span task. Indeed, subsequent analyses revealed that the dyslexic deficit was significant on the spatial working memory task but not on the Corsi block span task. There was no group x length interaction; a result consistent with the presence of a dyslexic spatial working memory deficit at all presented span lengths. That the group difference in spatial working memory performance remained significant after controlling for the Corsi block span also strengthens the argument that poorer Corsi block recall in the dyslexic group is likely to be a consequence of central executive difficulties rather than a simple span deficit. Of the dyslexic group, individual analyses following the method of Ramus et al. (2003) and Nicolson and Fawcett (2000) showed that 32% showed a significant deficit on the spatial working memory task (being greater than -1 effect sizes from the control mean). This compared to 18% on the Corsi block span task and 14% on the spatial updating measure. Whilst the frequency of these deficits is not as high as on the verbal measures, it would appear from these individual analyses, nevertheless, that quite a high proportion of dyslexics experience spatial working memory deficits, particularly when processing as well as storage is required. These data support Miles' (1993) characterisation of dyslexia as a multimorph syndrome, with some individuals displaying symptoms a, b, c, and d, for example, whilst others may show symptoms b, c, d, and e. The present results suggest that a significant number of dyslexics show a central executive deficit that is independent of phonological processing problems.

Decrements in verbal working memory span were also uncovered, with the participants with dyslexia obtaining significantly lower span scores than the controls even after controlling for simple verbal span. The dyslexic group was poorer at the simultaneous storage and processing of information required by both the computation and reading span tasks. The general pattern of findings reported in this paper is, therefore, consistent with recent views of the central executive as being domain-general rather than domain-specific in nature (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004). The data are in accord with the argument there is not a single pool of resources for storage and processing in working memory, but instead that there is domain-specific storage and domain-general processing within the working memory system. The dissociation between dyslexic performance on the simple spatial span and the spatial working memory span measures is particularly instructive in this regard, with the individuals with dyslexia only showing significant difficulties on when a processing component was added to task demands. Coupled with dyslexic deficits remaining on the working memory span measures after controlling for simple span, it would indeed appear that storage and processing resources are separable within working memory. Further to this, the central executive impairments apparent in the performance of the dyslexic group are indicative of a domain-general problem with this system and are not inextricably linked to dyslexia-associated deficits in the phonological loop slave system.

Dyslexic impairments were also evident on the updating tasks and were largely consistent with Smith-Spark et al. (2003). The phonological nature of the consonant updating task masks the presence of a dyslexic executive deficit, thereby reducing its effectiveness as a measure of central executive functioning (c.f. Smith-Spark et al.). This conclusion is supported by the ANCOVA carried out with letter span as the covariate which reduced the overall group difference to below significance. The significant dyslexic deficit is qualified by significant two-way interactions (group x list length and group x serial position) and a three-way interaction that fell just short of significance (group x list length x serial position). The group x serial position interaction revealed that the dyslexic deficit was most evident at serial positions 1 and 2, slightly reduced in the middle serial positions and largely absent in the later serial positions. With respect to the group x length interaction, the sharp decline in performance at the longer list lengths evident in the control group (presumably due to the increased load on executive resources) was not so evident in the dyslexic group. The dyslexic participants, in particular, appeared to make use of a recency-based strategy which, coupled with the task's phonological requirements, makes it difficult to draw conclusions about central executive performance. Indeed, a recency-based explanation is supported by Baddeley and Hitch (1993), who posit that a different mechanism is involved in the processing of longer lists than that involved when shorter lists are presented. They argue that the recency effect is independent of the operation of the working memory system (although for a dissenting view, see Ward, 2001). Moreover, Collette and Van der Linden (2002) state that the requirement to hold six items in memory is close to, or more than, the span level of many participants. As a result, they consider it possible that the central executive can increase the capability of the phonological loop (by engaging strategies such as chunking items into larger units or employing information from long term memory). They argue that, consequently, the six-item memory load may place demands on the central executive for both updating *and* storage.

In contrast, the spatial updating task appears to load generally on executive resources; that is, under all updating lengths. The results bear out those of Fisk and Sharp (2003) in finding a strong effect of serial position on performance and also a sequence length x serial position interaction. Fisk and Sharp report that the recall of cells presented early in a sequence was strongly influenced by conflicting demands on executive processes, with random generation disrupting recall of the first two serial positions disproportionately. Although there was no overall dyslexic deficit, there were significant group x serial position interactions at lengths Unknown 4 and 6, with the participants with dyslexia performing worse on the early serial positions. This is consistent with a spatial processing deficit affecting the recall of early serial positions in dyslexia. The interaction is just short of significance at length Unknown 8, although in this case the dyslexic deficit is evident in the final serial position. In fact, Fisk and Sharp found that the dual task-related decrement emerges at the Unknown 4 and 6 cell conditions, with performance tending to level off after the Unknown 6 condition. Importantly, there is no significant group x serial position interaction under the Known 4 condition and this supports the argument that the dyslexic deficit emerges *only* under updating conditions. Furthermore, the group x serial position interaction remained significant following an ANCOVA run with Corsi block span as the covariate. The results of the ANCOVA therefore provide evidence of a dyslexic impairment in working memory control processes (cf. Palladino et al., 2001). Indeed overall, the pattern of dyslexic deficits found on the spatial updating task is strikingly similar to that uncovered by Fisk and Sharp when they placed an additional load on executive resources. In both cases, recall of the early serial positions appears to be vulnerable especially at the Unknown 4 and Unknown 6 cell levels. The involvement of the central executive in updating (or running memory tasks) has been discussed in Morris and Jones (1990; although see Ruiz, Elosúa, and Lechuga, 2005, for a critique). Clear evidence that the dyslexic impairments observed here are likely to be a consequence of limited executive resources is provided by the fact that dyslexic deficits are most evident in those specific contexts where demands on executive resources are at their highest.

The results of this study argue for a broader explanation of dyslexia than one focused on phonological deficits alone (e.g., Vellutino, 1979), particularly in respect to the deficits shown on visuospatial measures. It would appear that an executive functioning impairment is implicated in dyslexia, consistent with the arguments of, for example, Jeffries and Everatt (2004), Palmer (2000), Smith-Spark et al. (2003), and Swanson and Sachse-Lee (2001).. When considering the present findings in relation to broader conceptualisations of dyslexia, the findings are broadly consistent with both Nicolson and Fawcett’s (1990) DAD hypothesis, although they would argue that the working memory tasks demand more controlled processing, with this leading to an *apparent*, rather than actual, executive deficit. However, the finding of a deficit in initial performance on the spatial updating task is a challenge to automaticity theory since the impairments shown by the dyslexics on the spatial updating task are shown early on in the testing process before schemata are developed and then become less noticeable later. It would be predicted by the DAD hypothesis that the opposite would be true, with poorer performance by the dyslexics after a level of automaticity (or at least some degree of familiarity) has been developed in response to the stimuli.

An explanation of executive dysfunction in dyslexia may lie in Norman and Shallice’s (1986) model of the attentional control of action (for more recent papers, see Cooper & Shallice, 2000, and Cooper, 2002). That there are two types of action, conscious and automatic, is well known (Schneider & Shiffrin, 1977). Controlled processing requires attentional and processing resources, whilst automatic processing does not make demands on these resources, thereby freeing-up capacity for higher level processing. Norman and Shallice’s model proposes two complementary processes that cooperate to control action. Contention scheduling proves to be sufficient to control relatively simple, well-learned action sequences, whilst the Supervisory Attentional System (SAS) draws on attentional control to modulate behaviour. The SAS is concerned with the control, coordination, and integration of information and has been proposed by Baddeley (1986) as a candidate for the central executive. Of most relevance to the present paper, it is instantiated when poorly learned or novel action sequences are necessary (Norman & Shallice, 1986). The significant three-way interaction that emerged on the spatial updating task between test-half, condition, and group, indicates that the dyslexic group had significantly greater problems than the control group when first encountering the task. The findings are, therefore, consistent with SAS impairment in dyslexia. Executive control processes are argued to be most strongly involved in performance when a task is first encountered and its demands are still novel (e.g., Shallice & Burgess, 1993; Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997; Rabbitt, 1997).

The results are also consistent with the cerebellar deficit hypothesis (Nicolson et al., 1995, 2001), which argues for mild cerebellar dysfunction in dyslexia. The cerebellum is involved in both the execution of learned skills and the acquisition of new skills (Ito, 1990) and also working memory function (e.g., Justus & Ivry, 2001). Evidence supporting the cerebellar deficit hypothesis in dyslexia bears a strong resemblance to some of the findings of the present paper. For example, Nicolson and Fawcett (2000) administered two procedural learning tasks to children with dyslexia. Consistent with performance on the spatial updating measure in the present study, they found that the dyslexic participants were poorer in the initial phases of learning the task and that this was not due to them misunderstanding the instructions. Furthermore, Nicolson, Fawcett, Berry, Jenkins, Dean, and Brooks (1999) found that there was a lower level of activation in the right cerebellar cortex when dyslexic adults were asked to carry out both novel and prelearned sequences of finger movements.

In addition, Nicolson et al. (1999) found that there was greater activation of the frontal lobes in the dyslexic groups when confronted with learning a novel sequence. The frontal lobes have been widely implicated in executive functioning (e.g., Moscovitch & Winocur 1992; although see Baddeley, 1996) and have been argued to house the SAS by Norman and

Shallice (1986).The SAS interrupts local level control over cognition when environmental conditions (or task demands) make the system vulnerable to distraction (Norman & Shallice, 1986). A central feature of Nicolson and Fawcett's (1990) Dyslexic Automatisation Deficit (DAD) hypothesis is that dyslexics employ a strategy of "conscious compensation" to hide their shortcomings on (what should be) automatic skills, allocating extra attentional capacity to the task in which they are involved. According to Fawcett and Nicolson (1994), there are four general types of skill prone to disruption in dyslexia: i) complex skills requiring fluency in component subskills, ii) time-dependent skills that call upon fast processing speed, iii) multi-modality skills involving the monitoring of various modalities or sources of information, and iv) vigilance tasks requiring concentration over time. The task demands made by each type of skill are such as to prevent the use of conscious compensation to guide performance. The conditions under which the SAS is called into play also fit well with the types of skill that Fawcett and Nicolson argue are vulnerable to the effects of dyslexia. Conversely, Fawcett and Nicolson predict that dyslexics will be good at "closed" skills (p. 184). This ties in with the role of the contention scheduling process in Norman and Shallice's model and suggests that this system is intact in dyslexia.

Higher working memory load is assumed to be associated with faster decay or displacement of information from working memory (e.g., Just & Carpenter, 1992). Impaired working memory in dyslexia would lead to the items presented early in a sequence being more susceptible to decay than more recent items as they will have been held in memory for a longer duration. The poorer recall by dyslexic participants of the early serial positions on the Unknown 4 and Unknown 6 cell levels of the spatial updating task can also be explained by Nicolson et al.'s (1995, 2001) cerebellar deficit hypothesis. Work by Ravizza, McCormick, Schlerf, Justus, Ivry, and Fiez (2006) has found evidence of cerebellar involvement in the encoding or strengthening of memory traces in phonological working memory. This was particularly evident with long delays between presentation and recall. Whilst the authors did not find a similar deficit in cerebellar patients on their forward and backward spatial span tasks, it may be that these were not sufficiently taxing to uncover an underlying deficit. It may be that the cerebellum is involved across modalities in the encoding and retrieval of information; a cerebellar deficit in dyslexia would thus result in poorer performance at the beginning of lists of stimuli. Consistent with this argument, Bauer and Emhert (1984) report a verbal memory task on which dyslexics showed a reduced primacy effect (a similar result to that on the consonant updating task in the present paper).

In conclusion, the data emphasise the continuing problems dyslexics have with working memory into adulthood, even in high-achieving individuals, and that these difficulties extend beyond the literacy domain. It would also appear that not only do dyslexics have problems with storing information in working memory but also with processing that information. In particular, the deficits uncovered on the visuospatial working memory tasks are a challenge to the phonological core deficit hypothesis of dyslexia. Instead, they suggest that there may be more central working memory impairments in dyslexia, with central executive or the SAS processes being implicated. Executive impairments in dyslexia have been reported previously, such as problems with inhibition, problem solving, set maintenance, and selective and sustained attention (e.g., Brosnan, Demetre, Hamill, Robson, Shepherd, & Cody, 2002; Everatt, Warner, Miles, & Thompson, 1997; Jeffries & Everatt, 2004; Reiter, Tucha, & Lange, 2005; van der Schoot, Licht, Horsley, & Sergeant, 2000). Similarly, the spatial updating task reported in this paper requires the suppression of previously relevant information as more cells are presented (Palladino et al., 2001; Passolunghi & Pazzaglia, 2004), as well as the novelty of the task meaning that there is no extant schema to guide performance (Norman & Shallice, 1986). However, another aspect of executive functioning, the shifting or switching of attention, has been found to function normally in dyslexia

(Moores, Nicolson, & Fawcett, 2003). Particular SAS operations may therefore be impaired in dyslexia, whilst others remain intact; consistent with the view of the SAS as a fractionated system (Andrés & Van der Linden, 2000; Shallice, 2002; Shallice & Burgess, 1993). The data are also consistent with cerebellar deficits in dyslexia (Nicolson et al., 1995, 2001), indicating problems in the initial acquisition of skill. Whatever the root cause, working memory deficits will have a significant impact on planning, problem solving, acting under novel situations, and learning. Appropriate support must, therefore, be provided across a range of modalities for adult dyslexics to achieve their full potential in both educational and employment settings.

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Figure Legends

Figure 1. A sample stimulus from the spatial working memory span test. The stimuli were presented in reverse video, but for ease of viewing the figure is presented here in video.

Figure 2. A schematic of the consonant updating task. In this example, the *last six positions only* must be recalled later in serial order. Initially 6 letters are presented and the participant must recall the letters in serial order (Updates 0)). Once a seventh letter is shown, then the participant must re-allocate ordinal tags to the letters held in working memory, dropping the first letter from the sequence and adding the seventh letter to it (Updates +1). The same re-tagging operation is required when the eighth cell is presented (Updates +2).

Figure 3. A schematic of the spatial updating task. The *last four positions only* must be recalled later in serial order. Initially 4 cells are highlighted with rows of "X"s and the participant must recall their positions sequentially (Updates 0). Once a fifth cell is marked, then the participant must re-allocate ordinal tags to the cell positions held in working memory, dropping the first cell from the sequence and adding the fifth cell to it (Updates +1). The same re-tagging operation is required when the sixth cell is presented (Updates +2).

Figure 4. Mean group x serial position data for the consonant updating task, collapsed across list length.

Figure 5. Mean group x serial position data for the spatial updating task, collapsed across list length.

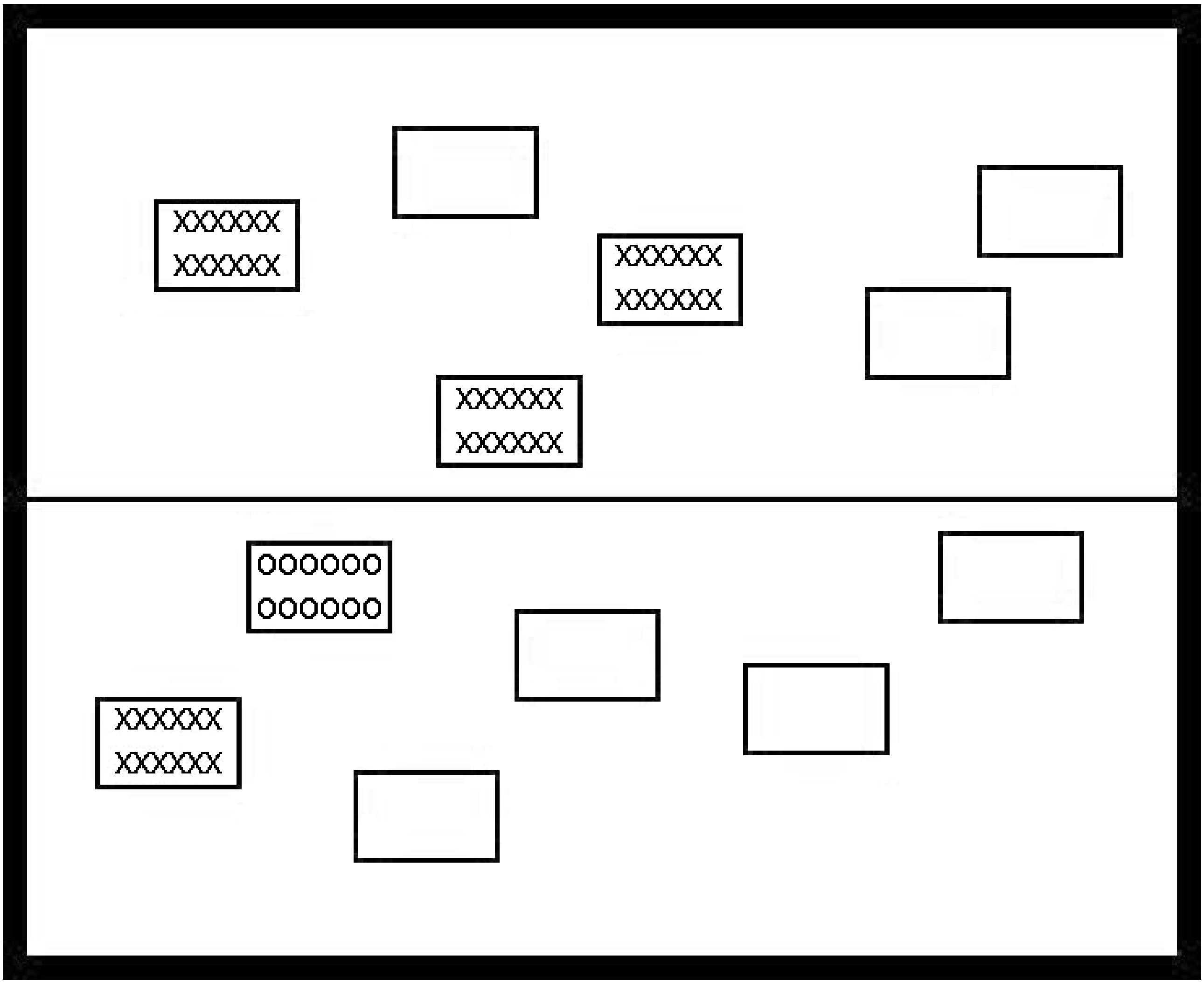
Figure 6. Mean recall x condition over the two halves of the spatial updating task.

Figure 6a: Control group.

Figure 6b: Dyslexic group.

Figure 7: Effect size analyses, indicating the relative severity of dyslexic span deficits in comparison to the control group (calculated by subtracting the control mean from the dyslexic

mean on each task and then dividing by the SD of the control group). The effect size of the control group on each task is thus 0 (and not shown in the figure).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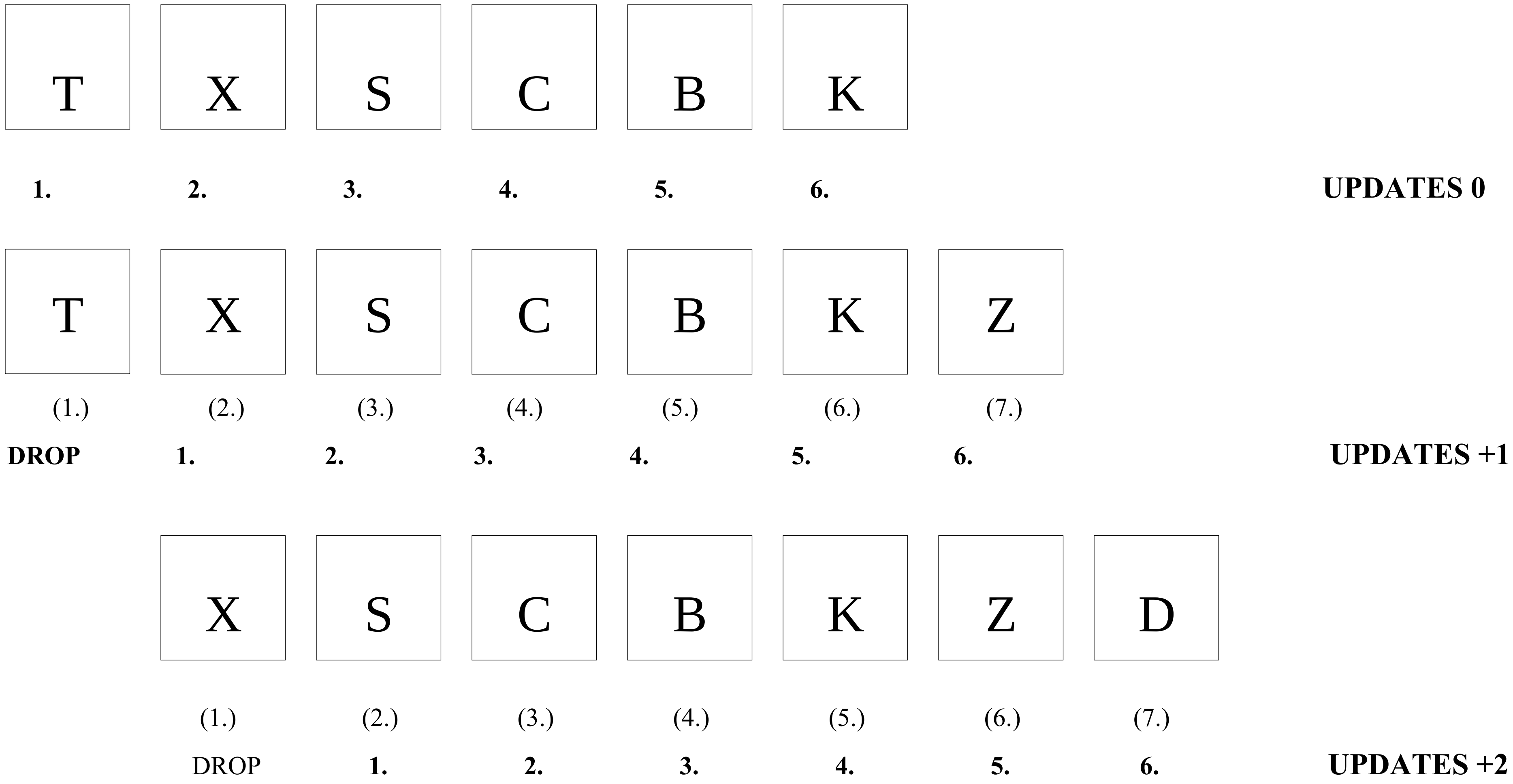
T X S C B K
1. 2. 3. 4. 5. 6.
UPDATES 0
T X S C B K Z
(1.) (2.) (3.) (4.) (5.) (6.) (7.)
DROP 1. 2. 3. 4. 5. 6.
UPDATES +1
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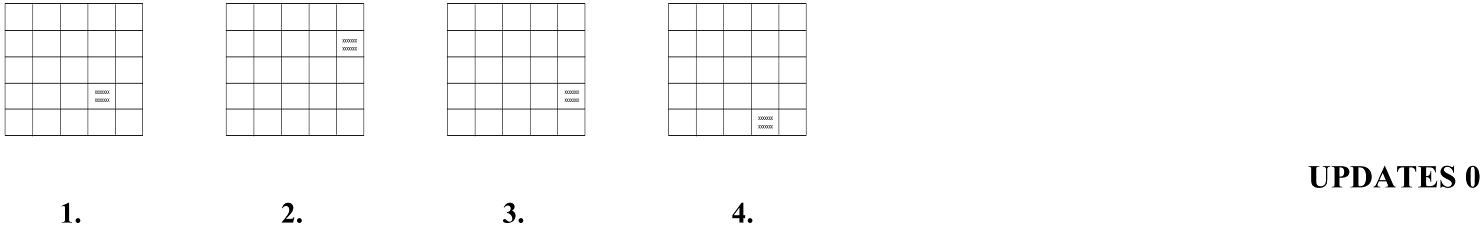
(1.) (2.) (3.) (4.) (5.) (6.) (7.)
DROP 1. 2. 3. 4. 5. 6.
UPDATES +2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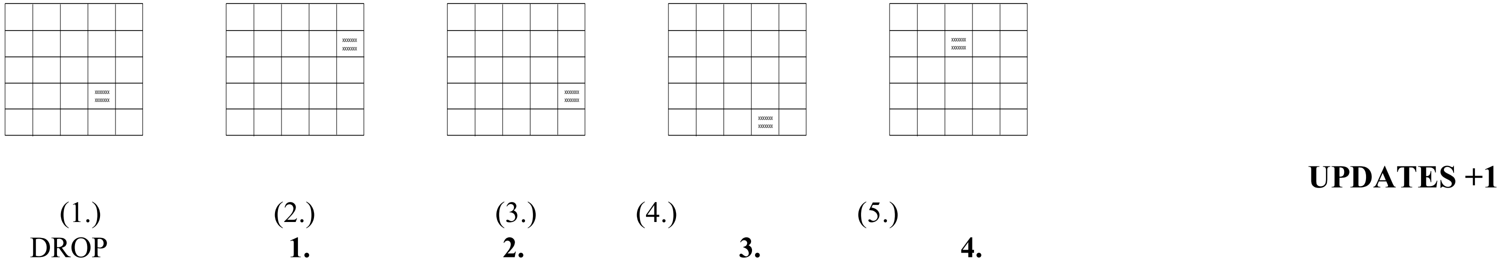
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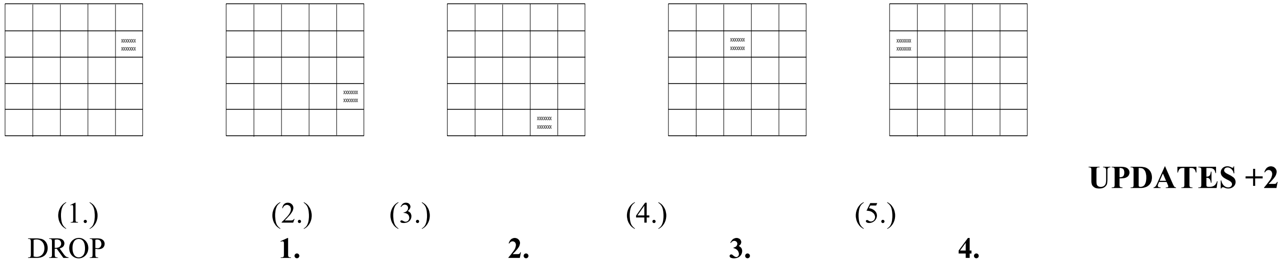
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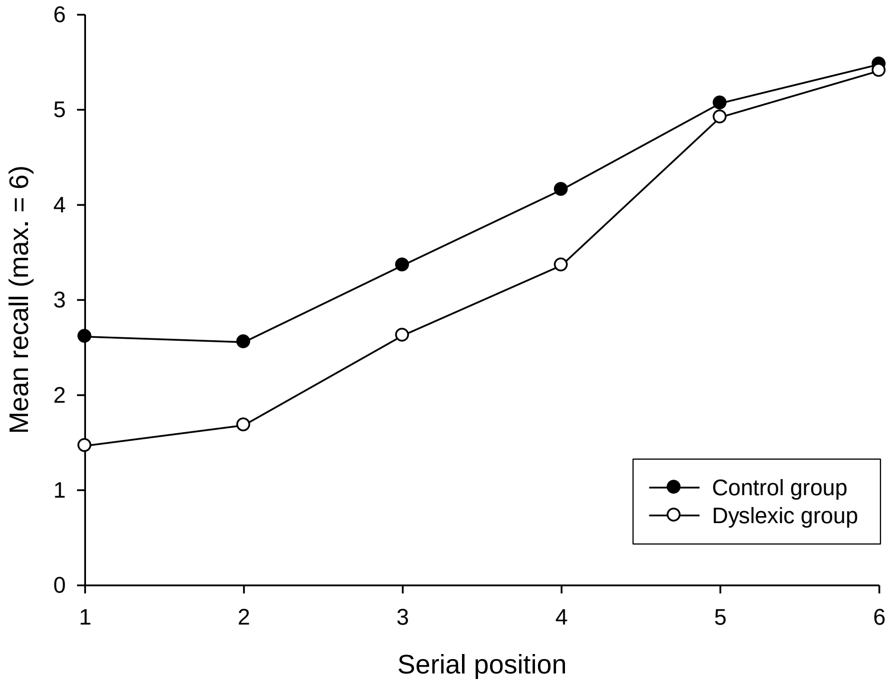
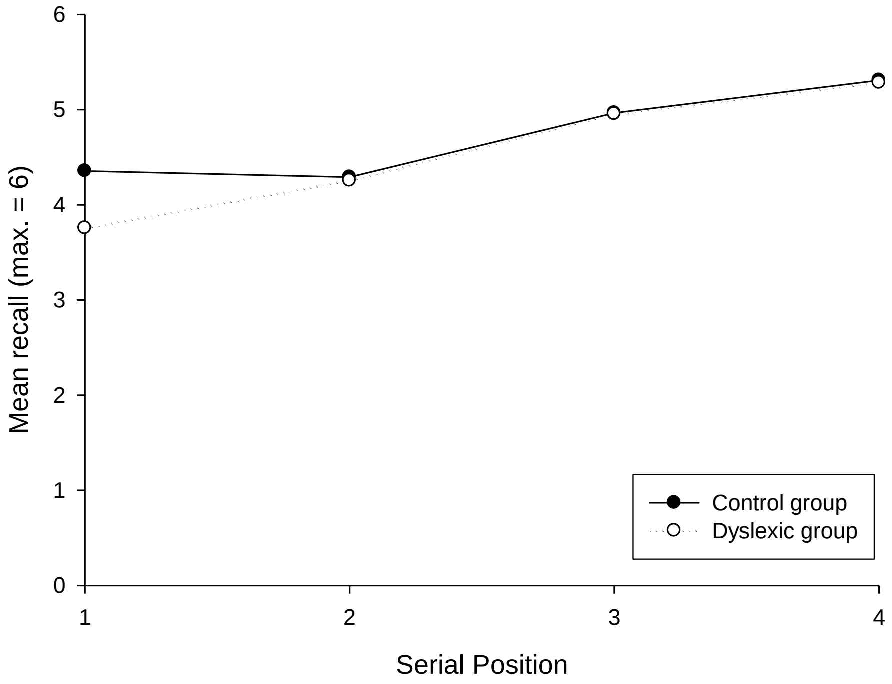

Mean recall (max. = 6)
0
1
2
3
4
5
6
Serial position
1
2
3
4
5
6
Control group
Dyslexic group


6
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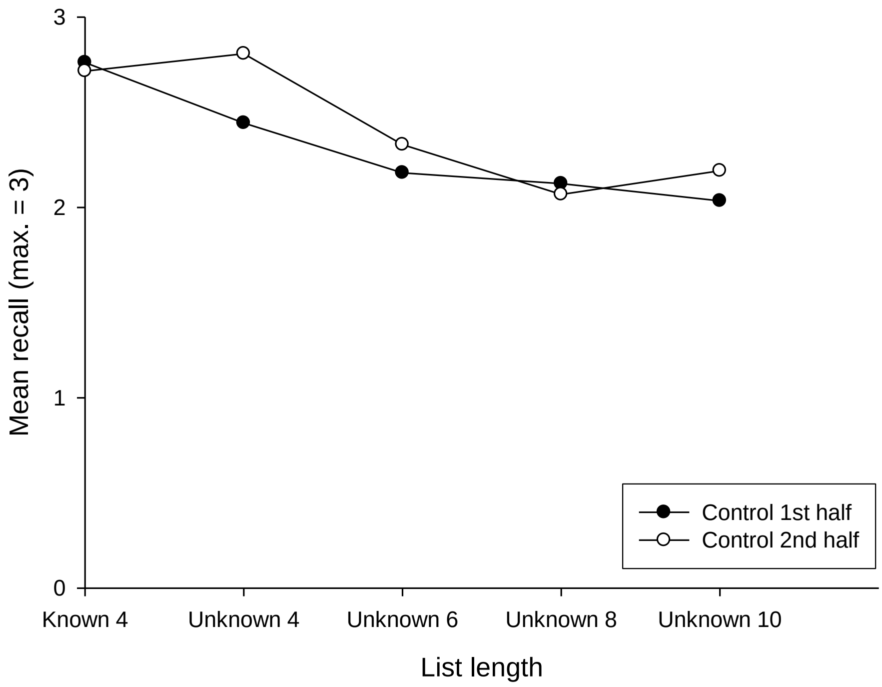
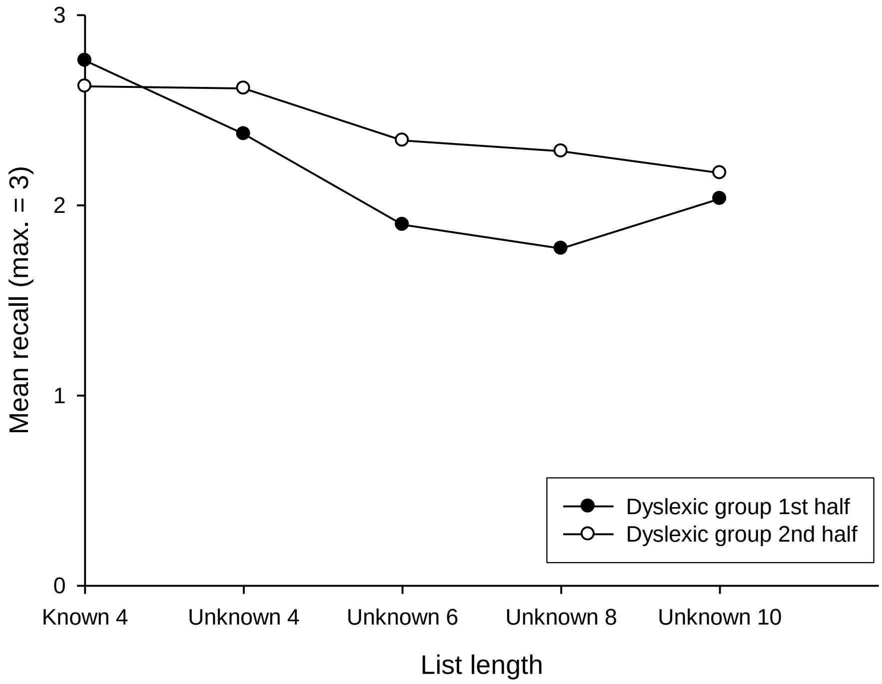
0
Mean recall (max. = 6)
1
2
3
4
Serial Position
Control group
Dyslexic group


3
2
1
0
Mean recall (max. = 3)
Known 4
Unknown 4
Unknown 6
Unknown 8
Unknown 10
List length
Control 1st half
Control 2nd half


Mean recall (max. = 3)
3
2
1
0
Known 4
Unknown 4
Unknown 6
Unknown 8
Unknown 10
List length
Dyslexic group 1st half
Dyslexic group 2nd half

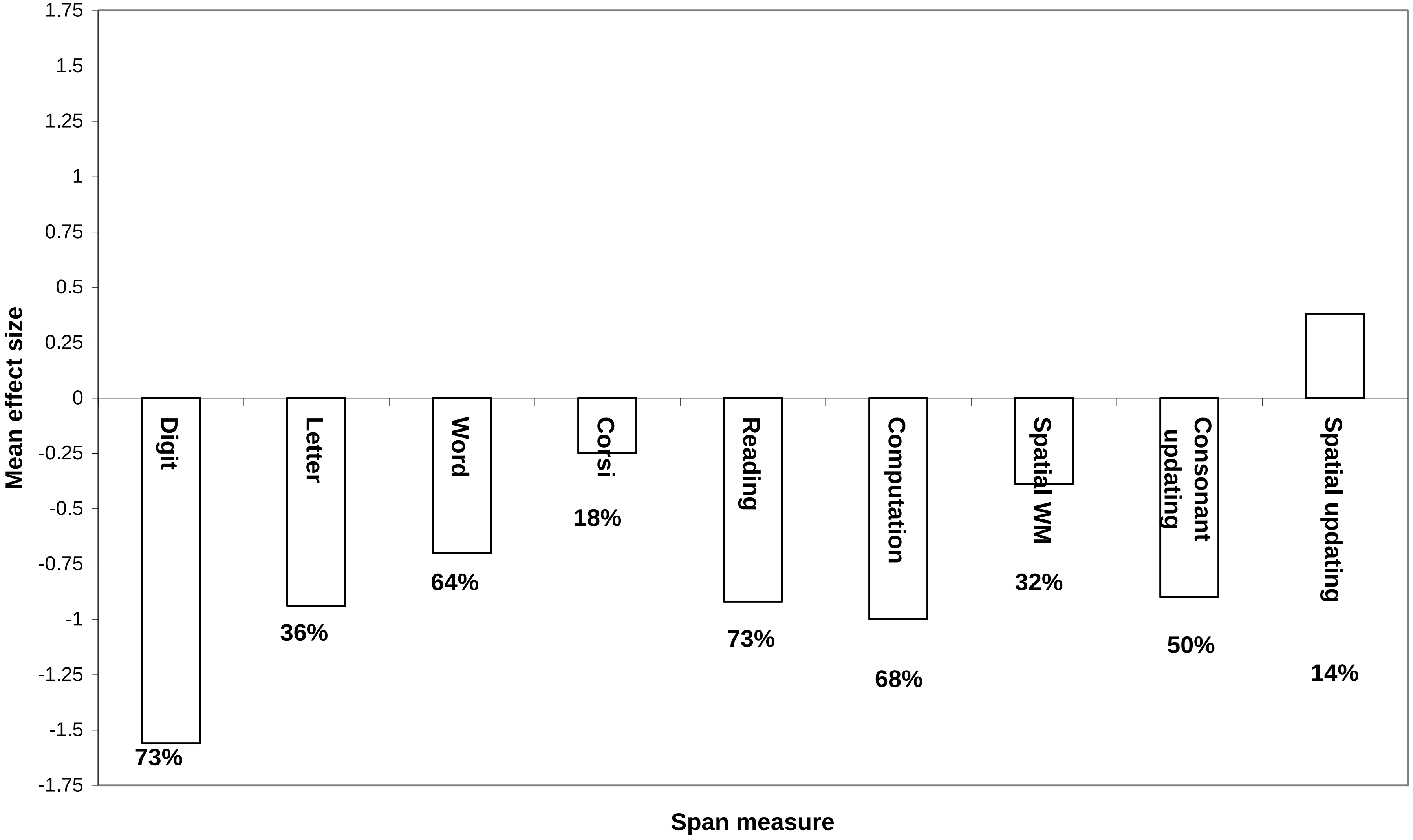

Mean effect size
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
Digit
73%
Letter
36%
Word
64%
Corsi
18%
Reading
73%
Computation
68%
Spatial WM
32%
Consonant updating
50%
Spatial updating
14%
Span measure

Table 1:

Background details on the participant groups. One-way ANOVA results are also displayed, with (1, 42) degrees of freedom, except for the short-form IQ analysis, where df = (1, 40).

Measure	Control Group	Dyslexic Group	*F*	Sig.
Mean Age in Years	20.82 (*SD* = 2.26; *SEM* = 0.48)	20.59 (*SD* = 2.68; *SEM* = 0.57)	0.09	.763
Mean WORD score (Max. = 50)	46.45 (*SD* = 1.71; *SEM* = 0.37)	39.18 (*SD* = 3.78; *SEM* = 0.81)	67.74	< .001
Mean Overall DAST Non-word Reading Score (Max. = 99)	92.55 (*SD* = 4.11; *SEM* = 0.88)	74.59 (*SD* = 11.27; *SEM* = 2.40)	49.30	< .001
WAIS-III Picture Completion	10.50 (*SD* = 2.48; *SEM* = 0.53)	10.75 (*SD* = 2.67; *SEM* = 0.60)	0.10	.755
WAIS-III Similarities	12.23 (*SD* = 2.02; *SEM* = 0.43)	12.45 (*SD* = 2.33; *SEM* = 0.52)	0.11	.742
WAIS-III Block Design	13.18 (*SD* = 2.72; *SEM* = 0.58)	12.15 (*SD* = 2.11; *SEM* = 0.47)	1.86	.180
WAIS-III Comprehension	14.05 (*SD* = 2.04; *SEM* = 0.43)	13.80 (*SD* = 2.38; *SEM* = 0.53)	0.13	.720
Mean Short-form IQ	116.36 (*SD* = 9.33; *SEM* = 1.99)	113.29 (*SD* = 9.22; *SEM* = 2.01)	.822	.370

Table 2:

Mean scores for the simple and working memory span measures. Standard deviations and standard error of the mean values are given in parentheses. One-way ANOVA results are also displayed, with (1, 42) degrees of freedom.

Measure	Control Group	Dyslexic Group	*F*	Sig.
Digit Span	7.36 (*SD* = 1.33, *SEM* = 0.28)	5.77 (*SD* = 1.31, *SEM* = 0.28)	16.03	< .001
Letter Span	5.77 (*SD* = 0.97, *SEM* = 0.21)	4.86 (*SD* = 0.83, *SEM* = 0.18)	11.08	.002
Word Span	4.86 (*SD* = 0.77, *SEM* = 0.17)	4.32 (*SD* = 0.57, *SEM* = 0.12)	7.10	.011
Corsi Block Span	4.41 (*SD* = 0.85, *SEM* = 0.18)	3.95 (*SD* = 0.65, *SEM* = 0.14)	3.93	.054
Reading Span	3.09 (*SD* = 1.34, *SEM* = 0.29)	2.18 (*SD* = 1.14, *SEM* = 0.24)	5.87	.020
Computation Span	3.82 (*SD* = 1.68, *SEM* = 0.36)	2.32 (*SD* = 1.29, *SEM* = 0.27)	11.05	.002
Spatial Working Memory Span	3.64 (*SD* = 1.47, *SEM* = 0.31)	2.77 (*SD* = 1.11, *SEM* = 0.24)	4.86	.033

Table 3:

Summary table of AN(C)OVA results.

Measure	Independent Variables	Covariates	Analysis Type	Results
Verbal Working Memory Composite	Group	Simple Verbal Memory Span Composite	One-way ANCOVA	F(1, 41) = 6.33, *MSE* = 0.489, *p* = .016*
Spatial Working Memory Span	Group	Simple Spatial Span	One-way ANCOVA	F(1, 41) = 4.33, *MSE* = 1.73, *p* = .044*
Spatial Working Memory Span, Spatial Span	Group Task (2 levels, SWM span versus Spatial Span) Length (6 levels)	None	Factorial Mixed ANOVA	Group: F(1, 42) = 4.03, *MSE* = 0.499, *p* = .007** Task: F(1, 42) =55.87, *MSE* = 0.221, *p* < .001*** Length: F(3.47, 145.76) = 82.75, *MSE* = 0.306, *p* < .001*** Group by Task: F(1, 42) =6.11, *MSE* = 0.209, *p* < .001*** Group by Length and Group by Task, *F* < 1.01, ns, in both cases
Consonant Updating	Group List length (4 levels) Serial Position (6 levels)	None	Factorial Mixed ANOVA	Group: *F(*1, 42) = 8.28, *MSE* = 12.60, *p* = .006** Length: *F(*3, 126) = 10.96, *MSE* = 2.22, *p* < .001*** Group by Length: *F(*3, 126) =3.03, *MSE* = 2.22, *p* = .032* Serial: *F(*2.06, 86.39)= 206.95, *MSE* = 4.28, *p* < .001*** Group by Serial: *F(*2.06, 86.39) = 4.58, *MSE* = 4.28, *p* = .012* Length by Serial: *F(*8.14, 341.94) = 30.57, *MSE* = 1.75, *p* < .001*** Group by Length by Serial: *F(*8.14, 341.94) = 1.57, *MSE* = 1.75, *p* = .132 ns

*** *p* < .001; ** *p* < .01; * *p* < .05; ns non significant, *p* > .05

Where Mauchley's test of sphericity was significant, Greenhouse-Geisser epsilon adjusted degrees of freedom have been used.

Table 3 (contd.):

Summary table of AN(C)OVA results.

Measure	Independent Variables	Covariates	Analysis Type	Results
Spatial Updating	Group Sequence length (5 levels) Serial Position (4 levels)	None	Factorial Mixed ANOVA	Group: $F(1,42) < 1$, $MSE = 8.83$, $p = .406$ ns Length: $F(2.55, 107.22) = 30.88$, $MSE = 2.91$, $p < .001$*** Group by Length: $F(2.55, 107.22) <1$, $MSE = 2.91$, $p = .771$ ns Serial: $F(2.55, 106.91) = 97.79$, $MSE = 0.89$, $p < .001$*** Group by Serial: $F(2.55, 106.91)=6.03$, $MSE = 0.89$, $p = .001$** Length by Serial: $F(7.67, 322.26)=14.58$, $MSE = 1.05$, $p < .001$*** Group by Length by Serial: $F(7.67, 322.26)=.2.15$, $MSE = 1.05$, $p = .033$*
Spatial Updating	Group Sequence length (5 levels) Test Half (2 levels)		Factorial Mixed ANOVA	Test Half: $F(1, 42) = 18.37$, $MSE = 0.743$, $p < .001$*** Test Half by Length: $F(4, 168)=3.19$, $MSE = 0.722$, $p = .015$* Group by Test Half: $F(1, 42) = 2.31$, $MSE = 0.743$, $p = .136$ ns Group by Test Half by Length: $F(4, 168) = 2.72$, $MSE = 0.722$, $p = .032$*

*** $p < .001$; ** $p < .01$; * $p < .05$; ns non significant, $p > .05$

Where Mauchley's test of sphericity was significant, Greenhouse-Geisser epsilon adjusted degrees of freedom have been used.

Table 4:

Mean span scores (max. = 3) on the Corsi block span and the spatial working memory span tasks.

	Corsi Block Span Task		Spatial Working Memory Span Task	
Span Length	Control Group	Dyslexic Group	Control Group	Dyslexic Group
One	2.95 (*SD* = 0.21, *SEM* = 0.05)	2.91 (*SD* = 0.29, *SEM* = 0.06)	2.59 (*SD* = 0.59, *SEM* = 0.13)	2.50 (*SD* = 0.51, *SEM* = 0.11)
Two	2.98 (*SD* = 0.11, *SEM* = 0.02)	2.95 (*SD* = 0.15, *SEM* = 0.03)	2.91 (*SD* = 0.20, *SEM* = 0.04)	2.68 (*SD* = 0.59, *SEM* = 0.13)
Three	2.98 (*SD* = 0.07, *SEM* = 0.02)	2.94 (*SD* = 0.17, *SEM* = 0.04)	2.85 (*SD* = 0.27, *SEM* = 0.06)	2.64 (*SD* = 0.37, *SEM* = 0.08)
Four	2.83 (*SD* = 0.26, *SEM* = 0.06)	2.68 (*SD* = 0.35, *SEM* = 0.07)	2.35 (*SD* = 0.57, *SEM* = 0.12)	2.09 (*SD* = 0.56, *SEM* = 0.12)
Five	1.96 (*SD* = 0.71, *SEM* = 0.15)	1.96 (*SD* = 0.52, *SEM* = 0.11)	2.21 (*SD* = 0.60, *SEM* = 0.13)	1.72 (*SD* = 0.56, *SEM* = 0.12)
Six	2.27 (*SD* = 0.53, *SEM* = 0.11)	2.00 (*SD* = 0.51, *SEM* = 0.11)	1.75 (*SD* = 0.76, *SEM* = 0.16)	1.47 (*SD* = 0.63, *SEM* = 0.14)

Table 5:

Mean group recall for each level of the consonant and spatial updating tasks.

Task and Level	Control Group	Dyslexic Group
Consonant updating: 6 letters	26.68 (SD = 4.83, SEM = 1.03)	20.95 (SD = 5.87, SEM = 1.25)
Consonant updating: 8 letters	22.50 (SD = 6.72, SEM = 1.43)	18.23 (SD = 4.92, SEM = 1.05)
Consonant updating: 10 letters	20.86 (SD = 6.07, SEM = 1.29)	19.36 (SD = 4.94, SEM = 1.05)
Consonant updating: 12 letters	22.50 (SD = 5.38, SEM = 1.15)	19.27 (SD = 3.74, SEM = 0.80)
Spatial updating: Known 4 cells	21.77 (SD = 2.69, SEM = 0.57)	21.45 (SD = 2.44, SEM = 0.52)
Spatial updating: 4 cells	21.00 (SD = 3.90, SEM = 0.83)	19.82 (SD = 3.55, SEM = 0.76)
Spatial updating: 6 cells	18.05 (SD = 3.39, SEM = 0.72)	16.91 (SD = 4.12, SEM = 0.88)
Spatial updating: 8 cells	16.82 (SD = 3.03, SEM = 0.65)	16.23 (SD = 4.35, SEM = 0.93)
Spatial updating: 10 cells	17.00 (SD = 4.05, SEM = 0.86)	16.82 (SD = 4.09, SEM = 0.87)

Table 6:

Mean overall scores on the first and second halves of the spatial updating task. Standard deviations and standard error of the mean values are given in parentheses.

Test-half	Control Group	Dyslexic Group
First Half	46.18 (*SD* = 7.49, *SEM* = 1.598)	43.36 (*SD* = 7.59, *SEM* = 1.618)
Second Half	48.45 (*SD* = 6.29, *SEM* = 1.340)	48.14 (*SD* = 7.31, *SEM* = 1.559)