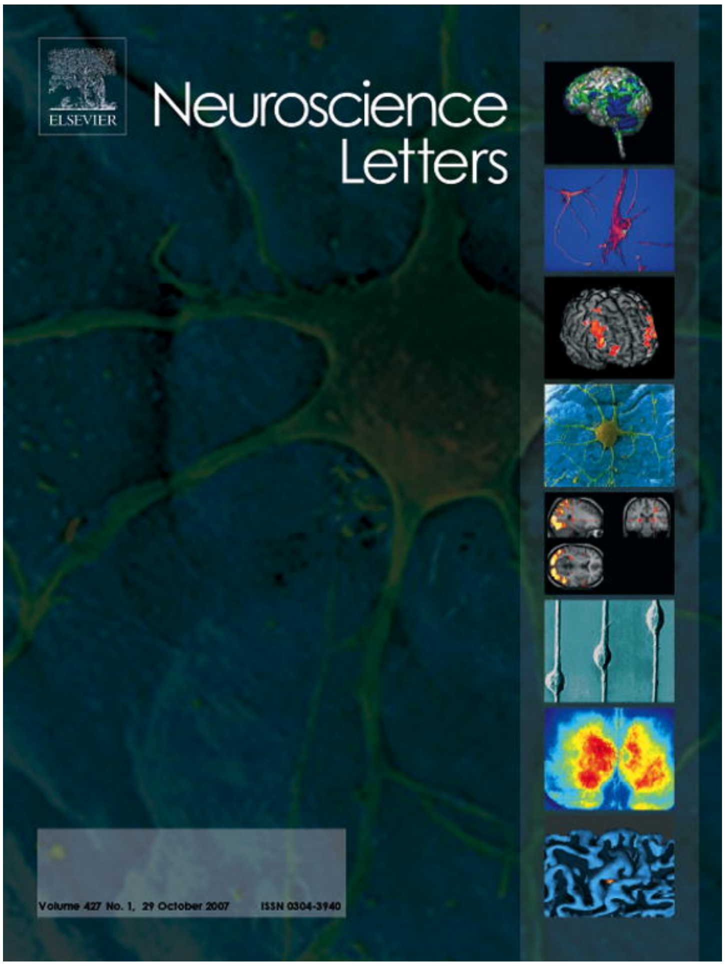
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Dyslexia and attentional shifting

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Abstract

Dyslexia is a neurocognitive deficit primarily expressed in reading difficulties, but also affecting non-linguistic performance. Several studies report that dyslexics perform differently in the attentional blink paradigm, which indicates an impaired capacity to rapidly shift visual attention. However, attentional shifting can occur at different levels of cognitive processing, and it is unclear whether dyslexic attentional shifting is impaired at all levels, or only at the peripheral levels. We studied performance on a task-switching paradigm by dyslexics and normal readers to test whether the difficulty with attentional shifting occurs at the level of central cognitive processing. We found no specific impairments in task-switching in dyslexics. However, dyslexics performed generally much more slowly across all conditions than normal readers. We conclude that while dyslexics have a problem with attentional switching at a perceptual level, their capacity to rapidly switch between tasks is normal. Our findings add to previous studies indicating that dyslexic problems with shifting visual attention are caused by anomalies in more peripheral neural pathways, such as the magnocellular layers in the lateral geniculate nucleus.

Keywords: Dyslexia; Cognition; Attention; Executive control

Dyslexia is a neurocognitive deficit characterized by reading difficulties. It affects between 5 and 17.5% of the population [20]. Estimates of dyslexia prevalence might differ between cultures because not all languages are equally impacted by the deficit [16].

The mechanisms underlying the deficit have been well studied at the behavioral and neural levels. The application of structural MRI and diffusion tensor imaging has revealed that multiple brain regions play a distinctive role in dyslexia, including parietal, inferior frontal, and cerebellar networks [4]. Post-mortem brain analyses of dyslexics have revealed a number of anatomical anomalies [5], including small cell bodies and a higher level of disorganization in magnocellular neurons of the lateral geniculate nucleus [13]. Despite the progress in dyslexia research, there is still considerable controversy about certain neural hypotheses regarding dyslexia, such as the exact interpretation of the role of the magnocellular pathways [22,23].

Analyses of the dyslexic anatomy and neurophysiology provide important information about the possible causes of dyslexia, but are not sufficient for a full understanding of the deficit. We also need behavioral analyses of dyslexic performance to identify which cognitive processes are impaired exactly, and how impairments might be related to the identified neural networks.

In the past decades, a large number of behavioral studies have aimed to identify the stages of cognitive processing that cause dyslexia. There is evidence from multiple studies that dyslexics have problems with shifting attention. This evidence comes from the reported deviations in dyslexic's performance on the attentional blink paradigm [7,8,12,14]. In the attentional blink paradigm, subjects are presented a fast sequence of stimuli containing one or more targets [3]. For example, participants are presented a sequence of both letters and digits, each item visible for a very short time (e.g., 100 ms). Participants may be instructed to memorize the letters of the sequence (i.e., letters are targets). The "attentional blink" refers to the finding that after people have identified the first target in a sequence, they are far less accurate in identifying a target that succeeds the first target in close temporal proximity (up to approximately 500 ms). It is assumed that the attentional blink reflects a sustained attentional state supporting the control of behavior [3].

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Several studies found impaired attentional shifting in dyslexics performing the attentional blink paradigm [8,14], while one study reports that dyslexics performed better than normal readers [12]. Nevertheless, all agree that the deviating dyslexic performance in the attentional blink paradigm points to impaired visual attention.

In a recent review of studies on attention in dyslexics [7], the "sluggish attentional shifting" hypothesis proposes that once attention is engaged it cannot as easily disengage as in normal readers. However, attentional shifting is a complex topic in cognitive neuroscience, and attentional shifting has been described to occur at different levels of processing. Attentional shifting at the perceptual level is the moving of attention between different perceptual scenes, for example when one shifts gaze from one location to another [11]. Such a shift of attention can be triggered independently of executive control and task goals (e.g., a suddenly appearing or flashing object might automatically attract attention). On the other hand, attentional shifting at the cognitive level requires some additional mechanisms. For example, one can keep gaze at the same stimulus, and yet the executive system can shift attention between different features of the same stimulus, or shift attention between different aims it may associate with the same stimulus [24]. While there is good evidence for a dyslexic deficit in shifting visual attention, it is unclear whether dyslexics would have a problem shifting their attention at a higher level, such as at the level of executive control, which is important for shifting attention between task rules and abstract thoughts [19].

There are reasons to hypothesize that dyslexics have a problem with attentional shifting at the cognitive level, because it has been argued that dyslexics have impaired executive functions [1,9], something typically associated with impaired mental flexibility. However, based on the available literature, it is still unclear whether attentional shifting is impaired only at the peripheral level, or also at higher cognitive levels.

Here, we aim to answer whether more central or more peripheral components of attentional shifting are affected by dyslexia using a task-switching paradigm, which measures the capacity to shift attention between abstract rules. Task-switching paradigms are well suited to study the flexibility of attention [15], and are helpful in characterizing impaired attentional shifting at the executive level [25].

Task-switching paradigms are specifically designed to measure the difficulty people have with switching between two tasks. People perform more slowly and less accurately on trials on which a task-switch is made compared to trials on which the same task is done as in the previous trial. This slowing down is known as a "switch cost", and is quantified by subtracting performance (e.g., response time or error rate) in trials in which the task is repeated from performance in trials in which there is a task-switch. Further, the task-switching paradigm measures the difficulty to ignore stimulus features that are relevant in one task, but not in the other task. This latter difficulty is known as "task interference", and is quantified by subtracting the performance in trials in which a stimulus has the same meaning in the two task contexts (i.e., congruent stimulus) from the performance in trials in which a stimulus has opposite meanings (i.e., incongruent stimulus). One of the major advantages of task-switching paradigms is the use of the identical set of stimuli in all tasks. This means that performance differences between conditions cannot simply be attributed to perceptual difficulties with the stimuli of one or the other task. In other words, in task-switching paradigms people need to switch between cognitive rules while the set of stimuli stays the same.

We hypothesized that if dyslexics have a general problem with attentional shifting, they would show larger switch costs than normal readers. However, if the dyslexic cognitive problem of attentional switching is more peripheral in nature, dyslexics should show normal switch costs.

Eleven dyslexic and 11 normal readers, with an age range of 19–25 years, were sampled from an undergraduate student population and volunteered in accordance with institutionally required ethical guidelines. All subjects had normal or corrected to normal vision. Inclusion criterion for the dyslexic participants was that they had been professionally diagnosed as dyslexic at some point in their life in the United Kingdom. An important inclusion criterion for the control participants was that they considered themselves to be good readers. While this self-assessed inclusion criterion would unlikely select dyslexics, we still performed two more tests sensitive to dyslexia, primarily to ensure that none of the control participants suffered from it. None of the participants suffered from attention deficit hyperactivity disorder, dyspraxia, or scotopic sensitivity, as was established during an interview between experimenter and participant at the beginning of the session.

The experiment was controlled by a PC running custom software. Stimuli were presented on a 17 in. cathode ray monitor. We used the *Revised Adult Dyslexia Check List* [28] and a non-word repetition test [6], primarily to spot control participants who might unknowingly be dyslexic. A color-blindness test ensured that none of the participants was color blind [10]. Interviewing and testing before the actual task-switching experiment took 20 min, and it was established that none of the control subjects showed signs of dyslexia.

Participants were seated behind the computer screen and keyboard, with ∼60 cm between eyes and screen. They used their index fingers for pressing the left or right shift key of the computer keyboard. All data collection was preceded by verbal instructions and 40 practice trials. The experiment was divided in blocks that lasted no more than 10 min each, and participants were encouraged to take a short break between blocks.

Participants performed a total of 720 trials of the paradigm. A trial could be one of two possible task types, namely a color discrimination task or a shape discrimination task. In the color discrimination task, participants needed to distinguish the color of stimuli, and in the shape discrimination task their shape. Each trial started with the presentation of a task cue for 500 ms (Fig. 1A), which was either a rainbow instructing to perform the color discrimination task, or a white triangle instructing to perform the shape discrimination task. The task cue was followed by a delay (with a blank screen) of 200 ms, and then followed by a target stimulus. The target stimulus was one of four possible stimuli: A red circle, a red square, a green circle, or a green square (Fig. 1B).

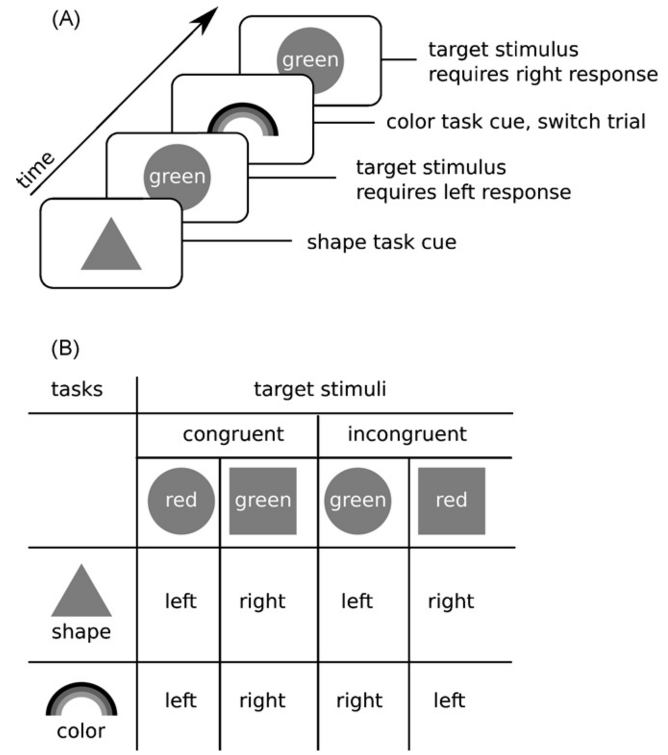

Fig. 1. Stimulus material and stimulus–response associations in the task-switching paradigm. (A) From bottom left to top right, an example sequence of trials in the task-switching paradigm is shown. The color name in the stimuli is for print purposes only, and indicates the colors of the stimuli the participants were presented with. (B) Stimulus–response associations in the two tasks. Congruent stimuli require the same response irrespective of task context, whereas incongruent stimuli require opposite responses in the two task contexts.

Fig. 1A shows an example sequence of events in two consecutive trials. The first example trial starts with a triangle (500 ms), instructing the participant to perform the shape discrimination task on the upcoming target stimulus. The triangle is followed by a 200 ms delay (blank screen), then followed by the target stimulus, which is a green circle. A green circle requires a left button press in the shape task (see Fig. 1B for stimulus–response associations). As soon as the left button has been pressed, the target stimulus disappears and the trial ends. The next trials follows after 500 ms with a color cue (rainbow), instructing the participant to apply the color discrimination on the following target. This trial is a *switch trial*, because this trial is of a different task type (i.e., color task) than the preceding task (i.e., shape task). The task cue is presented for 500 ms, followed by a 200 ms delay, followed by a green circle, now requiring a right button press, because the color green is associated with the right button press in the color task.

In the color discrimination task, red and green shapes required a left or right button press, respectively. In the shape discrimination task, circles and squares (irrespective of their color) were mapped on the left and right keys, respectively. One half of the stimuli were congruent, meaning that color and shape would be associated with the same key in both tasks, and one half was incongruent, meaning that color and shape of a stimulus were associated with different keys in the two tasks. For example, a green square is a congruent stimulus because it is always associated with a right button press. On the other hand, a green circle is incongruent because it is associated with the left response in the shape task and with the right response the color task (Fig. 1B).

Trials of both tasks were randomly interleaved, with a 500 ms pause between trials. The cues and stimuli were randomly selected on each trial. In each trial, a target stimulus was presented until a button was pressed, but no longer than 5 s. Wrong responses were followed by an error message and a 4 s delay. Switch trials were those on which a different task was to be performed than on the preceding trial. Repeat trials were those on which the same task was to be performed as on the preceding trial. Switch and repeat trials were randomly interleaved.

Statistical significance of comparisons in reaction times (RT) and error rates (PE) was determined using ANOVAs with one between subjects variable (i.e., dyslexia) and two within subjects variables (i.e., task-switch and congruency). The data of all participants were averaged into four conditions resulting from the two factors "task-switch" (with the levels switch and repeat) and "congruency" (with the levels congruent and incongruent). The alpha criterion for statistical significance was 5%. We report whether statistical tests were significant according to this criterion (i.e., $p < 0.05$), or whether they were highly significant (i.e., $p < 0.01$). Statistical tests were performed with the statistical package R [17].

We found significant switch costs in both groups of participants (Fig. 2A). On average, performance in switch trials was 25% slower than in repeat trials ($F(1,20) = 41$, $p < 0.01$). Switch costs were also present in the levels of accuracy, with a doubling of errors in the switch trials compared to repeat trials ($F(1,20) = 83$, $p < 0.01$). These findings were exactly as expected based on the many task-switching experiments.

Relevant to our study was whether dyslexics were different in their switch costs from normal readers. We found no significant differences in switch costs between the two groups. Switch costs in response time in the dyslexic group were 175 ± 32 ms (mean ± 1S.E.M.), and in the control group 145 ± 38 ms. Switch costs in the error rates in the dyslexic group were 4.8 ± 0.9%, and in the control group 4.4 ± 0.5%.

People responded 6% slower in incongruent trials than in congruent trials ($F(1,20) = 16$, $p < 0.01$). This task interference was similar in both groups (37 ± 15 and 32 ± 14 for dyslexics and normals, respectively). Dyslexic task interference in the error rates was 7.9 ± 1.3% and 4.6 ± 0.6% in controls. The statistical significance of this difference between the groups was near significant ($F(1,20) = 4$, $p = 0.06$).

Response times across conditions were significantly different between the two groups ($F(1,20) = 7$, $p < 0.05$), indicating that dyslexics were, on average, 168 ms slower than normal readers. This difference was obvious when visually inspecting the overall response times of the individual participants in the groups (Fig. 2B). For example, half of the control participants were faster than the fastest dyslexic participant (663 ms, Fig. 2B). While the control participants performed faster, their accuracy was in a similar range as the dyslexics (Fig. 2C), and there was no significant difference between the average error rates of the two groups.

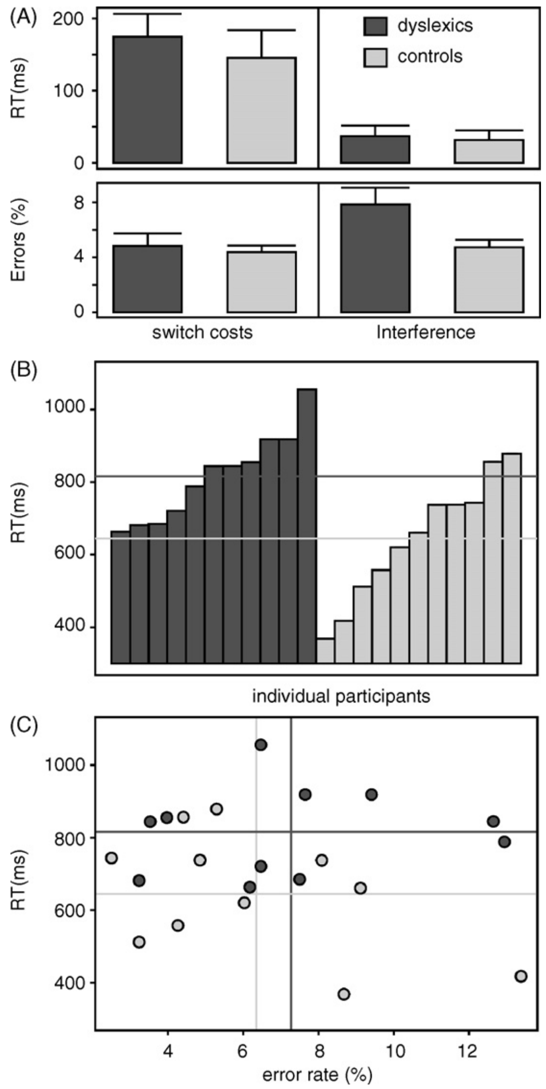

Fig. 2. Performance in the task-switching paradigm. (A) Switch costs and (task) interference for both dyslexics (black) and normal readers (grey) in response times and error rates. Switch costs are calculated as the mean RT (or PE) in the task-switch trials minus the mean RT (or PE) in the task-repeat trials. Task interference is calculated as the mean RT (or PE) in the incongruent trials minus the mean RT (or PE) in the congruent trials. Error bars indicate 1S.E.M. None of the group differences in switch costs and in task interference were statistically significant (as tested with ANOVAs). (B) Overall average response time of individual dyslexic (black) and normal (grey) readers. Responses in the dyslexic group were significantly slower (816 ± 37) than in the control group (644 ± 50, group means indicated by the horizontal lines). (C) Individual response times and group means (as in B) plotted against error rates for dyslexic (black) and normal (grey) readers, indicating a performance deficit in overall response time in the dyslexic group ($p < 0.05$), but not in error rates. No relationship between response time and error rate was found in either group.

The group difference in overall speed has implications for the interpretation of the switch costs and interference costs. For example, if the overall scores of one group are higher, the relative switch costs (i.e., the percentage of slowing down in switch trials) might be different from the absolute switch costs (i.e., the slowing down in milliseconds). Because psychologists are typically more interested in relative changes than in absolute changes in response time, the comparison of groups with different response times might lead to difficulties in the interpretation of data [2]. While the (statistically non-significant) absolute difference between switch costs in dyslexics and normal readers is 30 ms (175 ms in dyslexics, 145 ms in controls, Fig. 2A, top left), both groups show exactly the same relative switch costs of 25%. In a similar fashion, the (not statistically significant) relative higher error rate in incongruent trials in dyslexics is slightly less than the absolute higher error rate in incongruent trials (Fig. 2A, bottom right). Altogether, this analysis indicates that the absolute higher scores of dyslexics in switch and interference costs (as shown in Fig. 2A) are slightly smaller when calculated as relative costs. However, no different patterns of effects in the ANOVAs of relative scores were revealed.

Our study aimed to assess the capacity of task-switching in dyslexics. We found that dyslexic participants performed 27% slower than normal readers. However, we found no differences in the switch costs between the two groups. In fact, relative switch costs in both groups are exactly the same, that is, in both groups switch trials are performed 25% slower than repeat trials. We conclude that dyslexics have no specific problem with cognitive attentional shifting, and that problems with attentional shifting observed by other researchers are most likely due to deficits in more peripheral neural systems.

Slowing in the response speed of dyslexics has been reported by others in different tasks. For example, a recent study [21] reported a 20–30% slowing in response speed in a visual detection task compared to control participants. Another research team [26] argued that a motor deficit in dyslexics might be responsible for the 9% slower performance they observed in dyslexics compared to controls in the Annett peg-moving task. We therefore conclude that the general slowing in our data is not due to the specific cognitive demands of the task-switching paradigm itself, but pointing to the general slowing observed by several research groups in quite different tasks in dyslexics. In addition to the interpretations offered in the aforementioned studies of response slowing in dyslexics [21,26], it is possible that the skills studied in those studies themselves need specific training to be developed, and that a limited ability itself may reduce the capacity to train, and thus strengthen the observed limitations.

Could a fundamental group difference other than dyslexia better explain our data? For example, might our groups have differed on a feature such as general intelligence? We do not belief that the differences in response speed can be attributed to a potential mismatch in general intelligence between the two experimental groups. General intelligence is assumed to correlate with response time [27], while differences between dyslexics and normal readers, including slowness and reading problems are found despite otherwise intact mental capacities [26]. Thus, even though dyslexics are slower in their general response pattern, it is difficult to simply attribute this to lower intelligence. Whether or not the general response slowing would be related to lower general intelligence, the main finding of our study is that switch costs are *normal* in the dyslexic group. If our dyslexic participants had both scored significantly lower in general response time and in switch costs, one could have argued that such a general slowing in all measures could be due to a lower intelligence. However, our finding that switch costs are normal, despite slower overall response times indicates that slowing in dyslexics is not so much due to a problem in the central executive system, believed to be responsible for skills such as switching, but rather due to a more peripheral slowing.

Some studies have reported deficits in executive control in dyslexics [1,9]. These studies are relevant for our study, as it is generally assumed that task-switching paradigms measure correlates of executive control [15]. Based on the assumption that switch costs do reflect an executive function, and given that dyslexics show some impaired executive functions, they should certainly show increased switch costs. However, we found absolutely no evidence for impaired switching. We believe that this apparent paradox between different studies can be explained. Executive control is not referring to one homogeneous cognitive function, but to a collection a cognitive functions with the common purpose of coordinating and integrating multiple thought processes [19]. In the spirit of this idea, the aforementioned studies that found impaired executive functions in dyslexics did indeed find that some executive functions were impaired, whereas some other executive functions were normal. For example, one study found that dyslexic children and adults had difficulties dealing with temporal order, and performed worse than normal readers on digit span tasks; at the same time, planning was not impaired [1]. Another study found that impaired executive functions were related to the extent of linguistic abilities [9]. The task we used in this study was clearly non-linguistic in nature, and there was no need for judging temporal order. Therefore, it seems to be that the higher function of mental flexibility is intact, while executive functions related to language, including those related to processing temporal information, are impaired.

In summary, our study strongly suggests that dyslexic attentional shifting is not impaired at the executive level of the cognitive system; otherwise, we should have seen impoverished task-switching performance. We propose that any problem with attentional shifting in dyslexics is caused by peripheral pathways, rather than by central executive problems. This is in fact well in line with the hypothesis that an important part of the visual difficulties of dyslexia can be explained as a problem in fast processing in the visual pathways, leading to slower conduction between the eyes and the cortex [13]. Our findings are relevant in indexing the problems of dyslexia, which is, despite many decades of intensive research, still dividing the scientific community [18].

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