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RESEARCH ARTICLE

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Rehearsal by eye movement improves visuomotor performance in cerebellar patients

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Abstract In order to assess the effect of rehearsal by eye movement alone on visuomotor performance, the eye movements and visually guided stepping of two cerebellar patients were monitored before and after a first and second batch of eye-movement rehearsals, in which patients made saccadic eye movements to the first 6 footfall targets (in a sequence of 18) whilst standing stationary at the start of the walkway. There was a marked improvement in oculomotor and locomotor performance following the second batch of eye-movement rehearsal. Both patients showed reduced occurrence of saccadic dysmetria, evident as a significant increase in the proportion of single to multi-saccadic eye movements (from 46 to 77% for DB and from 75 to 94% for TP). This was accompanied by increased regularity and accuracy of stepping in both patients, and decreased stance and double support phase durations (one patient only). Separate testing confirmed that these improvements in eye movements and stepping did not result from simple repetition of the task. This is the first demonstration of a technique – rehearsal by eye movement – that improves the visuomotor performance of cerebellar patients. It is compelling evidence for our proposal that during visually guided stepping the locomotor control system is dependent on assistance from the oculomotor control system.

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Introduction

Recent studies (Hollands and Marple-Horvat 1996, 2001) have shown that the oculomotor and locomotor control systems interact during visually guided stepping, with the locomotor control system being dependent on assistance from the oculomotor control system, findings that parallel those for visually guided arm movements (Prablanc et al. 1986; Van Donkelaar 1998; Gauthier et al. 1998). In cerebellar patients, this beneficial influence becomes detrimental when they make inaccurate eye movements, and stepping performance, including accuracy, is compromised (Crowdy et al. 2000; see also Van Donkelaar and Lee 1994).

If the influence of the oculomotor controller onto the locomotor controller is as significant as these studies suggest, then a viable way of improving locomotor performance of cerebellar patients might be to improve the accuracy of their eye movements, for example by practice or rehearsal. This study was designed to test firstly whether eye movement rehearsal can lead to improved eye movements, and secondly whether any such improvement does indeed lead to better visually guided stepping.

Methods

Two patients participated in the study. DB (male, age 54 years) has a clinical diagnosis of autosomal dominant primary cerebellar degeneration, and TP (male, age 44 years) has mild familial cerebellar atrophy. Local Ethics Committee approval and informed written consent were obtained prior to testing.

Patients walked (under normal lighting) along a pathway of 18 irregularly placed ’stepping stones’ which required precise foot placement under visual guidance at each step (Crowdy et al. 2000). The experimental protocol was: 5 control walks (before rehearsal); 1st eye movement rehearsal; 3 test walks (after 1st rehearsal); 2nd eye movement rehearsal; 3 test walks (after 2nd rehearsal), making

11 walks in total. For all walks patients were instructed to make their way along the walkway at their fastest comfortable pace, trying to step accurately on each of the stepping stones. Just before 1st rehearsal patients were informed that during visually guided stepping they often made eye movements that were not big enough (hypometric saccades), followed by one or more additional, corrective saccades to look at the next footfall target, and that these inaccurate eye movements probably have a detrimental effect on their walking, i.e. an abnormal eye movement towards a footfall target can adversely affect the accuracy of the step to that target. They were asked, when next attempting the task, to concentrate on making accurate eye movements rather than just accurate steps. After this explanation, and immediately before the next set of walks, patients were asked to 'rehearse' the saccadic eye movements to the first 6 targets in the sequence whilst standing stationary at the start of the walkway. They rehearsed the sequence 5 times without interruption.

In a prior experimental session, each subject performed 11 repeated walks, but without eye-movement rehearsal or verbal explanation, to assess any improvement in performance that might result from simple repetition of the walkway task.

Horizontal and vertical eye-in-orbit rotations were recorded using a head-mounted eye-tracking system (ASL Model 501), which also displays direction of gaze (accurate to 0.5°) on a scene monitor as a cross hair superimposed on the view as seen by the subject. Stepping was monitored using copper fabric soles attached to the subject's footwear (see Crowdy et al. 2000). Real-time data streams of eye movement and foot-contact signals (sampled at 60 Hz) were recorded on a lap-top computer carried an unobtrusive distance behind the patient.

Step-phase durations were calculated and compared for the three conditions (before, after 1st, after 2nd rehearsal) using Student's *t*-test. Saccadic eye movements to fixate footfall targets were identified and the percentages of single, double, triple and quadruple saccades made under the three conditions compared using the Kolmogorov-Smirnov (KS) two sample test.

Results

Before eye-movement rehearsal both patients displayed characteristic oculomotor deficits (Crowdy et al. 2000). In the same task, healthy subjects make a 'double saccade', an initial hypometric saccade followed by a single corrective saccade to fixate the target in 9% of steps (mean for 20 subjects), but never made triple or quadruple saccades. DB and TP made hypometric saccades, followed by one or more corrective saccades, to fixate the next footfall target in 64 and 25% of steps, respectively (within the range previously reported for 8 cerebellar patients undertaking the same task): Fig. 1A (left). Both patients also displayed characteristic locomotor deficits. Compared to 20 healthy individuals, DB and TP were slower overall (mean walk duration 25 s and 23 s, respectively, healthy = 11.3 s), with prolonged stance, swing and double-support phase durations (cf Crowdy et al. 2000).

Figure 1A shows the percentages of single and multiple saccades made before and after the first and second set of eye-movement rehearsals for each patient.

After the second set of eye-movement rehearsals, both patients showed significantly decreased occurrence of saccadic sequences ($P<0.05$, KS test), and increased occurrence of single, accurate saccades to footfall targets along the whole walkway. For DB this oculomotor

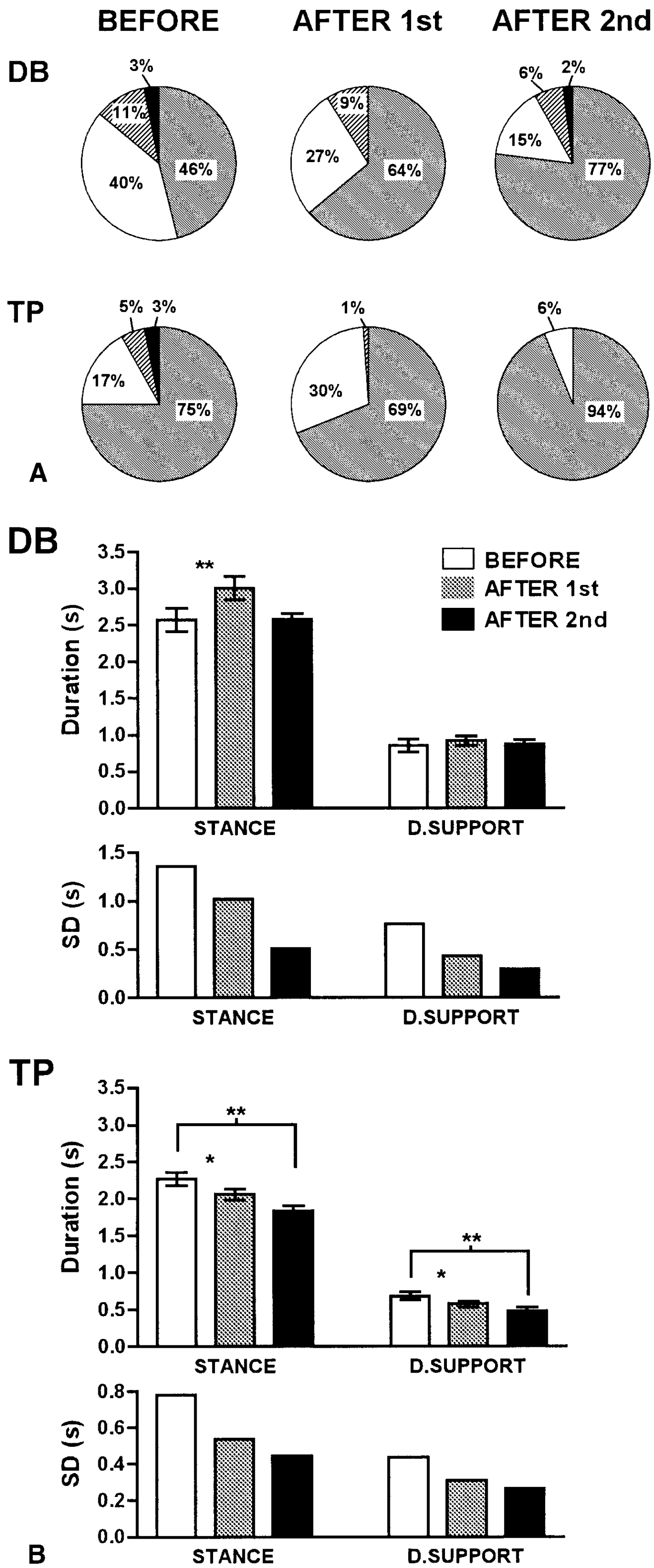

Fig. 1 A Pie charts showing percentage occurrence of single (*grey*), double (*white*), triple (*hatched*) and quadruple (*black*) saccades made to fixate all stepping stones in the walkway sequence before rehearsal, after the 1st rehearsal and after the 2nd rehearsal for DB and TP. **B** Histograms showing mean stance and double-support phase durations (*top*) with standard deviations (*bottom*) for all steps in the walkway sequence before rehearsal (*white*), after the 1st rehearsal (*grey*) and after the 2nd (*black*) rehearsal for DB and TP. *Significant at $P<0.05$ for two-tailed *t*-test. Error bars represent SEM

improvement was progressive, multiple saccades decreasing from 54 to 23% after two rehearsals. For TP, frequency of multiple saccades reduced from 25 to 6% after two rehearsals. TP then made no triple or quadruple saccades, and the occurrence of double saccades (6%) is lower than the mean value for healthy adults (9%).

Both patients also improved their locomotor performance, with significant improvement in all phases of the step cycle along the whole walkway. Figure 1B shows mean stance and double-support phase durations, and the variation about these values (expressed as standard deviations, SDs) for all steps before and after eye-movement rehearsal. For patient DB there was no overall decrease in stance duration, but there was a great decrease in the variability of stance duration progressively after the first and second set of rehearsals. A similar pattern is seen in DBs double-support phase; overall, no significant change in duration after rehearsal, but marked progressive decrease in variability after each set of eye movement rehearsals. This decrease in standard deviation of stance and double-support phase durations, from 1.36 s to 0.51 s (38% of original value) for stance and from 0.76 s to 0.3 s (39% of original value) for double-support phase is an impressive increase in regularity of stepping following rehearsal of eye movements alone by a stationary individual. For TP there was a significant decrease in stance duration after eye movement rehearsal (from 2.3 s to 1.8 s; $P<0.05$, *t*-test), and in double-support phase duration (from 0.7 s to 0.5 s). As for DB, there was a substantial increase in regularity of stepping; SDs of both stance and double-support phase durations decreased progressively, for stance from 0.78 s to 0.45 s (58% of original value) and for double support from 0.44 s to 0.26 s (59% of original value). No change in mean swing duration was seen, though again there was a decrease in variability.

Finally, both patients made a higher proportion of accurate steps (onto the target) following eye-movement rehearsal; DB improved from 92 to 98% and TP from 88 to 100%.

Both patients were also tested in a prior experimental session for any improvements in eye movements and stepping resulting from simple repetition of the walking task. Neither patient improved their eye movements with walk repetition; DB showed no significant difference, TP became significantly worse (perhaps because of fatigue). In the experimental session involving only walk repetition, DB took 21.5±1.2 s (mean ± SD) to complete a walk without significant change. In the session including eye-movement rehearsal, DB took 24.3±2.1 s to complete a walk without significant change after eye-movement rehearsal. As regards speed of progression, therefore, DB did not walk faster after either eye-movement rehearsal or walk repetition. TP's walk duration was one second faster than DB's for both walk repetition and eye-movement rehearsal. TP walked faster after eye-movement rehearsal (stance duration reduced by 19%); after walk repetition there was a smaller increase in speed (stance reduced by 13%). Both patients showed dramatic improvement in regularity of stepping following eye-movement rehearsal. DB showed a much smaller improvement with walk repetition (stance SD reduced by 32%, compared to reduction of 62% after rehearsal), TP showed a similar improvement following either eye-movement rehearsal or walk repetition (stance SD reduced by 42% in each case). Both patients improved their accuracy of stepping following eye-movement rehearsal. Neither improved with walk repetition.

Discussion

Prior to eye-movement rehearsal both patients displayed characteristic oculomotor and locomotor deficits (cf Crowdy et al. 2000). Healthy adults performing this task produce a clear pattern of eye movements with one saccade in each direction per step cycle made to fixate the next footfall target (Hollands et al. 1995; Crowdy et al., 2000). Although their eye movements and (directly visualised) gaze sometimes followed the same pattern, both patients frequently made multisaccadic eye movements – an initial hypometric saccade followed by additional corrective saccades (in 54 and 25% of steps for DB and TP, respectively). Direct visualisation of these sequences has confirmed that such additional saccades are indeed corrective and yield a foveal image of the target (Crowdy et al. 2001).

In comparison to healthy subjects, DB and TP took over twice as long to complete the walkway. Prolonged and highly variable stance, swing and double-support phase durations all contributed to their locomotor symptoms collectively termed ‘ataxic gait’.

The severity of cerebellar patients’ locomotor problems during visually guided stepping is linked to the severity of their oculomotor problems (Crowdy et al. 2000). This suggests that in a healthy individual the locomotor control system perhaps receives, and is dependent on, assistance from the oculomotor control system (though we cannot exclude the possibility of another unknown factor affecting both together); but in cerebellar patients, this beneficial influence becomes detrimental when they make inaccurate eye movements, and stepping performance is compromised. If this is the case, then any improvement in oculomotor performance through rehearsal of eye movements should result in improved locomotor performance.

Following eye-movement rehearsal both patients made significantly fewer multi-saccadic eye movements and more accurate single saccades which fixated the target, along the whole walkway. Significant improvement in oculomotor performance therefore resulted from the task-specific eye-movement rehearsal. For patient TP, whose symptoms were the less severe before eye-movement rehearsal, this resulted in oculomotor performance that was similar to that of healthy adults (double saccades in 6% of steps compared to a mean value of 9% across 20 healthy adults: Crowdy et al. 2000). This is, to our knowledge, the first demonstration of a technique that improves oculomotor performance of cerebellar patients.

Both patients also improved their visually guided stepping along the whole walkway. Most importantly, following each successive set of eye-movement rehearsals both patients displayed progressive and substantial reduction in the variance of all step-cycle phases. This represents an impressive increase in the regularity of stepping as a result of eye-movement rehearsal. Both patients also stepped accurately on the targets in a higher proportion of steps after eye-movement rehearsal (98 and 100%; healthy subjects are successful in all steps).

Since neither patient improved his eye movements with walk repetition, we conclude that none of the improvement in eye movements after their rehearsal was attributable to simple repetition of the walking task. Since only TP showed any increase in speed of progression with walk repetition, and that smaller than the improvement following eye movement rehearsal, we conclude that only a part of the improvement seen in TP following rehearsal could be attributed to repetition of the walking task. As regards regularity of stepping, for DB only a small part of the improvement following eye-movement rehearsal could be attributed to walk repetition; but for TP, the improvement following eye movement rehearsal could conceivably be attributed to walk repetition. Since neither patient improved his accuracy (made a higher proportion of accurate steps onto the target) with repeated walking, none of the improvement following eye movement rehearsal can be attributed to walk repetition. Thus, we are driven to conclude that most of the improvement in locomotor performance in the present study occurs as a direct result of the improvement in oculomotor performance following eye-movement rehearsal.

This study is the first demonstration that rehearsal by eye movement alone, while stationary, leads to improved locomotor performance. This is compelling evidence for a behaviourally important link from the oculomotor to the locomotor controller such that in a healthy individual, during visually guided stepping, the planning and generation of a saccade by the oculomotor control system provide the locomotor control system with information that it is to some extent dependent upon for the feedforward planning of the corresponding step (Hollands 1997; Hollands and Marple-Horvat 1996, 2001).

The standard of locomotor and oculomotor performance after eye movement rehearsal reflected the severity of the cerebellar ataxia prior to testing; DB still showed a larger than normal percentage of multiple saccades whereas TP, with milder initial symptoms, improved his oculomotor performance to that of a healthy adult. Perhaps additional rehearsals would result in further improved performance, a suggestion that can easily be tested. Another area for further study is the longevity of improvement. Once rehearsal is abandoned, does performance decay back to its original level, and if so, over what time course? Can improved performance be evoked in cerebellar subjects whose symptoms are more severe? Finally, how task-specific is the benefit of rehearsal? If its locus is cerebellar, then studies by Thach and co-workers (Martin et al.1996a, 1996b; Thach et al. 1992) suggest both that the change in visuomotor performance might be closely limited to the task that was rehearsed and that the benefit might be rather short lived.

This is to our knowledge the first demonstration that rehearsal by eye movement alone improves the visuomotor performance of cerebellar patients. Such improvement in this straightforward and non-invasive way has potentially great significance for the ability of patients to undertake everyday tasks requiring visual guidance. For example, if a patient wished to cross a room cluttered with obstacles, such as children's toys scattered on the floor, simple prior rehearsal of the intended steps by eye movements alone might well result in a big enough improvement in performance to allow the patient to complete the task with much greater ease and safety.

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