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Research Article

Visuospatial Executive Functions are Improved by Brief Brain Training in Young Rugby Players - Evidence of Far Transfer Test Effects: A Pilot Study

Aleksandra Oledzka [†], Lynne Ann Barker [†, *]

Centre for Behavioural Science and Applied Psychology, Department of Psychology, Sociology & Politics, Faculty of Social Sciences and Humanities, Sheffield Hallam University, Heart of the Campus, Collegiate Crescent, Sheffield S10 2BQ, UK; E-Mails: a.oledzka@outlook.com; L.barker@shu.ac.uk

† These authors contributed equally to this work.

* **Correspondence:** Lynne Ann Barker; E-Mail: L.barker@shu.ac.uk

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Abstract

Brain training apps are becoming increasingly popular for at home use and as an adjunct to more traditional therapies. There is uncertainty about whether the effects of brain training transfer to real-world cognition, or performance on other cognitive assessment tests, or is specific only to the brain training app. Executive functions (EF's) are higher-order cognitive processes important for activities of everyday living and autonomous goal-directed behaviour [1]. EF's are associated with frontal brain networks that are susceptible to injury after head trauma and concussion so it is important to know whether these functions can be trained after a short training period (transfer effects beyond gains on app play), to general cognitive ability but findings so far have been mixed. The present study investigated efficacy of brief computerised brain training to in producing far-transfer effects to performance on standardised clinical tests of cognition in young rugby players with mixed concussion history, over a 4-week period. Athletes cognitive ability was assessed at baseline and after the training period on standardised tests to establish whether there were transfer effects. The putative relationship between concussion frequency and severity on baseline cognitive performance was also investigated. Results showed effective transfer effects from initial training to selective visuospatial executive functions. There was also a decline over the training period in non-verbal strategy initiation, although ability remained at average levels. Players showed no cognitive deficits at baseline, but correlational analyses and MR results indicated that concussion frequency, not severity, was a significant predictor of some visuospatial executive function scores at baseline. These preliminary findings hold promise for full scale studies investigating efficacy of brief brain training and association between sport-related concussion and cognition.

Keywords

Transfer effects; brain training; executive function; sport-related concussion; visuospatial

1. Introduction

In the present pilot study, we investigated whether there were any transfer effects from a brain training application (Lumosity® [2]) reported to have robust transfer effects [3], to performance on standardised neuropsychological tests in young amateur rugby players with a mixed concussion history. Brain training using computerised cognitive tools has been shown to improve *executive* functions (EF's) in diverse cohorts [3] although other research has shown contrasting findings [4]. Executive functions (EF's) are *higher-order* cognitive processes important for autonomous activities of everyday living, planning and goal-directed behaviour [1, 5]. Canonical cognitive and neuropsychological theories of executive functions (EF's) include a broad range of abilities under the rubric *executive* including working memory, attention, behavioural inhibition, dual-tasking, planning, sequencing, reasoning and problem-solving [5-9]. Additionally, some theories also make the distinction between *hot* and *cold* EF's. Cold EF's are considered to be predominantly cognitive whereas hot EF's are associated with body-based functions such as emotion expression, inhibition and regulation [10].

1.1 Brain Training and Transfer Effects

Presently, there is controversy about how well learning and sensory-motor skills acquired on computerised training platforms transfer to ability in other contexts. *Transfer effects* describe the phenomena of applying skills and knowledge acquired in one context or task to the successful completion of different goals in another context or task. It is further distinguished on the basis of similarity between original context (task) and new context or task post-training (termed near-transfer), or *far*-transfer signifying improvement on tasks that differ qualitatively from the original task (for example, presentation mode, content and appearance). The latter occurs when the different tasks (pre- and post-training) share some underlying process (in this study executive functions) and therefore the training task demonstrates *far* transfer effects [11-13].

There is evidence of effective EF training in healthy children [14], adults [15, 16], the elderly [17, 18], and neuropathological groups [19]. Additionally, results from a meta-analysis of 103 studies (N = 6,113) found that working memory (WM) training led to lasting improvement, with transfer effects to untrained cognitive tasks among diverse healthy age groups, children, adolescents and traumatically brain-injured patients with WM deficits [19]. Evidence indicated that beneficial effects depended upon extent of training, and greater number of training sessions had larger transfer effect than shorter series' of sessions. For example, beneficial effects maintained for 6 months following training among children [20]. In contrast, a 6-week online brain training study with 11,000 participants showed no significant transfer effects to untrained cognitive tasks even where training tasks were similar (*near* transfer effects) to untrained tasks [4]. However, there was variation in amount of training across participants which may have influenced findings. Presently, it remains unclear whether optimal training time should be short or long duration and whether training on specific tasks, particularly commercial products, reliably transfers to *real life*.

1.2 Executive Functions

Recently, Chavez-Arana et al. [21] conducted a systematic review investigating training for *hot* and *cold* EF's in children and adolescents. Results of data analyses showed brief training periods (6-17) weeks were effective at improving attention (a *cold* EF) in youth with TBI. Studies targeting specific EF's; attention (55.5%), inhibition (50%), social abilities (42.8%), cognitive flexibility (50%), and problem solving (50%) were more effective than studies measuring *overall* EF ability (33.3). This finding suggests that targeted brain training is more effective than generalised training.

There is evidence that brain training is effective across a range of diverse cohorts. Brain training using computerised cognitive remediation therapy has also been shown to improve executive dysfunction in people with schizophrenia. In one study, participants completed treatment as usual or cognitive remediation: structural brain connectivity was also measured. The authors found significant changes to connectivity of brain regions associated with improved cognition. White matter microstructural change to posterior pathways of the left cerebellum were associated with improvements in executive function in patients [22]. Other work found that a robotic motor task combined with virtual reality trained attention and executive functions in people with traumatic brain injury [23].

Vander Linden et al. [24] used a brain training programme with adolescents in the acute stage post-TBI. The authors measured a range of executive functions including working memory, sustained attention, response inhibition, planning and problem solving and found significant improvements post-training [24]. The teenagers showed significant improvements in executive function abilities at 8-weeks post-training and at six-month follow up. In addition, other findings showed that executive functions can be improved through brain training in individuals with Down's Syndrome [25].

In the present study we are concerned only with cold executive functions and findings generally indicate that these are more sensitive to training than hot EF's.

1.3 Brain and Body Training

Sporting ability and game play depend upon attention, response initiation, inhibition, working memory updating and strategizing functions, under rigid time constraints suggesting that EF skills are crucial to successful sport performance [26]. However, sporting activities may also have costs for cognition as well as benefit. Sport-related concussion has been defined as a mild traumatic brain injury (mTBI) induced by biomechanical forces, such as direct or indirect blows to the head [27].

Common consequences include altered consciousness and cognitive change, working memory problems [28, 29], and executive functioning deficits [30], reduced processing speed, and attention [31], and reduced cognitive flexibility [32]. Tapper, Gonzalez, Roy et al., [33] found that history of concussion amongst retired rugby players was significantly associated with long-term deficits to EF's. Former players had worse performance on measures of attention, memory, processing speed and cognitive flexibility compared to non-contact sport control group. However, aside from cognitive retraining, new approaches indicate that cognition, particularly executive function ability, can be enhanced by exercise and athleticism [5, 34-37]. In sum, EF's are important for good sporting ability but disrupted by mild and repeated TBI. It is important to establish if EF's show transfer effects from brain training in athletes with mixed concussion history depending upon good EF ability for competitive sports play. It is precisely these functions, due to anatomical location of brain networks, and the locomotive forces of concussion, that are most disrupted after concussive events.

1.3.1 Lumosity®

One commercial training platform that supports brain training research is Lumosity®(https://www.lumosity.com/). Lumosity® offers games targeted at training various EF's, including flexibility, attention, memory, processing speed and decision-making; each game is intended to increase in difficulty, whilst adapting to player's individual progress [38].

The potential for Lumosity® as a cognition-enhancing tool has been widely researched, yet studies show inconsistent findings. For instance, undergraduate students who played a commercial video game [39] outperformed those who played Lumosity® on cognitive tests following gameplay; Lumosity® players showed no difference between baseline and post-training measures [39]. However, Ballesteros, Prieto, Mayas, et al. [15] found significant transfer effects to processing speed, attention and visual recognition memory scores compared to the non-active control group following brain training in older adults. Similarly, after 20 Lumosity® training sessions, older adults showed cognitive benefits on an untrained attentional cross-modal task (*Far*-transfer effect – [40]). However, traumatically brain injured patients showed limited transfer on an 8-week Lumosity® programme [41], although 2 of 3 TBI patients improved on most transfer tasks in another brain-training study [38].

In sum, findings of *near* and *far* transfer effects using a popular brain training app Lumosity® are presently equivocal: this may reflect different methodologies, different cohorts, training duration variation, and the diversity of transfer tasks used alongside Lumosity®. To progress the field, one recommendation is use of well-established standardised measures better to evaluate putative brain training transfer effects and facilitate inter-study comparisons with diverse groups.

1.4 Aims of Current Study

- To investigate whether there are *far*-transfer effects with Lumosity® training to standardised neuropsychological tests from baseline scores in young athletes.
- To determine whether effective far-transfer effects occur to standardised neuropsychological tests from baseline scores with a short 4- week period of daily training in young athletes.
- To investigate whether there any associations between putative transfer effects and concussion history in young athletes.

2. Materials and Methods

2.1 Procedure

The study was a repeated measures design. Participants were recruited from a professional northern UK rugby league club. Initially, 14 male rugby players were recruited but 3 participants withdrew due to injuries sustained during the testing period. Thus, no remaining participants sustained injury during the study period and 11 male participants (mean age 17.35, *SD* = 0.52) completed the study. The inclusion criteria included no previous experience of playing the Lumosity® brain training app and current active participation in the sport. The study was approved by Sheffield Hallam University Faculty ethics committee.

2.2 Measure of Far-Transfer Effects

Participants were assessed at baseline and following the brain training programme using a standardised battery of neuropsychological tests widely used in clinical and academic settings: the Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV) [42], Delis-Kaplan Executive Function System (D-KEFS) [43], Cambridge Neuropsychological Test Automated Battery (CANTAB – [44]) and Sport Concussion Assessment Tool 2 (SCAT2) [45]. Where possible, alternate versions of tests (Sample A and B), were used to avoid any practise effects, and test order administration was counterbalanced across participants for pre- and post-training assessments. Testing sessions took place in a quiet room at the rugby club. Baseline and post-training cognitive assessments lasted approximately one hour each with self-determined rest breaks. At study commencement, participants completed baseline cognitive testing and the SCAT2 measure [45], and received a step-by-step guide to Lumosity® training to ensure that they understood how to complete the brain training. The brain training period was scheduled for 4 weeks, with 5 training sessions per week as one study aim was to establish whether brief cognitive training periods produced transfer effects to standardised tests in young athletes. This is an important aim of the current study as professional players have little free time and a short training schedule aligned better with player availability and free time outside of training and game play during rugby league season. Additionally, there is supporting literature of transfer effects after relatively short brain training schedules [15, 40]. One of our main aims was to determine if whether transfer effects occurred after short training times because this is most likely to be feasibly implemented with professional athletes who have sustained concussion who do not have time to commit to longer programmes of brain training.

Each Lumosity® training session lasted approximately 10-15 minutes and consisted of three randomly generated Lumosity® tasks. Following the 4-week cognitive training programme, participants were re-tested on the neuropsychological battery of tests. All tests were administered in counterbalanced order and alternate samples (A or B) used where available.

2.3 Pre- and Post- Training Standardised Psychometric Tests

2.3.1 Sport Concussion Assessment Tool (SCAT2) [45]

The SCAT 2 is a widely used measure of concussion frequency and severity but has the limitation that it depends upon self-report [45]. We used the 22-item symptom evaluation checklist. Participants were asked to indicate the number of previous concussions and post-concussion period at the time of testing, symptoms experienced following any concussion that they sustained, rating each symptom from 0 (none) to 6 (severe). The possible total maximum symptom severity score is 132 [45]. The SCAT2 was only administered at baseline since participants were excluded if any injuries were sustained during the study.

2.3.2 Wechsler Adult Intelligence Scale-Fourth Edition [42]

We selected Processing Speed Indices subtests from the WAIS-IV, Symbol Search (SS) and Coding (CD) because other research findings indicate these functions are affected by head trauma and also sensitive to cognitive retraining (see below).

Symbol Search (SS). This subtest comprises 60 items. Participants must respond *yes* or *no*, as quickly as possible, to whether a target symbol is present among an array of different symbols for each item within a total time of two minutes. The overall score is based on the number of correct answers completed within the time frame [42]. This subtest measures short-term visual memory, cognitive flexibility/speed of mental processing, attention and concentration [42]. This subtest has been used in other research assessing EF's following TBI [46], and in other cognitive training studies [17, 47].

Coding (CD) Subtest. Participants were provided with an array of numbers paired with a specific symbol. Participants were instructed to complete the task as quickly and accurately as possible by drawing the correct symbol under the correct corresponding numbers within a two-minute time limit. This subtest measures visual scanning processing speed [42], a function particularly important for effective teamplay in ball-based sports.

2.3.3 Delis-Kaplan Executive Function System (D-KEFS; [43])

This neuropsychological battery is widely used in clinical and academic work to assess EF's in ages ranging from 8 to 89 years. Based on our earlier work, we selected the Sorting Test and Verbal and Design fluency for the current study [48], because of the need for brief (the free time of our cohort was limited) yet sensitive and reliable EF tests.

The Sorting Test. This task comprises free sorting and sort recognition conditions (it is a variant of the Wisconsin Card Sort Test – [49]). In the first condition, participants were presented with two sets of six cards. The task requires participants to sort their cards into two groups of three based on some feature of the card (colour, shape, type of stimulus) within a 4-minute time limit. In the second condition participants were asked to correctly identify the categorization rules of sorts created by the examiner [50]. This subtest is used in the assessment of problem solving, cognitive flexibility, concept-formation and reasoning [51]. During the baseline assessment card set 1 and 2 were used, whereas during the post-training testing card set 3 and 4 were used to minimize practice effects.

Verbal Fluency. This test consisted of three 60 second conditions: letter fluency, category fluency and category switching measuring the fluency of verbal responses [50]. In the first condition, participants were asked to name as many different words as they could think of beginning with a specific letter of the alphabet (F, A and S at baseline assessment and B, H and R in post-training assessment). The second condition required participants to name words belonging to a specific category (different animals and boys' names at baseline and items of clothing and girls' names at post-training testing). In the last condition, participants were asked to switch between two categories (fruit and furniture at baseline and vegetables and musical instruments at post-training assessment). Alternate test letters and categories were used at post-training assessment to minimize practice effects. This subtest has also been previously used in brain training research [47].

Design Fluency. This measure assessed visuospatial fluency [50], planning and cognitive flexibility [43]. Participants were required to connect an array of dots by using only 4 straight lines and generate as many novel designs as possible within 60 seconds. Repeated designs, or designs with more than 4 lines received a score of zero. The test consisted of three conditions: filled dots, empty dots, and switching between filled and empty dots; and total (scaled) score across all three conditions.

2.3.4 Cambridge Neuropsychological Test Automated Battery (CANTAB; [44])

CANTAB is a well validated and widely used battery of tests for the assessment of cognitive function and dysfunction and in various cohorts. In the present study, the Paired Associates Learning (PAL) test was used to assesses visual memory and acquisition of new learning. PAL has been shown to be sensitive in identifying functional deficits resulting from TBI, regardless of severity [44], and has been used in other brain training research [4]. Participants were presented with one or more patterned squares on a computer screen that had to be memorized by the examinee. Participants had to correctly remember the location of the target pattern, which appeared in an increasing number of locations over task difficulty levels. Outcome measures included the number of errors, completed stages, number of successful trials and memory scores [44]. In the present study, the parallel version of this test was used to enable repeated testing, as recommended in the examiner's manual.

3. Results

Participant mean age was 17.45 (*SD* = 0.52). Raw scores on psychometric measures at baseline and post-training were converted to age-scaled scores and entered into SPSS software [52] together with participant demographic variables. Scores from Lumosity® training games were converted into percentage *change* scores indicating the percentage of improved or worse performance on each training game across the study.

3.1 Statistical Analyses

Age-scaled scores can be interpreted as follows: 10 = Very Superior (99th percentile), 9 = Superior (90-95th percentile), 7-8 = High Average (80-90th percentile), 4-6 = Average (25-55th percentile), 3-4 Low Average (15-25th percentile), ≤ 3 = impaired. Scores from each of the Lumosity® training categories (memory, attention, flexibility, speed and problem-solving) were converted into mean percentage *change* scores on each training game across the study for the whole group (Table 1). Lumosity® gameplay ranged from 10-20 days, $\bar{x}$ = 15.91, (*SD* = 4.37), and indicated that most participants complied with instructions to achieve 20 training sessions across the 4-week period. There were some missing data for the Lumosity® speed and problem-solving scores (4 participants had missing values for speed and 3 participants for problem-solving scores).

Table 1 Descriptive data (mean and standard deviation - SD) for percentage of *improvement* in Lumosity® scores by function across the four-week training period.

Lumosity® training game type	Participants completed	Mean (SD) % change over the training period
Memory	11	8.9 (4.8) %
Attention	11	24.1 (9.3) %
Flexibility	11	31.1 (18.2) %
Speed	7	36.7 (14.7) %
Problem solving	8	21.5 (6.0 %)

Descriptive data presented in Table 1 shows that rugby players improved on all Lumosity® tasks over the 4-week period. The highest percentage improvement was in speed of processing (36.7%) and the lowest in memory (8.9%).

We compared whether there was any change to executive function ability from baseline to post-training putatively indicating far-transfer effects from the training to standardized tests. Table 2 shows baseline and post-training mean standardized scores on executive function test

Table 2 Descriptive data (mean and *SD*) of standardised IQ and executive function measures at baseline and post-training.

IQ and Executive task (function measured)	Means (SD)	
	Baseline	Post-training
WAIS Symbol Search (Processing Speed)	9.9 (2.3)	9.9 (2.7)
WAIS Coding (Visual scan processing Speed)	8.2 (2.0)	9.1 (1.8)*
Letter Fluency (Verbal strategy initiation)	9.2 (3.0)	9.9 (4.0)
Category Fluency (Non-verbal strategy initiation)	11.8 (3.0)	8.8 (3.5)*
Category Switching (Response inhibition and initiation -RII)	9.8 (2.3)	8.1 (2.6)
Total Switching Accuracy (RII accuracy)	5.3 (1.2)	4.6 (1.2)
Design Fluency Filled (Visual Strategy initiation)	8.4 (2.3)	11.7 (3.3)*
Design Fluency Empty (Visual response inhibition)	8.7 (2.5)	11.9 (2.8)*
Design Fluency Switching (Visual response inhibition and initiation -VRII)	9.6 (2.7)	11.7 (1.4)*
Design Fluency Total of Scaled Scores (Overall Visuocognitive Flexibility)	26.6 (6.8)	35.7 (6.3)*
Sorting Correct (Conceptual problem solving)	8.4 (1.1)	8.6 (1.7)
Sorting Description (Verbal problem solving)	8.0 (2.1)	8.9 (1.6)
Sorting Recognition (Visual problem solving)	7.5 (2.0)	8.8 (2.1)
PAL total errors adj. (Visual memory errors - VME)	**19.5 (15.7)**	**15.5 (17.5)**

PAL mean errors to success	**4.5 (3.9)**	**3.3 (3.4)***
PAL first trial memory score (Visual memory score at first trial)	12.6 (3.3)	13.7 (3.7)
PAL total trials adj.	8.6 (2.3)	7.7 (3.1)

*significantly different at Time 2 - $P < 0.5$, Bold scores: lower = better performance

Data presented in Table 2 indicate that baseline scores fell within a varied range of performance ability from low average to average (total switching accuracy), high average (Visual scan processing speed, Visual response inhibition and initiation; Visual Strategy initiation; Conceptual problem solving, Verbal problem solving, Visual problem solving), through superior (Processing Speed, Verbal strategy initiation, Response inhibition and initiation,) performance categories. Notably, participants were not impaired on any measures at baseline but showed variability in performance scores with stronger ability in vision-based tasks (as might be expected in ball-game athletes). Lower scores on *PAL total errors adj.*, *mean errors to success* and *total trials adj*. post-training indicated improved performance from baseline to Time 2 test.

Data were subject to conventional checks for normality and effect sizes also computed due to the small sample. Effect sizes are a standardized objective measure of effect magnitude in relation to the general population rather than the study cohort and indicate whether statistically significant findings are robust in small samples. Large effect sizes (*r* above 0.5) indicate that in all probability results are not due to chance.

After brain training, mean Visual Scan Processing Speed (WAIS coding) scores improved from High Average to Superior category, 0.91, 95% CI [-.01, 1.83], t (10) = 2.19, $p < .05$ $r = 0.57$, with moderate to large effects size, and Visual Strategy initiation (filled dots) 3.36, 95% CI [2.16, 4.61], t (10) = 6.00, $p < .01$, $r = .88$ improved from High Average to Very Superior category with large effect size. Visual response inhibition improved significantly with training 2.73, 95% CI [1.49, 3.97], t (10) = 4.89, $p < .01$ with a large effect size $r = .84$, again shifting from High Average to Very Superior level. Overall visuo-cognitive flexibility (combined scaled scores) showed robust improvement from baseline to Time 2, 8.73, 95% CI [6.92, 10.53], t (10) = 10.77, $p < .01$ with a large effect size $r = .96$. Visual response inhibition and initiation (VRII), 2.18, 95% CI [.66, 3.71], t (10) = 3.18, $p < .05$, $r = .71$ similarly improved to Very Superior levels also with a large effect size. Visual memory error correction (PAL mean error to success) scores, -1.19, 95% CI [-2.48, 1.0], t (10) = -2.06, $p < .05$ $r = 0.55$ were also significantly improved post-training with a moderate to large effect size. However, response inhibition and initiation (category switching) -1.73, 95% CI [-4.03, .60], t (10) = -1.67, $p > .05$ $r = 0.47$ was not different from baseline to Time 2 testing.

Unexpectedly, non-verbal strategy initiation (category fluency) mean score dropped from Very Superior score at baseline to a High Average mean score at Time 2, 3.00, 95% CI [-4.31, -1.69], t (10) = -5.10, $p < .01$ $r = 0.72$, with a large effect size. It is difficult to interpret this finding. It shows a significant decline from baseline but not to an impaired range – overall mean score remained in the above average range). However, it is possible that this is a latent cognitive marker of concussive effects that was not trained by the brain training sessions and requires further exploration.

Processing Speed, Conceptual problem solving, Verbal problem solving, Visual problem-solving task performance did not change significantly from mean baseline score to Time 2 scores on the neuropsychological battery.

Overall, findings show a pattern of improved ability to some functions after brain training, no change in ability to other functions, and a very specific pocket of poorer ability (from Superior to High Average) at Time 2 in a single task measuring Non-verbal strategy initiation.

3.2 Concussion Data

Self-reported post-concussion period ranged from one to twelve months at time of test $\bar{x}$ = 6.29 (*SD* = 5.38). Number of self-reported previous concussions ranged from 0 to 3, $\bar{x}$ = 0.82, (*SD* = 0.98), and SCAT2 scores ranged from (0 – meaning no symptoms) to 60, $\bar{x}$ = 29.6 (*SD* = 23.88) from a potential total of 132 indicating no (score = 0), mild or moderate concussive symptoms post-concussion at time of study.

SCAT2 number of symptoms ranged from 0 to 22, $\bar{x}$ = 11.82 (*SD* = 8.59), from a possible total of 22. Four participants reported zero across the three concussion measures, although, only one of the four scored zero on the SCAT2 measure of severity of post-concussive symptoms. Note the variability between scores on this measure shown by the numerically large standard deviation. This range of scores may indicate poor sensitivity of this measure and/or demonstrate the highly discrepant scores that can be generated by players in the same team playing the same match (raising issues of reliability of self-report in this context where there is pressure to *play on*).

3.3 Correlation Analyses Comparing Concussion Variables and Executive Function Scores

Pearson product-moment correlation analyses were conducted to establish whether there was any relationship between baseline concussion and executive function variables. Each variable was converted into a z-score to standardize variables, control for outliers and compare data across different scales. There were no values that exceeded the maximum absolute z score of -/+ 3 for the current sample size [53, 54].

Results of correlational analyses showed several significant relationships between baseline SCAT scores and executive function scores. Removed data treatment section.

There was a negative correlation between number of concussions and scores on visual executive functions including, - visual response inhibition (empty dots task) *r* (9) = -.703, *p* < .05, visual strategy initiation (filled dots task) *r* (9) = -.676, *p* <.05, and overall visuo-cognitive flexibility *r* (9) = -.705, *p* < .05 at baseline. Negative correlation is a relationship between two variables in which one variable increases as the other decreases, indicating that as number of concussions increased – scores on these cognitive functions decreased. Number of concussions explained 49.4% of the variation in visual response inhibition scores, 45.7% of the variance in visual strategy initiation and 49.7% of the variance in overall visuo-cognitive flexibility at baseline testing. Moreover, number of previous concussions also correlated negatively with non-verbal strategy initiation (category fluency subtest) *r* (9) = -.64, *p* < .05, explaining 41.3% of the variance. Recollect, scores on this measure declined from baseline to Time 2 test. Similarly, there was a strong negative relationship between SCAT2 concussion severity scores and visual strategy initiation (filled dots) *r* (9) = -.61, *p* < .05, overall visuo-cognitive flexibility *r* (9) = -.62, *p* < .05 and again, non-verbal strategy initiation (category fluency subtest) *r* (9) = -.63, *p* < .05. The SCAT2 scores explained 36.7% of the variance in visual strategy initiation scores, 37.9% of overall visuo-cognitive flexibility and 39.7% of the variability in non-verbal strategy initiation scores. To summarise, number of concussive events and concussion severity were negatively associated with baseline performance scores in the mostly in the visuospatial cognitive domain and in non-verbal strategy initiation before brain training.

3.4 Multiple Regression (MR) Analyses

Correlation analyses indicate a relationship between two variables, but not which variable is causative (predictive) of another variable. To explore correlational findings further, multiple regression (MR) analyses were conducted to investigate whether number of concussions and SCAT2 severity score predicted scores on the cognitive flexibility tests.

Number of concussions, and SCAT2 severity scores were entered into the MR model as predictor variables using the standard linear model (rather than stepwise etc). Multiple linear regression attempts to model the relationship between two or more explanatory (predictor) variables and a response variable by fitting a linear equation to data. Concussion variables significantly predicted visual response inhibition scores (empty dots condition), F (2, 8) = 4.46, $p < .05$ (Number of Concussions – NoC = β -.55, severity of symptoms scores – SoS = β -.24). They also predicted cognitive flexibility scores (total number of scaled scores), F (2, 8) = 4.70, $p < .05$ (NoC = β -.53, SoS = β -.27). Standardized beta coefficients indicated that number of concussions was the strongest driver of these predictive relationships compared to severity of symptoms score.

Predictor variables showed only a marginal trend for predicting performance on measures of non-verbal strategy initiation F (2, 8) = 3.87, $p > .05$, (NoC = β -.40, SoS = β -.37) and visual strategy initiation (filled dots condition), F (2, 8) = 4.08, $p > .05$. (NoC = β -.49, SoS = β -.29). That said beta values were still relatively large so these non-significant findings should be interpreted cautiously.

Overall these preliminary findings are promising and show transfer effects after a brief period of training in young athletes, evidenced by improved scores on standardised neuropsychological tests compared to baseline. Number of concussions experienced also predicted cognitive flexibility and visual executive functions and was non-significantly associated with non-verbal ability that declined over time.

4. Discussion

To the best of our knowledge, this study is the first to explore the putative effects of computerised brain training in professional adolescent rugby players at risk of sport-related concussions that may adversely affect cognition. The main aim of the study was to determine whether far transfer effects occurred after a brief training regime on the Lumosity® app. We were particularly interested in whether a brief regime produced transferable effects to standardised tests because sports players have little time outside of training and game play and brief cognitive training, if effective, is a possibility that could be implemented to ameliorate concussive effects on cognition. Despite the small cohort and relatively short training time, the results showed significantly improved performance ability, from baseline to Time Two test to specific executive functions measured by standardised and well-validated tests. The moderate to large effect sizes indicated robust findings (despite the small sample) and indicate that it is worth extending this pilot study with a larger cohort.

Notably, participants were not impaired on any measures at baseline but showed variability in performance scores with stronger ability in vision-based tasks (as might be expected in ball-game athletes). This is an interesting finding because one might hypothesise that young players exhibit some cognitive deficits due to high impact nature of the sport and frequency of concussive events.

Reassuringly, our findings indicate that this may not be the case in healthy young players at an early stage of their sporting career and offers hope for early intervention techniques that could be incorporated, as standard, alongside physical training sessions.

Overall, brain training findings showed a pattern of improved ability to some functions after brain training, with the possible interpretation that these functions were *trained,* no change in ability in other functions (potentially untrained), and a very specific pocket of poorer ability (from Superior to High Average) at Time 2 in a single task measuring non-verbal strategy initiation.

Interestingly, visuospatial switching and strategy executive functions were the most enhanced after training even though they were above average at baseline. This is a useful finding because these are the skills most important for effective and competitive contacts sport ball play, so we know that they can be enhanced by brief training periods; although the duration of these effects is not yet known or whether increased frequency of concussive events over time changes this relationship.

Results of statistical analyses found a negative correlation between number of concussions and scores on visual executive functions including, - visual response, visual strategy initiation and overall visuo-cognitive flexibility at baseline. This is a tentative but potentially important finding suggesting these *visual domain* executive functions may be susceptible to decline after concussion, yet they are also essential for competitive gameplay. There was no change in performance ability after brain-training for several other functions including processing speed, verbal strategy, switching, conceptual, verbal and visual problem solving. Additional research is needed to establish which functions are reliably improved and those that are unaffected by brain training.

In this pilot study we provide proof of concept that short periods of brain training may exhibit transfer effects to unrelated cognitive tests, adding to existing literature on near and far transfer effects after brain training [55]. Other work found transfer effects after 3-weeks of brain training using Lumosity® in young, healthy adults with standardised measures pre- and post-training, similar to our study design [56] suggesting that brain training *transfer* can be effective at even shorter durations than used here. Our findings also concord with results from other research using the same duration of training time [16, 17].

In the present pilot study, we measured concussion frequency and severity using the conventional measure used in sport, the self-report SCAT2. Results of Multiple Regression analyses showed that number of concussive events predicted cognitive flexibility and visual executive functions and was non-significantly associated with non-verbal ability at baseline that worsened from Time one to time two testing. Standardized beta coefficients indicated that *number* of concussions was the strongest driver of these predictive relationships compared to severity of symptoms score.

There is a physiological explanation for susceptibility of visual (and visual executive) processes to repeated concussion. Repeated mild brain trauma is known to affect integrity of neural tissue more severely than a single injury, resulting in visual function abnormalities [57]. This may reflect the brain's position in the skull and movement trajectory on impact, conferring vulnerability on frontal networks mediating executive functions and visual pathways [58].

Other research has shown a similar relationship between mild head trauma and visual functions, indicated by regression data in our study, including visual memory, recognition, acuity, processing, and reaction time [59-61]. This may be associated with neuropathy to the optic nerve due to brain movement on impact or changes to retinal neurons that relay visual information to the brain [62].

Indeed, our team recently showed that neuronal layers in the retina were abnormally affected by repeated head blows in Olympic boxers [63].

However, although our analyses found that concussive frequency predicted ability in executive visual domains at baseline, importantly our group were not impaired in any of these functions at baseline because they started out above average. However, if baseline performance begins to fall over time then visual executive functions are clearly at risk in contact sports players with repeated concussions. In contrast, non-verbal strategy initiation (category fluency task) fell from 11.8 to 8.8 at baseline falling from top of average range to bottom of average range. This could be considered of no importance because time two scores did not fall within the impaired range. However, a performance decline such as this within a four-week period is unexpected, and the small standard deviation showed that there was little variability around the mean at both test times signifying a group effect. None of the tasks that players completed in Lumosity® as part of their brain training were presented as training non-verbal functions so it is plausible that the mild decline in this function occurred as a lasting effect of earlier concussions in our group. Non-verbal strategy initiation is associated with frontal networks which we know to be vulnerable to injury after head blows and associated with dorsolateral prefrontal cortical circuitry. This is a tentative explanation of findings and needs replication in a much larger study, but it may be that non-verbal strategy initiation is a cognitive marker of concussive effects [64]. Although our cohort's performance was not impaired at time two, we speculate that over time, repeated head-blows could potentially contribute to measurable impairments in this cognitive domain. Future directions might investigate screening for cognitive problems purported to be sensitive to concussion and improved by brain training.

There is still much to learn about long lasting effects of concussion on cognitive ability. Martini and Broglio [65] proposed that recovery from acute effects of concussion takes two to four weeks but can persist for longer in some individuals, it is also likely that age is a factor in recovery. Most well documented post-acute effects are dizziness and headaches rather than marked change in cognitive domains. They also noted that there is scant information regarding effects of concussion on an athlete when gender, type of sport, player position, concussion history and age at injury are considered – although paediatric injuries seem to have longest duration of effect. Evaluation of cognitive ability after concussion found no evidence of cognitive decline associated with concussion history – although this may reflect the lack of sensitivity of particular tests used to capture subtle long-term deficits [66, 67]. Similarly, Hart et al., [68] found no correlation between concussion history, duration of play and cognitive performance in retired athletes. In contrast, Shah-Basack et al. [69], proposed that even though concussions may be considered *mild* they may produce lasting cognitive deficits that hold relevance for the millions who sustain mTBI each year [69]. Arguably, we are only just beginning to understand the effects of sports-related head blows, concussion and mild brain injury on cognitive function.

In other areas of research there is growing support for vision training as a concussion neuro-diagnostic tool and as an adjunct to concussion prevention strategies [70]. These methods include: computerised training, light board training to improve reaction times, Brock's string for eye convergence and strobe glasses for visual acuity under stress among others [70-72]. Morton [72] reported significant improvement in a case study of a 20-year old male following visual training using a computerised iPad application. Other studies used visual training in sport and found improved depth perception [70], hand-eye coordination, visual response speed, and stimulus anticipation in adult male rugby players [73], and improved peripheral perception and reaction time in youth in hockey players [71]. Importantly, vision training has been shown to be associated with *decreased* incidence of concussion among football players [70] so there are multiple benefits of brain training in contact sports where risk of head blows is high.

4.1 Limitations

Our pilot study had some limitations including the small sample size. However, despite this effect sizes ranged from moderate to large, and these population parameters indicate robustness of findings beyond cohort size. We did not collect data that would distinguish between concussion, mild-TBI and complicated MTBI in the present study as self-report scores on the SCAT2 provided the measure of concussion frequency and extent as is the convention for assessing concussion in contact sport in the UK. In future work we would seek to use more objective measures to establish concussive status including recording gameplay, motor and cognitive testing, RCT, longer follow up with repeated cognitive testing, and comparison of concussive and brain training effects in different age groups of players and control groups (untrained) for comparison.

5. Conclusion

Our study showed effective far transfer effects from a brain training app to standardised measures of cognition in young players after a 4-week training period. Visuospatial executive functions were most sensitive to brain training in our cohort, which could be particularly advantageous for athletes whose gameplay and sporting prowess depend upon visuospatial abilities, for example tracking the ball, being aware of other players' positions on the pitch, and constantly updating this information based on ball and player movement trajectories. Players showed no cognitive deficits as a result of concussion, but concussion frequency predicted some visuospatial abilities. Non-verbal strategy declined over time and did not improve as a result of brain training, although remained at average levels. Future studies should use objective cognitive and physiological measures to evaluate concussive effects because self-report of injury sequelae in competitive sports is problematic particularly when considering pressure to play from the player themselves, team and coach. We hope that findings presented here provide an impetus for more studies in this area because long term effects of repeated head trauma must be minimized as much as possible for the life-long health of our young contact sports players.

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Author Contributions

Both authors equally contributed to the study design and manuscript writing and revision. Aleksandra Oledzka: data collection, analyses and interpretation, manuscript writing. Dr Lynne Ann Barker: data interpretation, analyses, manuscript writing and revision.

Competing Interests

The authors have declared that no competing interests exist.

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