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Title: Reliability and Validity of the Functional Assessment of Neurocognition in Sport (FANS): A Paradigm Shift in Post-Concussion Return-to-Sport Decision-Making

Running Title: Reliability and Validity of the Functional Assessment of Neurocognition in Sport (FANS)

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Authors' Contributions

LBL, BLB, and DPT collaboratively conceived the FANS battery and overarching study design; LBL carried out all data collection, data processing, statistical analyses, and drafted the initial manuscript; All authors participated in overall statistical interpretation and have read, provided feedback, and approved the final version of the manuscript.

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Availability of data and material

Data are not available for sharing due to IRB restrictions. Study instrumentation (e.g., standardized scripts, data collection forms, etc) are available upon request at the discretion of the author team.

Research involving human participants

The study was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki. All study procedures were reviewed and approved by the University of [redacted]'s Institutional Review Board (IRB). Participants provided written informed consent prior to participation.

Code availability

Not available.

The Reliability and Validity of the Functional Assessment of Neurocognition in Sport (FANS): A Paradigm Shift in Post-Concussion Return-to-Sport Decision-Making

ABSTRACT

Context: Assessments used after concussion provide strong diagnostic accuracy and aid in initial healthcare planning, but can have limited utility after the acute timeframe. Current concussion assessments have low ecological validity in assessing return-to-sport readiness. We developed a functional assessment protocol, the Functional Assessment of Neurocognition in Sport (FANS) to address these limitations.

Objective: To evaluate the psychometric properties of FANS, including test-retest reliability, minimal detectable change, and divergent validity.

Design: Repeated measure design at two-timepoints, 14-days apart.

Setting: Clinical laboratory.

Patients or Other Participants: Seventeen healthy, physically active individuals (age:21.9±3.2years, 58.8% female; 76.5% no lifetime concussion history).

Main Outcome Measures: Participants completed FANS at two timepoints, and conventional clinical assessments (symptom checklist, balance, computerized neurocognitive testing) at the first timepoint. FANS examined 7-cognitive domains (verbal memory, visual memory, reaction time, processing speed, cognitive-motor flexibility, delayed verbal memory, delayed visual memory) through incorporating neuropsychological test paradigms with whole-body cognitive-movement tasks. We used intraclass correlation coefficients ($ICC_{3,k}$) with 95% confidence intervals (95% CI) and Pearson *r* correlations to evaluate test-retest reliability and divergent validity.

Results: All FANS outcomes displayed acceptable test-retest reliability (ICCs ≥ 0.63), with the lowest being verbal memory's interference subtest. Standard errors of measurement and minimal detectable changes overall displayed small values relative to score ranges. Correlations between FANS and conventional clinical assessments demonstrated select FANS reaction time and processing speed outcomes exceeding the divergent validity threshold with computerized neurocognitive testing reaction time (*r* range: -0.79-0.77).

Conclusions: FANS overall displayed acceptable test-retest reliability comparable to more traditional neurocognitive test platforms, and acceptable divergent validity. FANS reaction time and processing speed may partially overlap with computerized neurocognitive testing reaction time, and warrants further examination in a clinical population. Though FANS is reliable and valid for use, future research is needed to establish FANS utility for return-to-sport readiness.

Keywords: Return to Activity; Neurocognitive; Sensorimotor; Dual-Task.

INTRODUCTION

Concussions are a highly prevalent injury across many age groups and populations, particularly among athletes participating in contact and collision sports.[1–3] Concussions result in time-limited disruption to numerous domains such as physical, cognitive, and mental function.[4–7] Clinical recovery, as measured through current best-evidence clinical assessments (i.e., symptoms, neurocognition, balance),[8] often occurs between 14-28 days.[4] Current concussion assessments provide effective diagnostic accuracy and serve an important role for initial injury healthcare.[9,10] However, performance-based clinical measures are known to lose their diagnostic and prognostic utility after the acute timeframe.

Many evidence-based clinical assessments are susceptible to suboptimal test-retest reliability due to learning effects and standard measurement error,[11–14] which is problematic due to the need for repeat testing to help support decision-making regarding clinical recovery in athletes. For example, collegiate athletes often complete two or more clinical assessment batteries in a 2- to 3-week period post-concussion.[15] Further, current international consensus guidelines[8,16] employ a 6-stage return-to-sport (RTS) protocol and is most commonly completed after 6 days from starting.[4] Though current RTS guidelines have been successful at reducing subsequent concussion risk and improving recovery trajectories,[20,21] later RTS guideline stages focused on functional- and sport-specific reintegration could be augmented to empirically measure and determine RTS readiness.[22–25] Lastly, current concussion assessments typically only use simple motor activity (e.g., finger movement for computerized neurocognitive testing, static standing for balance). Sports, however, are played in highly dynamic environments requiring split second decisions. Thus, sport demands synchronized sensory intake, cognitive processing, and whole-body movement to successfully compete and avoid performance errors or avoidable player contact. The differences between current clinical assessments and on-field sport demands suggest the assessments may have limited ecological validity. Having assessment tools that are more ecologically valid may be an important factor for ensuring RTS readiness.

Numerous studies indicate an increased risk for subsequent musculoskeletal injury[23–25] and recurrent concussion[22,26,27] after the initial concussion for up to two years, and may indicate current concussion assessments do not adequately determine RTS readiness. Recent findings support this notion, as baseline and post-injury clinical assessment performance is not associated with subsequent musculoskeletal injury[23,24] while more dynamic- and sensorimotor-demanding gait evaluations are related to increased risk.[28,29] Further, professional athletes recovering from concussions have demonstrated decreased,[30–33] though inconclusive,[34–38] sport performance after being cleared to RTS following concussion, suggesting current RTS protocols may not be optimal indicators of sport readiness. Thus, considering a new approach to determining RTS readiness through objective measures evaluating concurrent cognitive and physical functioning may have major implications.

We have developed a functional RTS battery, the Functional Assessment of Neurocognition in Sport (FANS), to address the above shortcomings by integrating traditional neurocognitive assessments and principles with functional, sensorimotor movement assessments to target commonly impaired cognitive domains[39,40] through sport-emulating tasks, while also aiming to remain sport-agnostic. Before diagnostically validating and implementing FANS clinically, we must first establish whether it produces consistent and domain-appropriate outcomes to ensure accurate RTS readiness. Therefore, this study aimed to establish the psychometrics of FANS among healthy, physically active young adults. We hypothesized the subtests within FANS would display acceptable test-retest reliability (intraclass correlation coefficients [ICC] ≥0.61),[41,42] acceptable intercorrelations among subtests (i.e., Pearson r ≤0.70), and acceptable divergent validity (i.e. ≤0.70 Pearson r between FANS subtests and clinically used symptom, balance, and computerized neurocognitive assessments).

METHODS

An *a priori* power analysis was conducted using the Zou method,[41] and indicated 17 participants were needed to detect "substantial" reliability (ICCs ≥0.61)[41,42] among FANS (ICC_{H1}=0.61, ICC_{H0}=0.00, κ=2, α=0.05, β=0.80, 2-tailed test). Thus, 17 participants were enrolled in this repeated measure study design using a 2-timepoint with an approximate 14-day interval with convenience sampling to recruit from the University of XXX student body.

At timepoint 1, participants completed assessments in the following order: pre-FANS Sport Concussion Assessment Tool (SCAT) symptom checklist, FANS, post-FANS SCAT symptom checklist, balance testing, brief intellectual function proxy evaluation, and computerized neurocognitive testing. At timepoint 2, only the pre-FANS SCAT symptom checklist, FANS, and post-FANS SCAT symptom checklist were completed to evaluate test-retest reliability among FANS. All testing procedures and assessments were completed in a quiet, isolated testing environment consistent with neurocognitive testing recommendations.[43,44] Participants were modestly compensated for participating and completing testing timepoints in order to encourage maximal effort and study retention.

Participants

Participant characteristics are summarized in **Table 1**. Participants were included if they were 18-30 years old, met the American College of Sport Medicine physical activity guidelines,[45] and English was their primary language due to established language effects in neurocognitive testing.[46] Participants were excluded if they reported any diagnosed developmental, psychiatric, or balance disorders, musculoskeletal injury in the past month, and any orthopedic surgery or concussion in the past year to minimize potential confounding effects. All participants provided written informed consent following approval by the University of XXX institutional review board, with all study procedures conducted in accordance with the Declaration of Helsinki.

Functional Assessment of Neurocognition in Sport (FANS)

FANS was developed by the author team to integrate traditional cognitive domains used in neurocognitive testing with the sensorimotor-challenging and practical movement demands of sport-related activity, while also indirectly placing high demand on cardiovascular function. FANS was reviewed by multiple athletic trainers, sports medicine physicians, and clinical sport neuropsychologists internal and external to the author team to optimize a clinically feasible study paradigm leveraging standard neuropsychology principles with sport-related movement evaluations to promote an ecologically valid test battery. Specifically, the cognitive domains of verbal memory, visual memory, reaction time, processing speed, and cognitive-motor flexibility were targeted given their established impairments following concussion[39,40] and relevance to sport-related activities. Piloting for FANS occurred among two individuals (not included in the reported study sample) to ensure clear test instructions and appropriate difficulty. Upon final piloting, standardized instruction scripts, data collection forms, and scoring procedures were established. Two test versions of FANS were created for each timepoint to mitigate learning effects specific to a memorable word, shape, or similar rather than the domain evaluated. Below we outline each domain testing procedure and scoring, with each FANS domain performed in the order presented.

Verbal Memory was based on a classic list learning test reflecting different aspects of episodic memory,[58] with Supplemental Video 1 demonstrating a trial for this domain. Participants began jogging in place throughout the entire verbal memory evaluation, and stopped upon verbal memory completion. First, three consecutive learning (i.e., encoding) trials were completed during which participants were read a standard 15-word list (list-A) and then they recalled as many of the words back they remembered in any order while jogging in place. Then, an interference trial was conducted identical to the three learning trials, but with a new 15-word list (list-B). Next, immediate recall was conducted where participants recalled as many words from list-A as possible. Participants then continued the rest of FANS. After they completed the *cognitive-motor flexibility* section described below, they completed the delayed verbal memory. Delayed verbal recall had participants recite all words they remembered from list-A. Verbal memory recognition was evaluated using a 30-word list (15 from list-A, 15 new words) where participants jogged in place and identified words from list-A. Participants performed a lateral pivot and ran right if words were from list-A and left if they were not from list-A. Verbal memory outcome scores consisted of the sum of total words correct, repeated, and intrusions (i.e., non-target words) across all trials for learning, immediate recall, and delayed recall separately.

Visual Memory blended a standard visuospatial list learning test[59] with running and touching cones for speed and accuracy to illustrate the patterns shown on a 4 x 5 cone grid. Supplemental Video 2 is provided to demonstrate a trial for this domain. Cones were spaced 4-feet apart. Participants first completed a practice trial where they stood at the start cone outside the cone grid and viewed a single visual pattern of lines on a piece of paper that connected several dots, ranging from 4-10 dot connections depending on the shape, on a 4 x 5 dot grid. Participants viewed this design for 10s before replicating the pattern by touching the appropriate cones with their hand to indicate its use and connected cones by touching the next subsequent cone. Once a participant believed a pattern was completed, they exited the 4 x 5 cone grid and moved to the start cone. Once the practice trial was completed successfully, we assessed learning, immediate recall, delayed recall, and recognition in a similar method as verbal memory. Participants were asked to learn and recreate patterns from a 5-shape paper (bank-A) shown for 10s for three consecutive trials, then performed an interference trial with a new 5-shape paper (bank-B) shown for 10s, next an immediate recall trial through remembering shapes from bank-A, and then continued the rest of FANS. After completing delayed *verbal* memory, participants completed delayed visual recall where they remembered and recreated shapes from Bank-A. Lastly, visual memory recognition was evaluated using a 10-shape paper (5 bank-A, 5 new). For recognition, participants performed a forward run if a pattern was from Bank-A, and pivoted and ran backwards if the pattern was not from Bank-A.

Each visual memory shape per trial was scored on a 0-2 score scale (0-10 trial range): 2 was assigned for correct location on cone grid and shape/dimensions, 1 was assigned for having a correct shape/dimensions but in wrong grid location or rotated, or if in the correct location and was within 1 cone-to-cone connection line from a perfect shape, and 0 assigned for exceeding the above criteria or did not attempt the pattern. Visual memory outcome scores consisted of the sum score of total points across all trials for learning, immediate, and delayed recall separately. Additionally, a visual motor efficiency (VME) score for each outcome was calculated as the average of each trial score sum divided by the time to complete the trial.

Reaction Time was evaluated using the Standardized Assessment of Reaction Time (StART), a recently developed functional reaction time measure with established methods, reliability, and validity outlined elsewhere.[7,60,61] In brief, the reaction time was comprised of 3 movements (standing, single-leg balance, and cutting) across 2 cognitive conditions – single-task (i.e., just completing the task) and dual-task (i.e., subtracting by 6’s or 7’s from a random number while completing the task).[62,63] Each condition was performed 3 times (18 trials total per timepoint). All trials were video recorded on a mobile device recording at 240 frames per seconds (i.e., 4.2ms precision), the equivalent or faster than typical keyboard or motion capture system sampling rates.[62,64] A penlight was placed in the camera recording frame to provide the time-synchronized visual stimulus to participants and calculate reaction time. Reaction time was calculated as the time from the penlight illuminating to the first frame of hand (standing and single-leg balance) or any body movement (cutting). The trials are averaged together to formulate a single-task, dual-task, and StART (single- and dual-task combined) composite reaction time score.

Processing Speed was designed and modified from the Symbol Digit Modalities test,[65] with Supplemental Video 3 providing domain depiction for a snippet of the 2-minute test. In this task, there were eight unique symbols with two symbols assigned to each of the four colored bins (red, yellow, blue, green), and 40-cones with one of the eight symbols printed on it. A symbol color decoding grid was placed below the 40-cones and participants used it to sort the cones into their corresponding bin for speed and accuracy for the 2-minute test while recorded via stopwatch. The four bins were placed in a square with 1.98m between the first bin row and table holding the 40-cones, and 3.96m from the table to the back bin row. Participants could only take and decode a single cone at a time, and the 40-cones were stacked in a standardized order to control variability. The processing speed outcomes were speed (total correct and incorrect cones sorted divided by 120s, or time to complete all 40-cones) and accuracy (% correct).

Cognitive-Motor Flexibility incorporated the well-established tandem gait assessment[16,66,67] while incorporating a dual-task. For single-task, participants walked heel-to-toe along a 10-foot-long tape line, pivoted 180°, and walked back for speed for 3 trials while timed via stopwatch. For dual-task, participants completed tandem gait while simultaneously performing the letter-naming verbal fluency test,[68] where individuals named all words they could think of starting with a specified letter (i.e., “F”, “A”, “S”) for 3-trials using a different letter each trial. Participants were instructed to perform both tandem gait and the cognitive task to the best of their ability at the same time. The primary cognitive-motor flexibility outcome was single-task tandem gait time, dual-task time, and dual-task cost calculated as the following, with positive percentages indicating slower/worse dual-task performance:[29]

$$Dual\ Task\ Cost\ (\%) = \frac{dual\ task - single\ task}{single\ task}\ x\ 100$$

<u>Patient-Reported Outcomes and Standard Clinical Concussion Assessments</u>

Participants completed standardized questionnaires at study enrollment consisting of a demographic intake (sport, concussion, and medical health history questionnaire) and the 50-word Wechsler Test of Adult Reading[47,48] (raw score as outcome) as an estimation of intellectual functioning due to established relationships between performance on irregularly-pronounced word reading tests and overall cognitive and intellectual performance.[49] Limb dominance was self-reported by participants based on preferred arm or leg they preferred to kick or throw a ball with.

Participants completed pre- and post- FANS 22-item symptom checklist from the SCAT,[14,16] which evaluates symptomology presence and severity on a 0-6 Likert scale, with higher scores indicating greater symptom burden. The main outcome was total symptom severity (i.e., sum of all 22-item item scores).

Balance evaluations were evaluated using the Balance Error Scoring System (BESS)[50] which consisted of balancing with eyes closed in standardized start positions in three stances (double limb, single limb, and tandem limb) across two conditions (firm and foam surface) for 20 seconds each. Deviations from the starting positions during trials were counted (max 10 each condition).[50] The BESS total error score (error sum across all trials; 0-60 score range) was the primary outcome.

Computerized neurocognitive test performance was evaluated using the computerized CNS-Vital Signs (CNSVS)[51,52] due to its established reliability, validity, and frequent use within sports medicine.[53–57] The CNSVS seven cognitive domains (verbal and visual memory, reaction time, complex attention, cognitive flexibility, processing speed, motor speed) are consistent with other post-concussion neurocognitive batteries and theoretically comparable to FANS domains.

Statistical Analysis

Descriptive statistics were used for participant demographics and FANS test performance and time epochs. We used intraclass correlation coefficients ($ICC_{3,1}$)[69] with 95% confidence intervals (95% CI) to determine the test-retest reliability of the FANS subtest outcomes. Then, we used the ICCs to calculate the standard error of measurement (SEM) and subsequent minimal detectable change (MDC) to provide preliminary insights to change beyond error or chance.[70] All ICCs were interpreted as: fair (<0.40), moderate (0.41 – 0.60), substantial (0.61-0.80), and almost perfect (0.81-1.00),[42] with ICC≥0.61 being our acceptable threshold. All MDCs for FANS outcomes were qualitatively compared to their respective total score range (e.g., MDC for visual memory-delayed recall compared to its total score range) for descriptive interpretation purposes. We also evaluated statistically significant changes between timepoints for all FANS subtests to evaluate any repeat test effects using paired t-tests and Fisher's exact test where appropriate. Lastly, we used correlation matrices via Pearson *r* to evaluate the relationship strength among FANS subtests and between FANS and SCAT, BESS, and CNSVS domains (divergent validity; correlation ≤0.70). All models were evaluated for their respective assumptions via diagnostic plots and evaluations. Data processing and analyses were conducted using R v.4.3.1 with α=0.05 *a priori*.

RESULTS

Participants (n=17) were 21.9±3.2 year-old, physically active college students (of which n=3 were coincidentally student-athletes), 58% female, predominately right leg- and hand-dominant (both 94%). On average, participants slept 7.7±1.2 hours the night before testing. The majority (76.5%) did not have a history of concussions. Follow-up testing was conducted 12-16 days after the initial assessment (**Table 1**). The FANS took a median of 47 minutes to complete at the first timepoint, with a median 39-minute delay between verbal memory and delayed verbal memory, and 36-minute delay between visual memory and delayed visual memory (**Supplementary Table 1**). Further descriptive statistics (mean, standard deviation; median, interquartile range) for FANS subtest outcomes, time between delayed verbal and visual memory testing, and subtest test times at both timepoints are provided in **Supplementary Table 1**.

FANS Test-Retest Reliability

Overall, statistically significant differences between timepoints in FANS subtests were observed for all reaction time outcomes, processing speed - speed and accuracy, and cognitive-motor flexibility during single- and dual-task (p<0.05; **Supplementary Table 1**). These significant timepoint differences revealed timepoint 2 performance improvements with small magnitudes, except for processing speed – speed was slightly slower at timepoint 2. No floor effects were observed among outcomes, and ceiling effects were only noted for processing speed accuracy and delayed visual memory recognition as anticipated. Preliminary deciles and histograms for each FANS subtest outcome at timepoint 1 are provided in **Supplementary Table 2** to further characterize these data.

All FANS outcomes across domains displayed substantial test-retest reliability or better ($ICCs_{3,1}$ 0.63-1.00) and met our acceptable threshold, except for delayed visual memory's total score ($ICC_{3,1}$=0.56) being in the moderate test-retest reliability threshold (**Table 2**). Resulting SEMs and MDCs derived from the ICC values reflected relatively small values relative to their possible score ranges (**Table 2**).

Correlations among FANS subtests are presented in **Figure 1**. Verbal and visual memory both displayed moderate to high correlations (*r* range: 0.50-0.78) with their respective delayed outcome scores. Visual memory immediate recall, learning VME, and immediate recall VME demonstrated some moderate correlations with select reaction time and processing speed outcomes (*r* range: 0.48-0.58). Lastly, processing speed demonstrated moderate to high correlations with visual memory delayed recall and recognition (*r* range: 0.58-0.68).

FANS Divergent Validity from Concussion Clinical Assessments

Moderate to high correlations were observed between three FANS reaction time outcomes and CNSVS reaction time (*r* range: 0.63-0.77), and between all FANS processing speed outcomes and CNSVS reaction time (*r* range: 0.52-0.79). No other moderate to high correlations between FANS and CNSVS were observed (**Figure 1**). FANS verbal memory learning displayed a moderate to high correlation to SCAT symptom severity before testing (*r*=-0.49), CNSVS verbal memory (*r*=0.64), cognitive flexibility (*r*=0.54), and processing speed (*r*=0.50). FANS verbal memory-immediate recall was correlated with CNSVS processing speed

(r=0.56). Lastly, delayed verbal memory recognition was moderately to highly correlated with SCAT symptom severity before testing (r=-0.57) and CNSVS verbal memory (r=0.61). All other correlations between FANS and clinical measures were not statistically significant ($p<0.05$) and $r \le |0.48|$ (**Figure 1**).

DISCUSSION

Our study provides initial psychometrics for a hybrid neurocognitive-functional assessment battery called FANS to improve empirical RTS decision-making following concussion. We observed overall acceptable test-retest reliability across assessment domains with some statistically significant, though small magnitude, learning effects. The test-retest reliability led to relatively small SEMs and MDCs (i.e., smaller score changes necessary to detect change beyond chance) and may have future utility for using FANS following injury. We observed FANS to overall meet our divergent validity threshold, except for a few correlations between FANS reaction time and processing speed and computerized neurocognitive testing reaction time. Our findings indicate FANS is overall psychometrically reliable, has preliminary divergent and ecological validity, and is primed for future use in RTS decision-making. Though designed for concussion, a reliable and valid battery such as FANS may also have utility for musculoskeletal injury management, such as after anterior cruciate ligament (ACL) repair due to established relationships with functional neurocognitive performance.[71,72] The potential RTS decision-making utility of FANS however requires further research before recommending it be used for any post-concussion or post-orthopedic injury decision-making.

We observed overall strong test-retest reliability for FANS across most domains and subtests (**Table 2**) that was as high or higher than common computerized neurocognitive testing platforms used in sports medicine.[73] Notably, visual memory-delayed recall was below our threshold ($ICC_{3,1}$=0.56), but is likely attributed to the small score range possible (0-10) known to statistically bias ICC values, and most non-concussed, healthy participants scoring between 7-

10 (**Supplementary Table 1 and 2**). Weighting visual memory outcomes by the time needed to complete however appears to correct the low ICC as demonstrated by the evaluated Visual memory-delayed recall VME metric (ICC=0.81), and may potentially be more meaningful performance metric. Additionally, statistically significant learning effects were observed for all FANS reaction time outcomes, processing speed, and cognitive-motor flexibility. Though statistically significant, the performance differences between timepoint 1 and 2 were relatively small in magnitude and below their respective SEM and MDC values (**Table 2**), and therefore have limited clinical relevance. FANS overall demonstrated acceptable test-retest reliability, but future research will need to determine which FANS metrics may require adjustments and are most informative of RTS readiness post-concussion.

We observed overall acceptable validity for FANS subtests meeting our thresholds. Specifically, we did not observe any exceeding correlations between most FANS subtest and SCAT symptoms, BESS, or CNSVS domain scores. An exception was observed though for all three FANS processing speed subtests and all three reaction time subtests moderately to highly correlating with CNSVS Reaction Time (**Figure 1**). This finding may indicate some redundancy in FANS with current clinical evaluations warranting FANS modification, but further research evaluating the RTS utility is first needed before alterations. Further, FANS reaction time and processing speed correlating with CNSVS reaction time differs from prior work comparing the FANS reaction time (i.e., START battery) to CNSVS domains,[7,60] and other literature using functional vs computerized neurocognitive reaction time evaluations and indicating no meaningful correlations are present.[62,74] Our findings may be attributed to the relatively small sample size, which was powered only for test-retest reliability effect estimation and not between-assessment correlations, and is a limitation of the present work.

The FANS battery is primed to serve as a hybrid neurocognitive-functional assessment for objective RTS decision-making following concussion. Additional assessment protocols have also been developed with similar future intentions, such as the Dynamic Exertion Test[75] and the R2Play[76], all of which differ in their current stage of development and in the outcomes utilized. For example, the Dynamic Exertion Test is a reliable and valid protocol incorporating standardized athletic-related movements as well, but does not evaluate neurocognitive domains and instead measures cardiovascular metrics (e.g., blood pressure, heart rate) and one physical performance time measure. R2Play to date only has a future study protocol published and therefore its psychometrics are unknown, but does incorporate one executive function task and one reaction time task with exercise and sensory-tasking challenges incorporated. Though research has not yet determined the clinical utility of these multiple RTS paradigms for patients recovering from concussion, or which specific subtest components will have the strongest RTS decision-making utility, it is clear an objective RTS decision-making paradigm is warranted for optimal healthcare decision-making.

Limitations

Though we established test-rest reliability and preliminary validity of FANS, this study did not evaluate its prognostic or RTS readiness utility, and thus results should not be interpreted as such. This cohort was comprised of 17 college students (3 student-athletes) from a high-tier university, and therefore it is unknown whether FANS psychometric performance would change in younger cohorts or a dedicated student-athlete population with likely greater cardiovascular fitness and lean muscle mass. However, the cohort was physically active by study inclusion and may partially limit this concern. Lastly, the clinical implementation of FANS may pose a challenge for some clinicians or in some clinical settings due to the resources and time currently needed and is ultimately a decision of feasibility left to the reader. As future research evaluating FANS RTS utility begins, it is possible some evaluation elements may not be necessary, and thus reduce the resources and time needed to administer. Future work will likely involve optimizing FANS measures to reduce burden and only retain the most parsimonious combination of assessment components to yield similar utility with less resource utilization.

CONCLUSIONS

Our present work provides test-retest reliability and divergent validity metrics for FANS. FANS displayed acceptable test-retest reliability and acceptable divergent validity with limited learning effects observed, and thus indicating psychometric potential to serve as an objective RTS decision-making following concussion. The FANS subtests of reaction time and processing speed may partially overlap with computerized neurocognitive testing reaction time. Though FANS is reliable and valid for assessing hybrid neurocognitive-sport movement domains, future research is needed among individuals experiencing concussion to establish RTS decision-making utility.

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Figure 1. Correlations Within FANS and Between FANS and Standard Clinical Assessments

Figure 1 Legend. Correlation coefficients among FANS subtests (bolded labels) and between FANS and SCAT, BESS, WTAR, and CNS-VS assessments (green box). Cell values indicate correlation value, with bold values indicating a statistically significant correlation ($p \leq 0.05$), and colored boxes reflecting the correlation strength and directionality.

Table 1. Study Sample Demographics, N = 17[1]	
Age	
Mean (SD)	21.94 (3.15)
Median (IQR)	21.00 (20.00, 22.00)
Sex	
Female	10 (58.82%)
Male	7 (41.18%)
Height (cm)	
Mean (SD)	170.49 (11.42)
Median (IQR)	165.10 (162.60, 177.80)
Mass (kg)	
Mean (SD)	72.99 (26.72)
Median (IQR)	63.60 (57.70, 81.80)
Hand dominance	
Left	1 (5.88%)
Right	16 (94.12%)
Leg dominance	
Left	1 (5.88%)
Right	16 (94.12%)
Sleep night before (hrs)	
Mean (SD)	7.68 (1.17)
Median (IQR)	8.00 (7.00, 8.50)
Concussion history count	
0	13 (76.47%)
1	2 (11.76%)
2	2 (11.76%)
Years since last concussion	
Mean (SD)	4.60 (2.79)
Median (IQR)	4.22 (3.50, 5.32)
Not applicable	13
Days between testing sessions	
12	1 (5.88%)
14	15 (88.24%)
16	1 (5.88%)

[1]All values are frequency (proportion) unless specified otherwise. Abbreviations: SD= Standard deviation; IQR= Interquartile range.

Table 2. FANS Reliability Between Timepoints

Domain	Outcome	$ICC_{3,1}$	95% CI Lower	95% CI Upper	SEM	MDC
Verbal Memory	Learning, Correct	0.77	0.37	0.92	2.36	6.56
	Interference, Correct	0.63	0.00	0.87	0.77	2.14
	Immediate Recall, Correct	0.74	0.30	0.91	1.19	3.31
Visual Memory	Learning, Total Score	0.81	0.47	0.93	1.35	3.75
	Interference, Total Score	0.74	0.29	0.91	1.00	2.78
	Immediate Recall, Total Score	0.64	0.01	0.87	0.93	2.58
	Learning, VME	0.84	0.55	0.94	0.01	0.04
	Interference, VME	0.78	0.39	0.92	0.04	0.10
	Immediate Recall, VME	0.73	0.26	0.90	0.02	0.06
Reaction Time	ST, Standing	0.83	0.54	0.94	0.01	0.02
	DT, Standing	0.72	0.22	0.90	0.03	0.08
	ST, Single-Leg Balance	0.78	0.39	0.92	0.01	0.03
	DT, Single-Leg Balance	0.70	0.16	0.89	0.02	0.06
	ST, Cutting	0.78	0.38	0.92	0.01	0.03
	DT, Cutting	0.87	0.64	0.95	0.02	0.05
	ST Average	0.82	0.49	0.93	0.01	0.03
	DT Average	0.79	0.43	0.92	0.02	0.07
	StART Composite	0.82	0.49	0.93	0.01	0.04
Processing Speed	Total Correct	0.92	0.78	0.97	1.55	4.31
	Speed	0.93	0.82	0.98	0.01	0.02
	Accuracy	0.81	0.48	0.93	4.12	11.43
Cognitive-Motor Flexibility	ST, Time	0.91	0.75	0.97	0.44	1.23
	DT, Time	0.96	0.90	0.99	0.73	2.03
	Dual-Task Cost	0.93	0.81	0.97	6.27	17.37
Delayed Verbal Memory	Delayed Recall, Correct	0.64	0.00	0.87	1.33	3.67
	Recognition, Correct	0.76	0.33	0.91	0.65	1.79
Delayed Visual Memory	Delayed Recall, Total Score	**0.56**	0.00	0.84	0.91	2.52
	Delayed Recall, VME	0.81	0.47	0.93	0.02	0.05
	Recognition, Correct	1.00	1.00	1.00	0.00	0.00

Intraclass correlation coefficients (ICC) with 95% confidence interval lower and upper bounds, standard error of measurement (SEM), and minimal detectable change (MDC) for FANS domains and outcomes. Bold values indicate low (<0.61) ICCs.[42] VME= Visual Motor Efficiency; ST= Single-Task; DT= Dual-Task; StART= Standardized Assessment of Reaction Time.

Supplementary Table 1. FANS Performance Outcomes by Timepoints

Characteristic[1]	Timepoint 1, N = 17	Timepoint 2, N = 17	p-value
Verbal memory, learning, correct			0.113
Mean (SD)	29.24 (4.93)	30.76 (3.73)	
Median (IQR)	30.00 (28.00, 33.00)	31.00 (28.00, 32.00)	
Verbal memory, learning, errors			0.835
Mean (SD)	0.71 (0.92)	0.76 (0.75)	
Median (IQR)	0.00 (0.00, 1.00)	1.00 (0.00, 1.00)	
Verbal memory, learning, repeated			0.875
Mean (SD)	1.76 (1.48)	1.71 (2.05)	
Median (IQR)	1.00 (1.00, 2.00)	1.00 (0.00, 2.00)	
Verbal memory, interference, correct			0.320
Mean (SD)	7.00 (1.46)	6.47 (2.15)	
Median (IQR)	7.00 (6.00, 8.00)	6.00 (5.00, 8.00)	
Verbal memory, interference, errors			0.718
Mean (SD)	0.18 (0.53)	0.12 (0.33)	
Median (IQR)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	
Verbal memory, interference, repeated			0.083
Mean (SD)	0.06 (0.24)	0.24 (0.44)	
Median (IQR)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	
Verbal memory, immed. recall, correct			0.932
Mean (SD)	10.12 (2.34)	10.18 (1.85)	
Median (IQR)	10.00 (8.00, 12.00)	10.00 (9.00, 11.00)	
Verbal memory, immed. recall, errors			1.000
Mean (SD)	0.24 (0.56)	0.24 (0.44)	
Median (IQR)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	
Verbal memory, immed. recall, repeated			0.206
Mean (SD)	0.29 (0.59)	0.59 (0.94)	
Median (IQR)	0.00 (0.00, 0.00)	0.00 (0.00, 1.00)	
Visual memory, learning, total score			0.425
Mean (SD)	23.47 (3.10)	22.71 (4.01)	
Median (IQR)	22.00 (21.00, 26.00)	22.00 (20.00, 27.00)	
Visual memory, interference, total score			**0.002**
Mean (SD)	4.29 (2.05)	6.12 (1.87)	
Median (IQR)	5.00 (3.00, 6.00)	6.00 (5.00, 6.00)	
Visual memory, immed. recall, total score			0.632
Mean (SD)	8.18 (1.55)	8.41 (1.77)	
Median (IQR)	8.00 (7.00, 10.00)	9.00 (7.00, 10.00)	
Visual memory, learning, VME			0.124
Mean (SD)	0.14 (0.04)	0.13 (0.03)	
Median (IQR)	0.12 (0.11, 0.17)	0.12 (0.12, 0.14)	
Visual memory, interference, VME			**0.012**
Mean (SD)	0.11 (0.08)	0.15 (0.04)	
Median (IQR)	0.11 (0.07, 0.15)	0.15 (0.12, 0.17)	
Visual memory, immed. recall, VME			0.824
Mean (SD)	0.13 (0.04)	0.13 (0.03)	
Median (IQR)	0.15 (0.11, 0.16)	0.13 (0.10, 0.15)	

Characteristic[1]	Timepoint 1, N = 17	Timepoint 2, N = 17	p-value
Reaction time, ST Composite (ms)			**0.016**
Mean (SD)	0.21 (0.02)	0.20 (0.02)	
Median (IQR)	0.22 (0.20, 0.23)	0.20 (0.19, 0.21)	
Reaction time, DT, Composite (ms)			**0.000**
Mean (SD)	0.34 (0.05)	0.28 (0.04)	
Median (IQR)	0.33 (0.30, 0.36)	0.28 (0.26, 0.30)	
Reaction time, StART Composite (ms)			**0.000**
Mean (SD)	0.28 (0.04)	0.24 (0.03)	
Median (IQR)	0.28 (0.25, 0.29)	0.24 (0.22, 0.26)	
Processing speed, total correct			**0.001**
Mean (SD)	32.76 (5.49)	35.35 (4.15)	
Median (IQR)	34.00 (31.00, 36.00)	36.00 (33.00, 39.00)	
Processing speed, speed			**0.000**
Mean (SD)	0.28 (0.03)	0.30 (0.03)	
Median (IQR)	0.28 (0.26, 0.30)	0.31 (0.28, 0.33)	
Processing Speed, accuracy			0.186
Mean (SD)	96.77 (9.46)	98.70 (3.95)	
Median (IQR)	100.00 (96.88, 100.00)	100.00 (100.00, 100.00)	
cog-mot flex, ST, time (s)			**0.006**
Mean (SD)	10.66 (1.48)	10.01 (1.50)	
Median (IQR)	10.72 (9.46, 11.31)	9.77 (9.21, 10.98)	
cog-mot flex, DT, time (s)			**0.007**
Mean (SD)	14.55 (3.66)	13.52 (3.72)	
Median (IQR)	13.26 (12.35, 15.15)	12.50 (11.70, 13.60)	
cog-mot flex, DT, Accuracy			0.332
Mean (SD)	99.79 (0.87)	99.36 (1.44)	
Median (IQR)	100.00 (100.00, 100.00)	100.00 (100.00, 100.00)	
cog-mot flex, Dual-Task Cost			0.524
Mean (SD)	36.01 (23.68)	34.18 (21.31)	
Median (IQR)	33.64 (23.46, 41.83)	29.93 (17.58, 49.33)	
Verbal memory, Dlyd. recall, correct			0.323
Mean (SD)	9.00 (2.29)	9.76 (2.19)	
Median (IQR)	8.00 (8.00, 10.00)	10.00 (8.00, 11.00)	
Verbal memory, Dlyd. recall, errors			1.000
Mean (SD)	0.41 (0.62)	0.41 (0.62)	
Median (IQR)	0.00 (0.00, 1.00)	0.00 (0.00, 1.00)	
Verbal memory, Dlyd. recall, repeated			0.332
Mean (SD)	0.06 (0.24)	0.18 (0.39)	
Median (IQR)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	
Verbal memory, Dlyd. recog., correct			0.413
Mean (SD)	28.65 (1.41)	28.29 (1.65)	
Median (IQR)	29.00 (28.00, 30.00)	29.00 (28.00, 30.00)	
Visual memory, Dlyd. recall, total score			0.189
Mean (SD)	8.41 (1.37)	9.00 (1.54)	

Characteristic[1]	Timepoint 1, N = 17	Timepoint 2, N = 17	p-value
Median (IQR)	8.00 (8.00, 10.00)	10.00 (8.00, 10.00)	
Visual memory, Dlyd. recog., correct			0.111
Mean (SD)	9.94 (0.24)	9.59 (0.80)	
Median (IQR)	10.00 (10.00, 10.00)	10.00 (9.00, 10.00)	
Visual memory, Dlyd. recall, VME			0.373
Mean (SD)	0.16 (0.04)	0.15 (0.03)	
Median (IQR)	0.16 (0.14, 0.18)	0.15 (0.13, 0.17)	
Verbal memory, total test time			0.848
Mean (SD)	4.94 (0.83)	4.88 (1.27)	
Median (IQR)	5.00 (4.00, 5.00)	5.00 (4.00, 5.00)	
Visual memory, total test time			0.134
Mean (SD)	8.76 (1.35)	8.29 (1.10)	
Median (IQR)	9.00 (8.00, 10.00)	8.00 (7.00, 9.00)	
Reaction time, total test time			-
Mean (SD)	7.71 (0.85)	6.00 (0.94)	
Median (IQR)	8.00 (7.00, 8.00)	6.00 (5.00, 7.00)	
Cog-mot flex, total test time			-
Mean (SD)	3.35 (0.61)	3.06 (0.83)	
Median (IQR)	3.00 (3.00, 4.00)	3.00 (3.00, 3.00)	
Dlyd. verbal memory, total test time			-
Mean (SD)	4.06 (1.14)	3.59 (0.62)	
Median (IQR)	4.00 (4.00, 4.00)	4.00 (3.00, 4.00)	
Dlyd. visual memory, total test time			-
Mean (SD)	3.06 (0.66)	3.00 (0.94)	
Median (IQR)	3.00 (3.00, 3.00)	3.00 (3.00, 3.00)	
Verbal memory, delay time			-
Mean (SD)	39.12 (2.47)	33.35 (3.26)	
Median (IQR)	39.00 (37.00, 41.00)	34.00 (30.00, 36.00)	
Visual memory, delay time			-
Mean (SD)	35.88 (2.60)	30.29 (2.39)	
Median (IQR)	36.00 (34.00, 37.00)	31.00 (28.00, 32.00)	
FANS, total test time			-
Mean (SD)	46.88 (2.98)	40.59 (3.34)	
Median (IQR)	47.00 (45.00, 48.00)	40.00 (37.00, 43.00)	

[1]All values represent frequency (proportion) unless specified otherwise. P-values dervied from paired t-test for continuous outcomes, and Fisher's exact test for count outcomes. Abbreviations: immed.= immediate; VME= Visuo-Motor Efficiency; ST= single-task; DT= dual-task; ms= milliseconds; StART= Standardized Assessment of Reaction Time; cog-mot flex= Cognitive-Motor Flexibility; Dlyd= Delayed; Recog.= Recognition; FANS= Functional Assessment of Neurocognition in Sport.

Supplementary Table 2. FANS Outcomes by Deciles with Histogram for Timepoint 1 (n=17)

Outcome	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Histogram
Verbal memory, learning, correct	21.60	26.40	28.80	29.00	30.00	30.60	31.40	33.00	34.40	37.00	
Verbal memory, interference, correct	6.00	6.00	6.00	7.00	7.00	7.00	8.00	8.00	8.40	10.00	
Verbal memory, immed. recall, correct	7.60	8.00	8.80	9.40	10.00	10.60	11.20	12.80	13.00	14.00	
Visual memory, learning, total score	20.60	21.00	21.00	21.40	22.00	24.00	24.40	26.80	27.40	30.00	
Visual memory, interference, total score	2.00	3.00	3.80	4.00	5.00	6.00	6.00	6.00	6.40	8.00	
Visual memory, immed. recall, total score	6.60	7.00	7.00	8.00	8.00	8.60	9.20	10.00	10.00	10.00	
Visual memory, learning, VME	0.10	0.11	0.11	0.11	0.12	0.14	0.15	0.18	0.19	0.20	
Visual memory, interference, VME	0.04	0.05	0.07	0.09	0.11	0.12	0.13	0.16	0.23	0.27	
Visual memory, immed. recall, VME	0.08	0.09	0.11	0.12	0.15	0.15	0.15	0.16	0.19	0.21	
Reaction time, ST, standing (ms)	0.18	0.19	0.20	0.20	0.20	0.21	0.21	0.22	0.22	0.25	
Reaction time, DT, standing (ms)	0.30	0.31	0.32	0.32	0.33	0.36	0.37	0.38	0.42	0.46	
Reaction time, ST, single-leg (ms)	0.17	0.18	0.18	0.18	0.20	0.20	0.21	0.21	0.23	0.24	
Reaction time, DT, single-leg (ms)	0.26	0.29	0.31	0.32	0.33	0.33	0.34	0.35	0.36	0.37	
Reaction time, ST, cutting (ms)	0.20	0.21	0.22	0.23	0.23	0.23	0.24	0.24	0.25	0.27	
Reaction time, DT, Cutting (ms)	0.28	0.30	0.31	0.32	0.32	0.32	0.33	0.34	0.36	0.46	
Reaction time, ST Composite (ms)	0.19	0.19	0.20	0.21	0.22	0.22	0.22	0.23	0.24	0.25	
Reaction time, DT,	0.28	0.30	0.32	0.33	0.33	0.34	0.35	0.36	0.38	0.49	

Supplementary Table 2. FANS Outcomes by Deciles with Histogram for Timepoint 1 (n=17)

Outcome	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Histogram
Composite (ms)											
Reaction time, StART Composite (ms)	0.24	0.25	0.26	0.26	0.28	0.28	0.28	0.29	0.31	0.37	
Processing speed, total correct	28.40	30.20	31.00	31.80	34.00	34.60	35.20	36.80	38.20	40.00	
Processing speed, speed	0.24	0.26	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.34	
Processing Speed, accuracy	95.56	96.79	99.38	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
cog-mot flex, ST, time (s)	9.18	9.36	9.62	10.17	10.72	10.81	11.28	11.60	12.00	14.67	
cog-mot flex, DT, time (s)	11.26	12.32	12.47	12.79	13.26	14.48	15.05	15.32	19.12	23.67	
cog-mot flex, Dual-Task Cost	10.66	18.05	27.04	28.94	33.64	38.33	40.87	42.25	61.76	102.89	
Verbal memory, Dlyd. recall, correct	8.00	8.00	8.00	8.00	10.00	10.00	10.00	10.80	11.40	15.00	
Verbal memory, Dlyd. recog., correct	26.60	28.00	28.00	29.00	29.00	29.00	29.20	30.00	30.00	30.00	
Visual memory, Dlyd. recall, total score	7.00	8.00	8.00	8.00	8.00	8.60	9.20	10.00	10.00	10.00	
Visual memory, Dlyd. recall, VME	0.11	0.13	0.14	0.14	0.16	0.16	0.17	0.19	0.22	0.24	
Visual memory, Dlyd. recog., correct	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	