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Confirmatory factor analysis of two computerized neuropsychological test batteries: Immediate post-concussion assessment and cognitive test (ImPACT) and C3 logix

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Abstract

Introduction: Tests of memory and speed of cognitive and motor responses have been the primary foci in sports-related concussion assessment. This study sought to assess the construct validity of neuropsychological tests within C3 Logix.

Method: Results of both baseline C3 Logix and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) computerized tests from 86 Division I collegiate athletes were submitted to a two-factor confirmatory analysis using structural equation modeling. The two factors of Speed and Memory have been confirmed in previous studies of ImPACT.

Results: Results confirmed the two-factor model of ImPACT, whereas C3 Logix did not conform to a pure two-factor model. Instead, along with additional error terms, a cross-loading was required between Speed and Memory factors in order to obtain the best model fit (χ^2 = 22.91, p= 0.12, CFI = 0.94, TLI = .90, RMSEA = 0.07 (90% CI [0.00, 0.13], SRMR = .06)): all factor loadings exceeded 0.30.

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Conclusions: The final model suggested C3 Logix employs three pure indicators of Speed and one indicator of both Speed and Memory. The lack of a pure indicator of Memory in C3 Logix raises a concern about its specificity and ultimately, its sensitivity to a sports-related concussion.

Keywords: Factor analysis, structural equation modeling, neuropsychological assessment, computerized neuropsychological testing, concussion

Introduction

Neuropsychological testing has a long history in the management of traumatic brain injury and is a recommended practice in sports concussion (SRC). Functions related to cognitive and motor response speed (reaction time, processing speed) and memory (primarily working memory), have been the primary focus of assessment in SRC, beginning with Barth's seminal work in the 1980s (Barth et al., 1989; Barth et al., 1983; McAllister, Flashman, Sparling, & Saykin, 2004; Schatz & Maerlender, 2013).

The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is widely used amongst sports teams at middle and high school levels, as well as college and professional levels. The ImPACT produces four composite scores for clinical interpretation: Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time (Lovell, 2007). Research has suggested that these composite scores fit a two-factor model, acting as indicators of latent Speed and Memory factors (see Figure 1) (Gerrard et al., 2017; Iverson, Lovell, & Collins, 2005; Lovell, 2004; Schatz & Maerlender, 2013). Further, these scores have demonstrated acceptable test–retest reliability over time (Maerlender et al., 2010).

An additional concussion management system that assesses neurocognitive functioning is known as C3 Logix. This system has been used less frequently than ImPACT, and there is some debate over the assessments used by the program for evaluation (e.g., Kattiria, Wheeler, Decoster, Hollingworth, & Valovich McLeod, 2018; Valovich McLeod, 2014). The four neuropsychological tests that makeup C3 Logix include Simple Reaction Time, Choice Reaction Time, Trail Making Difference (Trails A subtracted from Trails B), and Symbol-Digit Modalities (SDM) (Neurologix Technology, Inc., 2015). Simple and Choice Reaction Time tests, as well as Trail Making tests, use speed of responding as the critical variable. SDM is a test of cognitive processing speed (Charvet, Beekman, Amadiume, Belman, & Krupp, 2014), although attention and concentration also have been implicated (Smith, 1982). Although research on this assessment is limited, test–retest reliability has been determined acceptable for two of the neuropsychological tests (Simon et al., 2017).

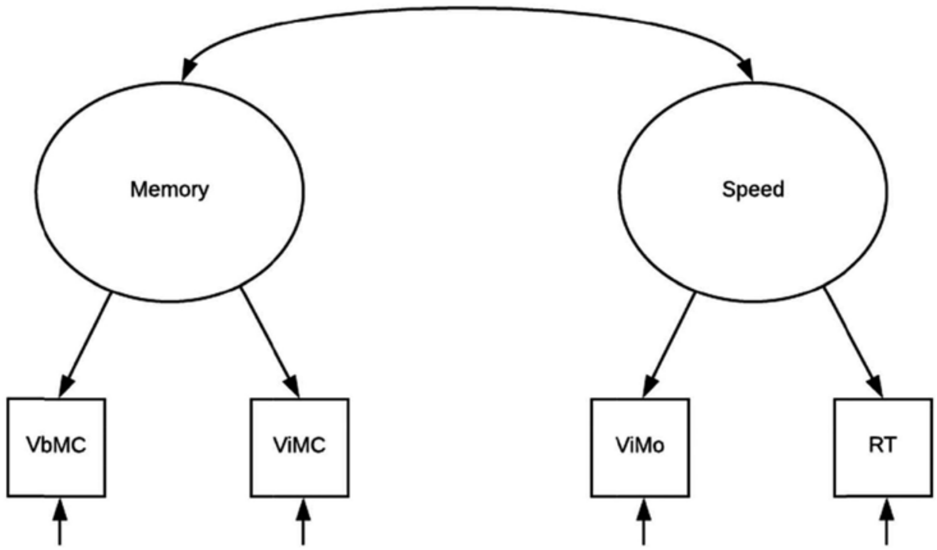

Figure 1. Established two-factor model of Speed and Memory latent factors with ImPACT indicators. Note: VbMC = Verbal Memory, ViMC = Visual Memory, ViMo = Visual Motor Speed, RT = Reaction Time.

To determine the construct representations of C3 Logix, a confirmatory factor analysis (CFA) was employed to examine C3 Logix neuropsychological test scores within the well-described factor structure of ImPACT (Allen & Gfeller, 2011; Schatz & Maerlender, 2013). Using a confirmatory factor analysis with an already established two-factor model (ImPACT) allows for a greater understanding of the C3 Logix tasks in the context of the expected Speed and Memory latent factors (as opposed to an exploratory factor model). Additionally, there are many disagreements surrounding exploratory factor analysis as a tool for the study of phenomena such as cognition (Greve, Stickle, Love, Bianchini, & Stanford, 2005). Data patterns obtained through confirmatory factor analysis are more easily interpreted because they are constrained via *a priori* predictions, which are limited to those strongly supported by theory and existing literature (Brown, 2015).

Method

Participants

Baseline ImPACT and C3 Logix data from 86 Division I collegiate athletes (55 males; mean age: 18.45, SD = 0.97) were extracted from larger data sets. Participants were only included in analyses if they took both assessments within six months, had no history of a head injury before or between assessments and had valid baseline test results. Valid results were determined by built in validity mechanisms within both assessments. The ImPACT baseline test (online version 2.1) was administered in groups of approximately 10 athletes supervised by a neuropsychologist and/or trained graduate students. C3 Logix baseline assessment was completed in groups of approximately five athletes on an iPad under the supervision of a neuropsychologist and/or a trained graduate student. The Institutional Review Board approved this research.

Measures

Tests were administered according to test standardization procedures (i.e., ImPACT on computers, C3Logix on iPads). In accordance with the University's typical measuring practices, ImPACT tests were administered on 2012 iMac's with 27" monitors, Intel Core i7 processor (3.40ghz), running 16GB RAM, whereas C3 Logix tests were administered on iPad Air2, 12GB, version 10.2, 9.7in screen with retina displays. Although there is concern regarding neurocognitive testing in group environments, this concern is more applicable to younger individuals. Research has suggested no difference in valid baseline scores for older youth athletes (such as our sample) whether they were tested in a large group (10 per room) setting or in a small group (1–3 per room) setting (Lichtenstein, Moser, & Schatz, 2013).

C3 Logix employs four scores in their assessment of brain injury: Simple Reaction Time, Choice Reaction Time, Trail-Making Difference, and SDM (called Speed). Simple and Choice Reaction Time are measures of a participant's response time to different types of stimuli. Simple reaction time tasks typically only involve one stimulus and one response, whereas choice reaction time tasks require the participant to give a response that corresponds to a stimulus (e.g., pressing a button when a particular letter appears on the screen) (Kosinski, 2010). Trail-Making Difference consists of two parts: A and B. Trail-Making A requires a participant to draw lines sequentially with the purpose of connecting encircled numbers (i.e., 1–2-3, etc.) distributed on a piece of paper. Trail-Making B is similar to A; however, during this task, the participant must alternate between numbers and letters (i.e., 1-A-2-B-3, etc.). The score for each part represents the amount of time it took for the participant to complete the task. In order to compute Trail-Making Difference (the score used for assessment), the score from part A is subtracted from the score from part B (Tombaugh, 2004). Finally, SDM requires individuals to identify nine different symbols that correspond with numbers one through nine. Participants first practice writing the correct number under the corresponding symbol. Once it can be confirmed that participants understand the task, they then are given 90 s to fill in as many blank spaces under the symbols as they can. The score is calculated by totaling the number of correct answers (e.g., Sheridan et al., 2006; Smith, 1968).

Analyses

Although the time between tests varied across participants, every participant took both tests within three months (mean days in-between = 29.59, *SD* =32.12). According to Morgan, Muetzelfeldt, and Curran (2010), neurocognitive function in healthy adults does not change significantly when assessed one year apart; therefore, it was deemed unnecessary to include the time between tests as a variable within the analyses.

Typically, reaction time scores of healthy participants do not produce a normal distribution. Histograms were examined across variables to determine if the data were in fact non-normal. All reaction time variables were positively skewed and suggested a leptokurtic kurtosis. In order to account for this nonnormality within the data, the MLR estimator was employed across all models. The significance of correlations within and across factors were appropriate (i.e., significant correlations between common measures within factors) (Cohen, 1988); therefore, it was concluded that the constructs are relatively broad and are comprised of unique indicators (Table 1). Descriptive statistics of observed variables can be found in Table 2.

Confirmatory factor analyses were conducted for a two-factor solution (Speed and Memory), with ImPACT composite scores and C3 Logix scores using Mplus, Version 7 (Muthén & Muthén, 1998–2012). Data collected from participants were complete (i.e., no missing data). ImPACT composite scores were loaded onto Speed and Memory latent factors as previous literature

Table 1. Correlation matrix of observed variables.

	TrailDif	*Simple*	*Choice*	*ViMo*	*RT*	*SDM*	*VbMC*	*ViMC*
TrailDif	1							
Simple	−0.13	1						
Choice	0.20	0.59**	1					
ViMo	−0.25*	−0.10	−0.10	1				
RT	0.05	0.41**	0.38**	−0.30*	1			
SDM	−0.28*	−0.19	−0.39**	0.29*	−0.32*	1		
VbMC	−0.09	0.05	0.04	0.20	−0.06	0.18	1	
ViMC	0.08	−0.03	−0.04	0.14	−0.09	0.39**	0.34*	1

* Correlation is significant at the 0.01 level.
** Correlation is significant at the 0.001 level.
Note: TrailDif = Trail-Making Difference, Simple = Simple Reaction Time, Choice = Choice Reaction Time, ViMo = Visual Motor Speed, RT = Reaction Time, SDM = Symbol-Digit Modalities, VbMC = Verbal Memory, ViMC = Visual Memory.

Table 2. Descriptive statistics of indicators.

Indicator	*N*	*Mean*	*SD*
TrailDif(s)	86	21.34	10.87
SDM	86	68.57	10.74
Simple(ms)	86	270.26	24.86
Choice(ms)	86	392.22	47.56
VbMC	86	87.78	9.35
ViMC	86	79.91	10.56
ViMo	86	39.90	5.17
RT(s)	86	0.59	0.07

Note: TrailDif = Trail-Making Difference, Simple = Simple Reaction Time, Choice = Choice Reaction Time, ViMo = Visual Motor Speed, RT = Reaction Time, SDM = Symbol-Digit Modalities, VbMC = Verbal Memory, ViMC = Visual Memory.

suggests: Verbal and Visual Memory as indicators of the Memory latent factor, and Visual Motor Speed and Reaction Time as indicators of the Speed latent factor (e.g., Gerrard et al., 2017; Iverson et al., 2005; Lovell, 2004; Schatz & Maerlender, 2013). The variance of each latent variable was fixed to one, standardizing scores of latent variables and freely estimating all factor loadings. Additionally, the latent variables were covaried with each other.

CFA allows for estimating relationships among unique variances by modeling correlated measurement error in our solution. The specification of correlated errors between indicators implies that although the indicators are related in part by the shared influence of the latent factor, some of their covariations is due to sources other than that common factor (Brown, 2015).

In order to adequately assess the global fit of the models, multiple indices of fit were employed. Wheaton, Muthen, Alwin, and Summer (1977) claim that a non-significant chi-square test may provide evidence that the model is a good fit. The Comparative Fit Index (CFI) and the Tucker-Lewis Index (TLI), as “goodness of fit” indicators (Kline, 2015), can be interpreted as higher values indicating better fit, with 0.90 acting as the threshold (Hu & Bentler, 1999). Finally, the Standardized Root Mean Square Residual (SRMR) and the Root Mean Squared Error of Approximation (RMSEA), along with its 90% confidence interval, as “badness of fit” indicators (Kline, 2015), associate lower values with better fit; 0.05 acts as a “good” threshold for SRMR, whereas RMSEA values below 0.10 denote acceptable fit (MacCallum, Browne, & Sugawara, 1996). Examining the 90% confidence interval associated with RMSEA is a recommended practice in SEM. Ideally, the lower end of the confidence interval includes 0 (Kenny, 2015). These values provide information about the precision of the estimate and can be of great assistance when drawing appropriate conclusions about model quality (MacCallum et al., 1996). The analysis relied heavily on values of CFI and RMSEA (as well as its associated confidence intervals), as they are preferential interpretations for smaller sample sizes (Bentler, 1990; Browne & Cudeck, 1992). All model respecifications were guided by relevant research and theory (e.g., Indicator Cross Loadings/Model Parsimony; Brown, 2015).

Finally, as is typically recognized, SEM works best with larger samples. However, when this is not feasible (e.g., limited population pools such as current varsity collegiate athletes with no history of head injury) it can be used with smaller sample sizes. A basic rule of thumb for simplistic models is a minimum of 10 participants per variable/measure (Nunnally, 1967).

Results

Three models were tested to determine the fit of C3 Logix within the context of the two-factor criterion model.

Model 1. In order for C3 Logix to fulfill the two-factor requirement for comprehensive neuropsychological screening, at least one component would need to load onto the Memory factor. Consequently, the first model tested loaded SDM onto the Memory latent factor, whereas the other tasks (Simple Reaction Time, Choice Reaction Time, and Trail-Making Difference) served as indicators of the Speed factor. Global fit of the model was poor ($\chi^2 = 35.71$, $p < .01$, CFI = 0.84, TLI = 0.73, RMSEA = 0.12 (90% CI [0.06, 0.17]), SRMR = 0.09).

Model 2. It was also possible that the SDM component was simply another indicator of Speed; therefore, the next model tested loaded SDM onto the Speed latent factor. All other indicators remained with their original latent factor. Loading SDM only onto the Speed latent factor again resulted in poor global fit ($\chi^2 = 42.69$, $p < .01$, CFI = 0.78, TLI = 0.63, RMSEA = 0.13 (90% CI [0.08, 0.18]), SRMR = 0.08).

Model 3. Due to the results of the previous models, the next step was to attempt to improve on Model 1 by examining standardized residuals and modification indices, which suggested cross-loading SDM onto both Speed and Memory. Global fit indices suggested the model fit was quite good ($\chi^2 = 22.91$, $p = 0.12$, CFI = 0.94, TLI = 0.90, RMSEA = 0.07 (90% CI [0.00, 0.13]), SRMR = 0.06). Additionally, all standardized estimates (factor loadings) exceeded 0.30, suggesting that each indicator was a salient measure of the corresponding latent variable (Brown, 2015) (Table 3). The amount of variance accounted for can be seen in Table 4. The final Model construction appears in Figure 2.

Table 3. Unstandardized and standardized factor loadings of the final model.

	Unstandardized Estimates		
	Factor Estimate	*p-value*	*Standardized Estimates*
Memory			
VbMC	3.50	< .01	0.38
ViMC	9.35	< .01	0.89
SDM	4.05	< .01	0.38
Speed			
TrailDif	3.88	0.04	0.36
SDM	−6.04	< .01	−0.57
Simple	11.15	< .01	0.45
Choice	28.02	< .01	0.59
ViMo	−2.06	< .01	−0.40
RT	0.04	< .01	0.57

Note: TrailDif = Trail-Making Difference, Simple = Simple Reaction Time, Choice = Choice Reaction Time, ViMo = Visual Motor Speed, RT = Reaction Time, SDM = Symbol-Digit Modalities, VbMC = Verbal Memory, ViMC = Visual Memory.

Table 4. R-square statistics (variance accounted for).

Indicator	*Variance Accounted For*
TrailDif	13%
Simple	20%
Choice	35%
ViMo	16%
RT	33%
SDM	51%
VbMC	14%
ViMC	79%

Note: TrailDif = Trail-Making Difference, Simple = Simple Reaction Time, Choice = Choice Reaction Time, ViMo = Visual Motor Speed, RT = Reaction Time, SDM = Symbol-Digit Modalities, VbMC = Verbal Memory, ViMC = Visual Memory.

Discussion

The strong loadings of ImPACT composites on the Memory and Speed latent traits confirmed the factor structure of ImPACT obtained in previous studies, while providing important information about the factor structure of a newer set of computerized neuropsychological tests for use in concussion management (C3 Logix). The factor structure of C3 Logix tests weakly fitted to the criterion model.

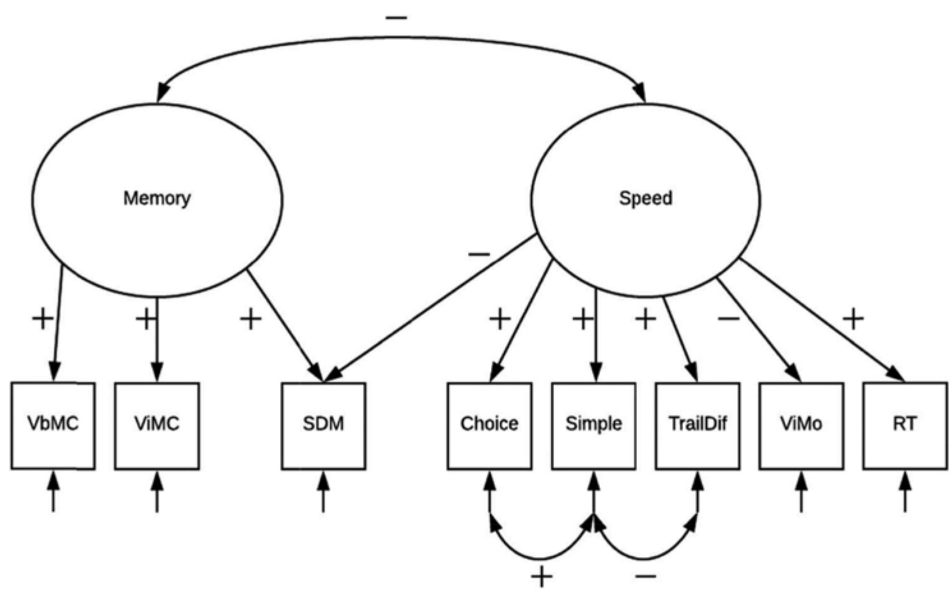

Figure 2. Model 3: SDM as an indicator of memory and speed. Errors of simple reaction time and choice reaction time and simple reaction time and trail-making difference correlated. Note: VbMC = Verbal Memory, ViMC = Visual Memory, SDM = Symbol-Digit Modalities, Choice = Choice Reaction Time, Simple = Simple Reaction Time, TrailDif = Trail-Making Difference, ViMo = Visual Motor Speed, RT = Reaction Time.

As the point of interest, the SDM indicator loaded onto both Memory and Speed latent factors, whereas the other C3 Logix tests clearly loaded onto the Speed factor. Loading SDM only onto Memory or Speed produced poor global fit; therefore, the suggestion and exploration of cross-loading SDM between Speed and Memory latent traits were warranted. Participants are able to get better scores on this task not only if they are responding faster, but also if they are able to remember the corresponding numbers and symbols instead of depending on the visual code provided. In fact, multiple studies have identified a contribution of memory to one's performance on the SDM task (e.g., Forn et al., 2009; Joy, Kaplan, & Fein, 2004).

Consequently, the conclusion that SDM score relies on components of both speed and memory is justified.

Ignoring crossloadings can result in multiple strains within the model, causing relationships to be overestimated as well as underestimated. This can include factor correlations, covariances, and even estimates between factors and their corresponding indicators. Because all relationships within the model are interdependent, respecifying one parameter (i.e., cross-loading SDM) may have successfully eliminated the aforementioned strains and allowed for the "true" model to be accurately represented (Brown, 2015).

Interpreting the direction of the relationships within the model can be somewhat misleading. Although all indicators of memory have the expected positive relationship with the latent factor, it is not surprising for indicators of speed to have mixed relationships with the latent factor. This is because the makeup of the indicators varies. Speed (i.e., latency) as a construct associates lower scores with better performance (i.e., lower scores means the participant is responding faster, hence, better). Therefore, indicators based on reaction time, or latency, have positive associations with the latent factor of Speed, whereas indicators such as Visual Motor Speed and SDM, which associate higher scores with better performance, have negative relationships with the Speed factor.

The addition of correlated error terms of Simple and Choice Reaction Time, and Simple Reaction Time and Trail-Making Difference is fundamentally grounded. Simple Reaction Time and Choice Reaction Time share similar functions and are scored in the same direction, they systematically change together. Therefore, their error terms share a positive relationship. Conversely, a negative relationship between the error terms of Simple Reaction Time and Trail-Making Difference was expected. The relationship between Simple Reaction Time and Trail-Making Difference is primarily driven by the relationship between Simple Reaction Time and Trail-Making A (Simple RT and Trails A, $r = 0.29$, $p < 0.01$; Simple RT and Trails B, $r = 0.01$, $p = 0.92$). Thus, as Trails B stays the same, and Trails A and Simple Reaction Time become faster, the value of Trail- Making Difference increases, resulting in a negative relationship.

Note that it is important to be consistent in the decision rules used to specify correlated errors. According to Brown (2015), if error of the indicators X1 and X2 and X2 and X3 is correlated, then the errors of X1 and X3 also should be estimated. Our correlated error estimations are consistent in that the error of Simple Reaction Time is correlated with errors of both Choice Reaction Time and Trail-Making Difference. One could assume that it would be necessary to correlate the errors of Choice Reaction Time and Trail-Making Difference. However, because the reasoning for correlation differs between indicators, correlating these errors would not be theoretically justified.

The correlations across our indicators met Clark and Watson (1995) recommendations (Table 1). They note that when identifying constructs, researchers should aim for a target mean inter-item correlation within the range of 0.15–0.50. This wider range is suggested because the optimal value varies with generality versus specificity of the target construct(s). As both of our constructs are relatively broad, lower correlational values (i.e., closer to 0.15) are expected, whereas correlations exceeding 0.50 would suggest redundancy (Clark & Watson, 1995). Moreover, not only are the correlations among indicators within the anticipated range, but the standardized factor loadings further support the saliency of the indicators for measuring our latent factors (Brown, 2015).

Covariance between our latent factors was found to be non-significant (standardized coefficient = −0.11, $p = 0.47$). This simply means two distinct and unrelated constructs were measured. This should add to any clinical specificity between concussed and nonconcussed athletes (Schatz & Sandel, 2013).

As with any study, there are limitations to the results. Despite mechanisms that are built into C3 Logix tests to guard against unusually slow responses or non-performance, there are no empirical data to support this approach as a validity indicator. Although an interesting approach, further research is needed to determine its effectiveness.

Moreover, structural equation modeling is typically used with relatively large samples. As noted, the basic rule of thumb for simple models is at least 10 participants per variable/measure (Nunnally, 1967). The study model had eight measures with a sample size of 86. Further, the model did converge, and we used global fit indices (CFI, RMSEA; Bentler, 1990) that are appropriate in the context of smaller samples.

It also should be noted that executive functioning is frequently included as an important function in SRC (Feddermann-Demont et al., 2017). However, as noted in their systematic review, Feddermann-Demont et al. (2017) state that in fact, the term "executive function" is frequently represented by Trail Making B and/ or Color-Word Interference (Stroop) tests. These tests have a speed component and therefore may reflect cognitive efficiency more directly than the nonspecific term "executive functions." The Trails B minus A time-score of C3 Logix attempts to partial out pure speed; however, this score still loaded on the speed factor. Indeed, ImPACT includes a Stroop interference- like task in the Visual Motor Speed composite. Thus, the term "executive functions" in relation to SRC may be too variable of a construct for computerized tests such as these. Similarly, the Memory factor captures different aspects of memory function and does not separate working memory from longer-term memory recall.

Further, as there is no universally accepted definition of processing speed (Kibby, Vadnais, & Jagger-Rickels, 2018), one must consider the multiple elements that contribute to this term in its entirety. According to Salthouse (1996), the most prominent operational definitions used to measure processing speed include reaction time along with psychophysical, perceptual, psychomotor, and decision speeds. To build upon this, Shanahan et al. (2006) proposed a concise and adequate definition of processing speed as the "the underlying cognitive efficiency at understanding and acting upon external stimuli, which includes integrating low level perceptual, higher level cognitive, and output speed."

ImPACT separates reaction time from processing speed ("Visual Motor Speed"), but both composites are highly correlated and have been shown to represent a single simple factor (Iverson et al., 2005; Schatz & Maerlender, 2013). C3Logix includes a Digit Symbol task, simple and a choice reaction time tasks, and Trail Making A and B. Thus, across platforms, reaction time, decision speed, perceptual speed, and psychomotor speed. Of course, these tasks involve varying degrees of incidental learning and working memory. Therefore, through the use of latent trait analysis (e.g., SEM), we are able to describe the underlying construct across these measures.

The final model of this study identified three pure indicators of speed and one indicator of both speed and memory for C3 Logix. Although sensitivity and specificity for diagnostic classification are an empirical question not addressed here, the lack of a pure indicator of memory in C3 Logix does raise a concern about its specificity and ultimately its sensitivity to SRC. Clinicians who use C3 Logix should be aware of this potential limitation for concussion assessment.

References

Allen, B. J., & Gfeller, J. D. (2011). The immediate post-concussion assessment and cognitive testing battery and traditional neuropsychological measures: A construct and concurrent validity study. *Brain Injury*, *25*(2), 179–191.

Barth, J. T., Alves, W. M., Ryan, T. V., Macciocchi, S. N., Rimel, R. W., Jane, J. A., & Nelson, W. E. (1989). Mild head injury in sports: Neuropsychological sequelae and recovery of function. In H. S. Levin, H. M. Eisenberg, & A. L. Benton (Eds.), *Mild head injury* (pp. 257–276). Oxford: Oxford University Press.

Barth, J. T., Macciocchi, S. N., Giordani, B., Rimel, R., Jane, J. A., & Boll, T. J. (1983). Neuropsychological sequelae of minor head injury. *Neurosurgery*, *13*(5), 529–533.

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin*, *107*, 238–246.

Brown, T. A. (2015). *Confirmatory factor analysis for applied research*. New York, NY: The Guilford Press.

Browne, M. W., & Cudeck, R. (1992). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds.), *Testing structural equation models* (pp. 136–162). Newbury Park, CA: Sage.

Charvet, L. E., Beekman, R., Amadiume, N., Belman, A. L., & Krupp, L. B. (2014). The symbol digit modalities test is an effective cognitive screen in pediatric onset of multiple sclerosis (MS). *Journal of Neurological Sciences*, *341*, 79–84.

Clark, L. A., & Watson, D. (1995). Constructing validity: Basic issues in objective scale development. *Psychological Assessment*, *7*(3), 309–319.

Cohen, J. (1988). Set correlation and contingency tables. *Applied Psychological Measurement*, *12*(4), 425–434.

Feddermann-Demont, N., Echemendia, R. J., Schneider, K. J., Solomon, G. S., Hayden, A., Turner, M., & Dvořák, J. (2017). What domains of clinical function should be assessed after sport-related concussion? A systematic review. *British Journal of Sports Medicine*, *51*, 903–918.

Forn, C., Belloch, V., Bustamante, J. C., Garbin, G., Parcet-Ibars, M. A., Sanjuan, A., … Avila, C. (2009). A symbol digit modalities test version suitable for functional MRI studies. *Neuroscience Letters*, *456*, 11–14.

Gerrard, P. B., Iverson, G. L., Atkins, J. E., Maxwell, B. A., Zafonte, R., Schatz, P., & Berkner, P. D. (2017). Factor structure of ImPACT in adolescent student athletes. *Archives of Clinical Neuropsychology*, *32*(1), 117–122.

Greve, K. W., Stickle, T. R., Love, J. M., Bianchini, K. J., & Stanford, M. S. (2005). Latent structure of the Wisconsin card sorting test: A confirmatory factor analytic study. *Archives of Clinical Neuropsychology*, *20*(3), 355–364.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. Structural equation modeling. *A Multidisciplinary Journal*, *6*, 1–55.

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2005). Validity of ImPACT for measuring processing speed following sports-related concussion. *Journal of Clinical and Experimental Neuropsychology*, *27*(6), 683–689.

Joy, S., Kaplan, E., & Fein, D. (2004). Speed and memory in the WAIS-III digit-symbol–Coding subtest across the adult lifespan. *Archives of Clinical Neuropsychology*, *19* (6), 759–767.

Kattiria, S. Y., Wheeler, B. M., Decoster, L. C., Hollingworth, A. T., & Valovich McLeod, T. C. (2018). Horizontal dynamic visual acuity test on C3 Logix provokes symptoms in healthy collegiate athletes.

Kenny, D. A. (2015, November 24). *Measuring model* fit. Retrieved from http://davidakenny.net/cm/fit.htm

Kibby, M. Y., Vadnais, S. A., & Jagger-Rickels, A. C. (2018). Which components of processing speed are affected in ADHD subtypes? *Child Neuropsychology*. Forthcoming. doi: 10.1080/09297049.2018.1556625

Kline, R. B. (2015). *Principles and practice of structural equation modeling* (4th ed.). New York, NY: The Guilford Press.

Kosinski, R. J. (2010). A literature review on reaction time. Retrieved from http://archive.li/jw9W#selection-347.0-367.176

Lichtenstein, J. D., Moser, R. S., & Schatz, P. (2013). Age and test setting affect the prevalence of invalid baseline scores on neurocognitive tests. *The American Journal of Sports Medicine*, *42*(2), 479–484.

Lovell, M. R. (2004). ImPACT version 2.0 clinical user's manual. Retrieved from http://www.impacttest.com/clients.htm

Lovell, M. R. (2007). ImPACT version 6.0 clinical user's manual. Retrieved from http://www.impacttest.com/ MacCallum, R. C., Browne, M. W., & Sugawara, H. M. (1996). Power analysis and determination of sample size for covariance structure modeling. *Psychological Methods*, *1*, 130–149.

Maerlender, A., Flashman, L., Kessler, A., Kumbhani, S., Greenwald, R., Tosteson, T., & McAllister, T. (2010). Examination of the construct validity of ImPACT computerized test, traditional, and experimental neuropsychological measures. *The Clinical Neuropsychologist*, *24*, 1309–1325.

McAllister, T. W., Flashman, L. A., Sparling, M. B., & Saykin, A. J. (2004). Working memory deficits after traumatic brain injury: Catecholaminergic mechanisms and prospects for treatment- a review. *Brain Injury*, *18*(4), 331–350.

Morgan, C. J. A., Muetzelfeldt, L., & Curran, H. V. (2010). Consequences of chronic ketamine self-administration upon neurocognitive function and psychological wellbeing: A 1-year longitudinal study. *Addiction*, *105*(1), 121–133.

Muthén, L. K., & Muthén, B. O. (1998–2012). *Mplus user's guide* (7th ed.). Los Angeles, CA: Muthén & Muthén.

Neurologix Technology, Inc. (2015). *C3 logix: A concussion management system*. Retrieved from http://www.neurologixtech.com/

Nunnally, J. C. (1967). *Psychometric theory*. New York, NY: McGraw-Hill.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychology Review*, *103*(3), 403–428.

Schatz, P., & Maerlender, A. (2013). A two-factor theory for concussion assessment using ImPACT: Memory and speed. *Archives of Clinical Neuropsychology*, *28*(8), 791–797.

Schatz, P., & Sandel, N. (2013). Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *American Journal of Sports Medicine*, *41*(2), 321–326.

Shanahan, M. A., Pennington, B. F., Yerys, B. E., Scott, A., Boada, R., Willcutt, E. G., … Defries, J. C. (2006). Processing speed deficits in attention deficit/hyperactivity disorder and reading disability. *Journal of Abnormal Child Psychology*, *34*, 585–602.

Sheridan, L. K., Fitzgerald, H. E., Adams, K. M., Nigg, J. T., Martel, M. M., Puttler, L. I., … Zucker, R. A. (2006). Normative symbol digit modalities test performance in a community-based sample. *Archives of Clinical Neuropsychology*, *21*(1), 23–28.

Simon, M., Maerlender, A. C., Metzger, K., Decoster, L., Hollingworth, A., & Valocich McLeod, T. (2017). Reliability and concurrent validity of select c3 logix test component. *Developmental Neuropsychology*, *42*(7–8), 446–459.

Smith, A. (1968). *The symbol-digit modalities test: A neuropsychologic test of learning and other cerebral disorders*. (J. Helmuth, Ed.). Seattle, WA: Learning Disorders, Special Child Publications.

Smith, A. (1982). *Symbol digits modalities test: Manual*. Los Angeles: Western Psychological Services.

Tombaugh, T. N. (2004). Trail making test a and b: Normative data stratified by age and education. *Archives of Clinical Neuropsychology*, *19*(2), 203–214.

Valovich McLeod, T. (2014). *Current research perspectives: What we know now and where we are headed*. Presented at the New Hampshire Musculoskeletal Institute in Manchester, NH.

Wheaton, B., Muthen, B., Alwin, D. F.3, & Summer, G. F. (1977). Assessing reliability and stability in panel models. *Sociological Methodology*, *8*(1), 84–136.