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Improvement of Perceptual-Motor Function among Elite Athletes with Concussion History

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Context: The potential for upper extremity (UE) perceptual-motor training to enhance whole-body (WB) reactive performance could be an important consideration for injury risk reduction among athletes who possess subtle impairment of neural processing.

Objective: To identify any perceptual-motor performance differences between athletes with history of sport-related concussion (HxSRC) and those without such history (NoSRC) and to assess any UE training effect on WB reactive performance.

Design: Longitudinal cohort study.

Setting: Residential Olympic training center.

Participants: 20 elite athletes (ages 18-34; 12 males, 8 females), which included 10 with HxSRC.

Interventions: One-minute UE training sessions were completed 2-3 times per week over a 3-week period, which involved verbal identification of center arrow direction for 20 flanker test trials (incongruent: <<><< or >><>>; congruent: <<<<< or >>>>>) with simultaneous reaching responses to deactivate randomly illuminated buttons.

Main Outcome Measure: Pre- and post-training assessments included both UE and WB reactive responses. Key metrics included UE flanker test conflict effect (CE: incongruent minus congruent reaction time) and WB lateral average asymmetry (Lat Avg Asym) derived from the average of reaction time, speed, acceleration, and deceleration values for left versus right movement directions.

Results: Pre-training discrimination between HxSRC and NoSRC was evident for CE ≥80 ms (79% PPV; 62% PPV) and WB Lat Avg Asym ≥18% (100% PPV; 71% NPV). All participants completed at least 6 training sessions, which improved UE reaction time from 848 ±119 to 646

±68 ms (P<.001) and reduced CE from 96 ±49 to 53 ±66 ms (P=.039). A significant group X trial interaction was evident for WB Lat Avg Asym (P=.029), which was reduced from an average of 24% to 13% among those with HxSRC.

Conclusions: Suboptimal perceptual-motor performance may represent a subtle long-term effect of concussion that is modifiable through UE training, which appears to improve WB reactive capabilities.

Key Words: Mild Traumatic Brain Injury, Reaction Time, Neuromechanics, Training Adaptation

Introduction

Any sport-related injury can result in elevated susceptibility to a subsequent injury, with multiple injuries often leading to chronic dysfunction and the potential for progressive disability. The speed of multi-segmental and whole-body motor responses to the rapidly changing demands of a sport environment represents an intuitively important aspect of injury avoidance. Execution of such goal-directed motor responses to sensory inputs depends on brain functional connectivity, which represents temporal dependence of neural activity patterns between spatially separated brain regions. Disrupted functional connectivity of brain networks slows processing of neural signals, which may result from either mild traumatic brain injury[1,2] or loss of proprioceptive afference following musculoskeletal injury.[3] Detection of subtle impairment of neural processing capabilities currently relies on advanced neuroimaging and electrophysiological procedures that are not feasible for injury risk screening or clinical assessment of mTBI.[4] Because neural processes involved in perceptual decision-making for the formation of motor goals consume the major portion of the time required to respond to a stimulus,[5] measurement of reaction time (RT) and other time-related performance metrics offer an indirect means to clinically assess the efficiency of perceptual-motor neural processing.

The term RT is broadly used to represent the amount of time that elapses between the onset of a stimulus (e.g., visual, auditory, or tactile) and the initiation or completion of a specified motor response.[5] Depending on the specific nature of the stimulus and response, various methods used to measure RT can produce an extremely wide range of values. The term "Simple RT" often designates a measure derived from a button press or mouse click response to the appearance of a single type of stimulus, whereas "Choice RT" requires cognitive interpretation of a given stimulus to make a response decision (e.g., go versus no-go or left versus right). If a multi-segmental or whole-body "functional" response is required, visual-spatial calibration and motor programming will increase the complexity of the neural processing required for generation of the response. Clinical assessments of neurocognitive RT that involve a simple stimulus-response task do not demonstrate substantial correlations with measures of RT derived from tests that simultaneously challenge cognitive and motor capabilities.[6]

Decisions about actions activate many of the same brain regions that plan and execute motor actions, which suggests that cognitive decision-making is not a distinctly separate process from sensorimotor control.[7-9] Cognitive control represents an executive function of the brain that relates to the capacity to plan and execute purposeful behavior.[10,11] Specific cognitive control processes include selective attention, working memory, visual-spatial calibration, conflict resolution, decision-making, and motor planning, all of which activate overlapping neural circuitry.[12] Perception specifically refers to cognitive recognition of the causes of sensations,[13] such as visual, auditory, vestibular, and proprioceptive signals. Perceptual-cognitive training is a term used to designate activities designed to develop improved anticipation and decision-making skills.[14] Despite the complexity of the neural circuitry that integrates perceptual, cognitive, and motor processes, some tasks elicit unique neural activation patterns that relate to functional connectivity within and between specific brain networks.[15-17] Neural processing speed can be represented by stimulus-response RT, decision-making skill can be represented by response accuracy, and the composite of the two metrics can be used to represent perceptual-motor efficiency.[18]

The complexity of the combined perceptual-cognitive and motor tasks used to assess and train perceptual-motor efficiency appears to be an extremely important consideration for injury prevention.[19,20] Properly designed perceptual-motor training activities may facilitate integration of neural processing between networks to make them function as a single network.[19,21] Extensive utilization of the Eriksen flanker test (FT) in neurophysiological research has established well-characterized neural activation patterns in the right hemisphere, which include the anterior cingulate cortex, dorsolateral prefrontal cortex, and posterior parietal cortex.[16,22-24] The FT involves determination of the direction of a center arrow that has two arrows on either side. A key metric derived from the FT is conflict effect (CE), which is the difference in time required to respond to incongruent trials (<<><< or >><>>) versus congruent trials (<<<<< or >>>>). Simple finger responses to identify center arrow direction have consistently revealed a significant effect of concussion history on CE magnitude.[22,25-27]

The combination of the FT with rapid deactivation of randomly illuminated buttons by upper extremity reaching responses discriminated athletes with sport-related concussion history (HxSRC) from those who denied such a history (NoSRC) on the basis of RT difference between the left and right visual fields.[28] Previous research has also identified asymmetrical whole-body (WB) performance capabilities as another discriminating factor.[28,29] An important question is the transferability of upper extremity (UE) perceptual-motor training adaptations to performance in a dynamic sport environment.[14] A recent study of a UE visual-motor training program failed to identify any beneficial effect for lower extremity performance on a similar task, but neither the UE training task or the post-training lower extremity test incorporated a simultaneous cognitive demand.[30] The purpose of this study was to assess the extent to which training-induced improvement in measures of UE perceptual-motor efficiency might transfer to WB reactive agility performance.

Methods

All 20 of the training program participants (Table 1) were members of a larger cohort of 35 healthy elite athletes, which provided data for a previously reported cross-sectional comparison of survey responses and perceptual-motor performance metrics for HxSRC and NoSRC.[29] The Institutional Review Board of xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx approved all study procedures, which included written informed consent from each participant. Pre-training data was the same as that used for the previously reported study, and post-training data collection procedures were identical. The UE perceptual-motor training task required the athletes to verbally identify the direction of the center arrow of 20 FT trials displayed on the centrally located tachistoscope of a height-adjustable board (Dynavision D2™ System; Dynavision International; West Chester, OH) with simultaneous performance of reaching movements to deactivate randomly illuminated buttons (Figure 1). The 60-s dual-task activity presented 10 incongruent and 10 congruent FT trials for 250 ms, with an interstimulus interval that ranged from 2 to 4 s. Training sessions involved a single 60-s test that was performed 2-3 times per week over a 3-week period for a total of 6-8 sessions. In addition to RT, a derived metric of interest previously found to discriminate HxSRC from NoSRC was left minus right difference in RT (L-R RT Diff) for reaching responses in opposite directions. Assessment of the reliability of dual-task RT measurements derived from the device has yielded good to excellent ICC values in the range of .75 to .90.[31]

Pre- and post-training assessments included another version of the UE perceptual-motor training test that used the FT center arrow direction as a cue for the correct direction of 48 reaching responses to pairs of illuminated buttons in corresponding locations on opposite sides of the board, which was used to acquire the measurement of CE. To assess the possible transfer of

UE training adaptation to WB reactive movement capabilities, pre- and post-training assessments included testing of lateral and diagonal movements with a virtual reality motion analysis system (TRAZER® Sports Stimulator; Traq Global Ltd; Westlake, OH) using the same procedures reported previously.[29] Performance metrics included RT, speed (Spd), acceleration (Acc), and deceleration (Dec), as well as magnitude of bilateral asymmetry (Asym) calculated as absolute difference divided by the better performance value for the opposite movement directions. Our previous research identified the average of lateral movement asymmetries for RT, Spd, Acc, and Dec (Lat Avg Asym) as a strong predictor of HxSRC, which made this composite value a metric of primary interest. Because our previous analyses of the WB diagonal movements demonstrated relatively poor discriminatory power for diagonal-forward movements, we focused our analysis on performance values for the diagonal-backward (D/B) movement direction.

Repeated measures analysis of variance was used to assess change in UE perceptual-motor RT from the baseline assessment, which included evaluation of group X trial interaction effect. Receiver operating characteristic (ROC) analysis quantified the association of baseline assessment continuous variables with HxSRC. Variables that demonstrated a clearly definable cut point on the ROC curve were converted into binary variables to perform cross-tabulation analysis and calculation of the odds ratio (OR). Each variable that demonstrated an OR > 4 was further analyzed in its continuous form for assessment of pre- to post-training change with repeated measures analysis of variance. All analyses were performed with SPSS® version 25 (IBM Corporation; Armonk, NY). Statistical significance was defined as $P < .05$ and borderline statistical significance was defined as $P < .10$. No adjustment for multiple comparisons was applied to the analysis results.[32]

Results

The training program produced a highly significant UE perceptual-motor RT improvement from baseline assessment of 864 ±96 ms to session 6 performance of 646 ±68 ms ($F_{6,108}$=38.79; *P*<.001; η^2=.683), with no significant pre- to post-training difference between cohort subgroups (*P*=.423). Table 2 presents baseline pre-training test variables that demonstrated substantial discriminatory power between HxSRC and NoSRC in order of OR magnitude (variables of primary interest in bold font) and Table 3 presents pre- to post-training change in the same variables. A significant main effect for trial was evident for reduction of FT Conflict Effect (*P*=.039; η^2=.216). A significant group X trial interaction effect was evident for the composite WB Lat Avg Asym variable (P=.029; η^2=.237) and WB Lat Avg RT (P=.002; η^2=.422). Table 4 presents pre- to post-training change for the 10 HxSRC cases, which demonstrates that post-training mean values were lower than the optimally discriminating cut point identified prior to training for 7 of the 9 performance metrics.

Discussion

The 24% improvement in UE perceptual-motor RT observed in this cohort of 20 elite athletes was remarkably consistent with previously reported improvement magnitude in the range of 20-28% for training that has utilized the same equipment.[33-35] Derived FT metrics such as L-R RT difference and CE appear to be much more important for discrimination between HxSRC and NoSRC than average RT for UE reaching responses. The ability to generate coordinated movements depends on efficient interhemispheric interactions,[36] and decreased frequency of eye saccades to the left visual field has been associated with impairment neural processing in the right-lateralized attention network.[37] The observed tendency for HxSRC cases to exhibit a positive pre-training value for L-R RT difference (i.e. Left RT slower than Right RT) suggests that impaired brain network connectivity may contribute to asymmetrical WB responses.[38] The observed post-training improvements in UE perceptual-motor performance suggest that the simultaneous FT demand enhanced the functional connectivity of brain networks,[22,23,25,27] which provides a plausible explanation for the observed post-training improvements in WB reactive movement capabilities.[21]

Inconsistent use of terminology in reports of perceptual-motor research has interfered with clear communication of key concepts.[39] The elapsed time between presentation of a visual stimulus and generation of a proper motor response predominantly reflects the amount of time required to complete the perceptual decision-making process.[5] Thus, hyphenated terms such as visual-motor and cognitive-motor fail to convey the importance of integration among the somewhat distinct exteroceptive, interoceptive, and cognitive control processes that formulate motor goals. The hyphenated term perceptual-motor seems more appropriate for designation of these integrated neural processes. We have previously used the term "neuromechanical responsiveness" to designate the ability to integrate neurocognitive and neuromuscular processes for generation of effective responses to rapidly changing environmental demands.[28] Because an advanced neuroimaging or electrophysiological procedure is required to measure neural processes directly, properly designed clinical tests of neuromechanical responsiveness might yield measures that indirectly represent the efficiency of perceptual-motor processing.[40]

Activation of the attention components of the executive control network requires deactivation of the default mode network by the salience network.[17] A key component of the salience network is the anterior cingulate cortex, which also plays a key role in suppression of distracting visual stimuli during the process of making a response decision.[4,15,24,27] Thus, the FT appears to provide an indirect measure of the time required to recognize a target stimulus and complete a decision that initiates a motor response, with its CE representing the incremental time required to complete the same process for incongruent trials that include visual distractors. Our finding that CE differentiated HxSRC from NoSRC was consistent with the findings of previous research.[26,27] The observation that the UE perceptual-motor training program produced an identical 48% magnitude of improvement in CE and WB Lat Avg Asym among HxSRC cases suggests that some common neural impairment may have been responsible for the pre-training performance deficiencies. The training program also reduced the magnitude of the L-R RT Diff among HxSRC cases, which suggests that residual abnormalities in perceptual-motor function were resolved to some extent.

The primary limitations of the study include its relatively small cohort size and lack of any direct measures of functional connectivity. The necessity to rely on self-reported HxSRC was a limitation, but the strength of the study findings suggest that it was not a confounding factor. Future research should establish neural correlates of change in performance capabilities measured by clinical tests of neuromechanical responsiveness, as well as duration of training benefit retention and long-term surveillance for determination of a reduction in injury rate. Despite the acknowledged limitations, the findings suggest that our assessment procedures were sufficiently sensitive to detect a subtle neural processing deficit. Further, the UE training program clearly reduced both UE and WB reactive performance deficiencies that differentiated HxSRC cases from NoSRC athletes.

Conclusions

Detection of a subtle and potentially modifiable impairment of perceptual-motor efficiency is necessary to initiate a corrective intervention. Otherwise, an undetected deficiency may elevate risk for future injury. Our findings suggest that a properly designed clinical test can detect such impairment, and that as few as 6 UE perceptual-motor training sessions can substantially improve both UE and WB reactive performance capabilities.

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Figure Legends

Figure 1. Device used for assessment and training of upper extremity perceptual-motor performance.

Figure 2. Change in average upper extremity dual-task reaction time (simultaneous verbal responses to flanker test trials) from baseline assessment to last of 6 training sessions.

Table 1. Cohort Characteristics (N=20)

	Concussion History			No Concussion History		
N	10			10		
Age (years)	27.6 (20-34)			24.2 (18-31)		
	Male	Female		Male	Female	
Sex	5 (50%)	5 (50%)		7 (70%)	3 (30%)	
Height (cm)	178.3 ±9.2	164.6 ±6.6		175.6 ±10.3	168.5 ±5.3	
Mass (kg)	78.6 ±12.7	61.2 ±9.6		71.5 ±9.6	66.4 ±10.1	
	Right	Left	Neither	Right	Left	Neither
Hand Dominance	9	0	1	8	1	1
Sport Type:						
Bobsled/Skeleton	4			1		
Boxing	0			1		
Figure Skating	2			3		
Gymnastics	1			2		
Wrestling	2			2		
Modern Pentathlon	1			1		
Sport Fitness Index	64.8 (34-88)			69.8 (40-90)		
Depression, Anxiety, & Stress Scale	17.6 (0-44)			11.8 (6-26)		

Table 2. Results of Univariable Analyses

Variable	AUC	Cut Point	*P*	PPV	NPV	+LR	−LR	OR	(90% CI)
WB Lat Avg Asym*	**.770**	**≥ 18%**	**.005**	**100%**	**71%**	**13.00****	**0.40**	**30.33****	**(2.29, ∞)****
WB Lat Avg RT	.705	≥ 460 ms	.043	100%	63%	9.00**	0.60	14.54**	(1.10, ∞)**
WB D/B Dec Asym	.590	≥ 24%	.043	100%	63%	9.00**	0.60	14.54**	(1.10, ∞)**
WB Lat RT Asym	.780	≥ 16%	.029	69%	86%	2.25	0.17	13.50	(1.77, 103.11)
UE FT L-R RT Diff	**.770**	**≥ 38 ms**	**.029**	**86%**	**69%**	**6.00**	**0.44**	**13.50**	**(1.77, 103.11)**
WB D/B Acc Asym	.700	≥ 10%	.085	67%	75%	2.00	0.33	6.00	(1.12, 32.15)
WB Lat Spd Asym	.610	≥ 10%	.085	79%	62%	3.09	0.52	6.00	(1.12, 32.15)
UE FT Conflict Effect	**.690**	**≥ 80 ms**	**.085**	**79%**	**62%**	**3.09**	**0.52**	**6.00**	**(1.12, 32.15)**
WB D/B Spd Asym	.570	≥ 17%	.152	80%	60%	4.00	0.67	6.00	(0.79, 45.83)
WB Lat Acc Asym	.730	≥ 12%	.089	70%	70%	2.33	0.43	5.54	(1.09, 27.11)
WB Lat Dec Asym	.570	≥ 14%	.175	71%	62%	2.55	0.63	4.00	(0.76, 21.15)
Sport Fitness Index	**.600**	**≤ 76**	**.175**	**62%**	**71%**	**1.60**	**0.40**	**4.00**	**(0.76, 21.15)**

AUC: Area Under Curve; *P*: Fishers Exact Test One-Sided *P*-Value; PPV: Positive Predictive Value; NPV: Negative Predictive Value; +LR: Positive Likelihood Ratio; −LR: Negative Likelihood Ratio; OR: Odds Ratio; CI: Confidence Interval

WB: Whole-Body; D/B: Diagonal/Backward; Acc: Acceleration; Dec: Deceleration; RT: Reaction Time; Spd: Speed; Avg: Average; Asym: Asymmetry; UE: Upper Extremity; FT: Flanker Test; L-R RT Diff: Left RT minus Right RT

* Composite of Lat Asym values for RT, Spd, Acc, and Dec

** Estimated by adding 0.5 to each 2 X 2 cell to eliminate division by zero

Table 3. Pre- to Post-Training Change; Mean ±Standard Deviation (Entire Cohort, N=20)

Variable	Pre-Training	Post-Training	Pre – Post	*P*[a]	η^2	Change	*P*[b]	η^2
WB Lat Avg Asym (%)*	**17.6 ±18.1**	**14.2 ±8.5**	**3.4 ±17.6**	**.347**	**.049**	**19%**	**.029**	**.237**
WB Lat Avg RT (ms)	388 ±76	388 ±65	0 ±92	1.000	.000	0%	.002	.422
WB D/B Dec Asym (%)	18.3 ±12.5	17.6 ±13.2	0.7 ±18.0	.864	.002	4%	.312	.057
WB Lat RT Asym (%)	38.8 ±54.4	27.4 ±22.6	11.4 ±55.0	.330	.053	29%	.052	.194
UE FT L-R RT Diff (ms)	**11 ±92**	**–8 ±61**	**19 ±87**	**.317**	**.056**	**2%****	**.105**	**.139**
WB D/B Acc Asym (%)	14.1 ±9.8	11.4 ±10.0	2.6 ±16.4	.483	.028	19%	.338	.051
WB Lat Spd Asym (%)	8.6 ±8.0	7.8 ±5.9	0.8 ±0.8	.660	.011	9%	.071	.170
UE FT Conflict Effect (ms)	**96 ±49**	**53 ±66**	**43 ±85**	**.039**	**.216**	**45%**	**.542**	**.021**
WB D/B Spd Asym (%)	11.7 ±7.4	10.0 ±5.1	1.7 ±8.9	.400	.040	15%	.443	.033
WB Lat Acc Asym (%)	10.0 ±7.7	10.7 ±6.0	–0.7 ±9.1	.703	.008	–7%	.033	.229
WB Lat Dec Asym (%)	12.9 ±11.5	10.7 ±9.3	2.2 ±13.3	.471	.029	17%	.480	.028

[a] *P*: Repeated Measures Trial Main Effect

[b] *P*: Repeated Measures Group X Trial Interaction Effect

WB: Whole-Body; D/B: Diagonal/Backward; Acc: Acceleration; Dec: Deceleration; RT: Reaction Time; Spd: Speed; Avg: Average; Asym: Asymmetry; UE: Upper Extremity; FT: Flanker Test; L-R RT Diff: Left RT minus Right RT; Avg Asym: RT, Spd, Acc, and Dec

* Composite of Lat Asym values for RT, Spd, Acc, and Dec

** Left (25% Change) > Right (23% Change)

Table 4. Pre- to Post-Training Change; Mean ±Standard Deviation (SRC Hx, n=10)

Variable	Pre-Training	Post-Training	Pre – Post	Change
WB Lat Avg Asym (%)*	**24.3 ±23.9**	**12.5 ±9.5**	**11.8 ±21.1**[a]	**48%**
WB Lat Avg RT (ms)	416 ±83	357 ±38	59 ±68[a]	14%
WB D/B Dec Asym (%)	21.5 ±15.6	16.6 ±14.3	4.9 ±21.8	23%
WB Lat RT Asym (%)	58.3 ±71.6	23.4 ±20.0	34.9 ±66.7[b]	60%
UE FT L-R RT Diff (ms)	**52 ±87**	**2 ±45**	**50 ±87**	**4%****
WB D/B Acc Asym (%)	17.5 ±11.0	11.3 ±11.3	6.2 ±19.3	36%
WB Lat Spd Asym (%)	10.8 ±9.9	6.7 ±5.3	4.1 ±9.3	38%
UE FT Conflict Effect (ms)	**114 ±46**	**59 ±80**	**55 ±101**[c]	**48%**
WB D/B Spd Asym (%)	12.6 ±8.7	9.3 ±5.0	3.3 ±10.4[b]	26%
WB Lat Acc Asym (%)	12.8 ±7.8	9.3 ±6.0	3.5 ±2.5[a]	27%
WB Lat Dec Asym (%)	15.0 ±13.6	10.6 ±12.0	4.4 ±16.2	29%

WB: Whole-Body; D/B: Diagonal/Backward; Acc: Acceleration; Dec: Deceleration; RT: Reaction Time; Spd: Speed; Avg: Average; Asym: Asymmetry; UE: Upper Extremity; FT: Flanker Test; L-R RT Diff: Left RT minus Right RT; Avg Asym: RT, Spd, Acc, and Dec

* Composite of Lat Asym values for RT, Spd, Acc, and Dec

** Left (25% Change) > Right (21% Change)

[a] Group X Trial Interaction $P<.05$ [b] Group X Trial Interaction $P<.10$ [c] Trial Main Effect $P<.05$

Figure 1

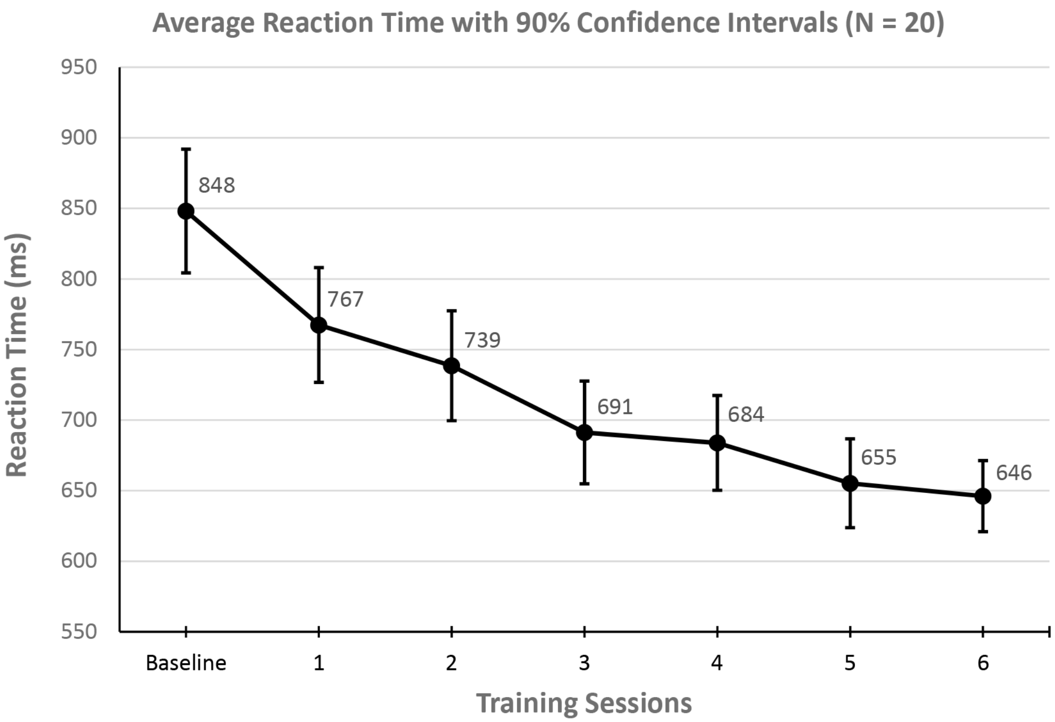
Average Reaction Time with 90% Confidence Intervals (N = 20)
Reaction Time (ms)
950
900
850
800
750
700
650
600
550
848
767
739
691
684
655
646
Baseline
1
2
3
4
5
6
Training Sessions

Figure 2