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REVIEW

Are Divided Attention Tasks Useful in the Assessment and Management of Sport-Related Concussion?

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Abstract This article is a systematic review of the literature on divided attention assessment inclusive of a cognitive and motor task (balance or gait) for use in concussion management. The systematic review drew from published papers listed in PubMed, MEDLINE, EMBASE and CINAHL databases. The search identified 19 empirical research papers meeting the inclusion criteria. Study results were considered for the psychometric properties of the paradigms, the influence of divided attention on measures of cognition and postural control and the comparison of divided attention task outcomes between individuals with concussion and healthy controls (all samples were age 17 years or older). The review highlights that the reliability of the tasks under a divided attention paradigm presented ranges from low to high (ICC: 0.1–0.9); however, only 3/19 articles included psychometric information. Response times are greater, gait strategies are less efficient, and postural control deficits are greater in concussed participants compared with healthy controls both immediately and for some period following concussive injury, specifically under divided attention conditions. Dual task assessments in some cases were more reliable than single task assessments and may be better able to detect lingering effects following concussion. Few of the studies have been replicated and applied across various age groups. A key limitation of these studies is that many include laboratory and time-intensive measures. Future research is needed to refine a time and cost efficient divided attention assessment paradigm, and more work is needed in younger (pre-teens) populations where the application may be of greatest utility.

Keywords Brain injury · Postural control · Cognition · Dual-task

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Introduction

Cerebral concussion is a complex injury that may be difficult to evaluate and manage given the variability in presentation and the multiple systems affected by the injury (Giza and Hovda 2001). Best practices recommended for concussion evaluation include a multimodal assessment inclusive of symptoms, cognition, balance and a detailed clinical evaluation. This combined approach may be over 90 % sensitive to concussive injury (Broglio et al. 2007) and is much more sensitive than using any single measure in isolation (Register-Mihalik et al. 2013). A growing body of research suggests that many of the commonly used measures of concussion (e.g., self-report symptoms, clinical balance assessments, and computerized neurocognitive assessments) may not be as sensitive to deficits further out from the injury and that other measures such as Electroencephalography (EEG) or types of analysis (e.g. Approximate Entropy) on the currently used measures may be more beneficial (Cavanaugh et al. 2005; Prichep et al. 2013; Slobounov et al. 2010). In addition, recent literature has suggested that gait assessments such as

gait speed, stride length and coordination during gait may also be important assessment measures, as they are also affected post-concussion (Catena et al. 2007b, 2009a).

One of the recommended measures that may provide additional information in the concussion assessment process is a simultaneous assessment of motor and cognitive functions, often referred to as a dual-task or divided attention assessment. These types of assessments are functional in nature as most activities, particularly those in sport require a division of attention while still producing appropriate motor and cognitive responses. Although numerous studies have examined these paradigms in controls and concussed individuals, they are not widely used in concussion assessment across the medical field. In addition, these types of activities may also be a way to assess changes and deficits throughout the graduated return to play protocol prior to full return to sport. While single tasks require attention, divided attention tasks lead to competition for attention resources between the simultaneous tasks. If the individual is not given specific instructions about which task to prioritize, then their brain must decide which task to unconsciously prioritize. This competition for attention, or increase in cognitive load, typically causes decreased performance in one or both tasks. Concussion leads to cognitive deficits, so divided attention tasks may be more sensitive to concussion than single task assessments.

As the landscape of concussion management continues to advance, understanding the key components that should be included in the assessment process is essential to developing an appropriate treatment and management plan. Understanding the effects of divided attention on cognition and postural control may also allow for the use of these types of concurrent activities in the rehabilitation process in cases of prolonged recovery following concussion.

There is a need for understanding the role of divided attention tasks in assessing the interaction of multiple systems post-concussion. This review provides a systematic examination of the published literature involving the use of divided attention tasks incorporating a cognitive and motor task in the assessment and management of sport-related concussion. The goal is to further our understanding of the role of divided attention tasks in the concussion management process. The review will address the following questions:

1. What are the psychometric properties of divided attention paradigms proposed in the literature concerning assessment of concussion?
2. Following sport-related concussion, are there greater deficits in cognitive or motor performance when performed under a dual-task paradigm than when performed alone?
3. What differences exist in divided attention performance between injured individuals and controls?

Methods

Search Strategy

Multiple databases including PubMed/MEDLINE ($n=37$), Embase ($n=37$) and CINAHL ($n=350$) were searched for relevant articles using the search terms “dual-task” OR “divided-attention” AND “concussion.” These article titles and abstracts were then reviewed for inclusion. Each article meeting the criteria after abstract review was then reviewed entirely to ensure all inclusion criteria were fully met in the study. All articles meeting relevant inclusion criteria were then hand searched for additional relevant articles to include in the review using the same inclusion criteria.

Study Selection

The search yielded a broad set of articles, not all relevant to the review with a total of 424 articles initially identified and a total of 38 articles meeting initial inclusion criteria after title and abstract review. However, after full review of each the remaining 38 articles by two separate reviewers, only 19 of these articles met all inclusion criteria including referencing a dual-task inclusive of a cognitive and motor task and were included for the systematic review. The articles, detailed in Table 1, were then hand searched for potential additional references to include in the review, with no additional articles being included. All articles were reviewed for duplication and the following inclusion criteria:

1) Published on or before July 9, 2013
2) Participants 17+ more years old (college-aged and older)
3) Dual-task (including a cognitive and motor (balance or gait) task) assessment used
4) Discussion of application to concussion or mild TBI assessment or management

The inclusion criteria were selected to understand the body of literature surrounding sport-related concussion assessment and management. The criteria were restrictive to those studies citing or implicating direct implications for concussion assessment.

Summary of Study Designs and Methodologies

Most studies ($n=15$) had a longitudinal design with at least two testing/data collection sessions (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Kleffelgaard et al. 2012; Martini et al. 2011; Okumura et al. 2013; Parker et al. 2005, 2006, 2007, 2008; Ross et al. 2011; Teel et al. 2013). The remaining 4 had a cross sectional design (Broglio et al. 2005; Cavanaugh et al. 2007; Fait et al. 2013; Resch et al. 2011); however, two of these studies also included a session where tasks were practiced but not assessed. (Broglio et al. 2005;

Table 1 Details and key findings of articles included in the systematic review[a]

Study details (First Author, Publication Year, Journal)	Dual-task/divided attention paradigm description	*n*, Sample, setting	Study design/assessment time points	Descriptive data highlights	Key findings
Broglio, 2005, Med Sci Sport Exer	- Eyes open conditions of SOT with task switching cognitive task (but 10 s trials)	*n* = 20, healthy young adults, laboratory	- Cross-sectional - Session 1: orientation; Session 2 (24–72 h later): assessment	- Faster reaction time under the dual-task (1234.50 ms vs. 1460.01 ms) - Overall better balance under dual-task compared to single task	- Balance and cognitive performance improved during the dual-task - Supports posture first principle
Catena, 2007, Gait and Posture	- Level walking with a continuous question and answer task	*n* = 28, 14 concussed and 14 controls, young adults, laboratory	- Cross-sectional - Acute concussion, but the specific time since injury was not included	- Concussed group (1.007 m/s) had slower gait velocity under the dual-task compared to controls (1.276 m/s) - Concussed group (0.043 m) had greater medial-lateral displacement than controls (0.034 m) under the dual-task - Concussed group (0.149 m/s) had greater medial-lateral velocity than controls (0.122 m/s) under the dual-task	- Under the dual-task, concussed individuals showed a conservative gait adaptation and signs of instability with increased side-to-side sway acutely following injury - Gait velocity slower and peak forward CoM in concussed group than controls acutely following injury
Catena, 2007, Exp Brain Res	- Level walking with a continuous question and answer task and level walking with a reaction time task (responding to an audible cue)	*n* = 28, 14 concussed and 14 controls, young adults, laboratory	- Cross-sectional - Concussed subjects were tested within 48 h post-injury	- Concussed individuals gait velocity slower under question and answer task (1.097 m/s) than the reaction time task (1.245 m/s) and single task walking (1.219 m/s) - All concussed gait velocities (see above) were slower than that of controls in the single task (1.361 m/s), reaction time task (1.369 m/s) and the question and answer task (1.276 m/s)	- Concussed individuals gait velocity slower across single and both dual-tasks than controls - Question and answer task resulted in a more conservative gait strategy than the simple reaction time task, making the question and answer task a potentially more useful secondary task
Catena, 2009, Exp Brain Res	- Level walking with obstacle avoidance and a continuous question and answer task	*n* = 34, 17 concussed and 17 controls, young adults, laboratory (subset from another study)	- Cross-sectional - Concussed subjects were assessed over 1 month post-injury	- In the concussed group only, within 48 h of injury, the relationship with the orienting effect of attention was significantly correlated with lead foot clearance (R^2=0.477, p=0.004) and spatial orientation attention was correlated to trailing foot obstacle clearance (R^2=0.265, p=0.050)	- When the dual-task was performed, the ability to orient attention was correlated even more with lead foot clearance and also correlated to trailing foot clearance - By day 6, these correlations are no longer seen in the concussed group and coincide with the return of the ability to spatially orient attention
Catena, 2009, J Neuroeng and Rehab	- Level walking with a continuous question and answer task	*n* = 30, 15 concussed and 15 controls, young adults, laboratory	- Longitudinal, repeated measures - Concussed subjects were assessed at approximately days 2, 6, 14 and 28 post-injury	- Concussed individuals (1.245 m/s) have reduced anterior-posterior velocity at 2-days post-injury compared to controls (1.326 m/s) under the dual-task	- Concussed individuals reduce their forward motion acutely following injury when performing a dual-task - The divided attention task was only able to better distinguish conservative gait adaptations immediately following concussion as by day 6 the groups were similar

Table 1 (continued)

Study details (First Author, Publication Year, Journal)	Dual-task/divided attention paradigm description	*n*, Sample, setting	Study design/assessment time points	Descriptive data highlights	Key findings
Catena, 2011, J of Neuroeng and Rehab	- Level walking with an auditory Stroop task	*n* = 20, 10 concussed and 10 controls, young adults, laboratory	- Longitudinal, repeated measures - Concussed subjects were assessed at approximately days 2, 6, 14 and 28 post-injury	- No differences on Stroop tasks across groups or conditions - In concussed individuals (not controls) moderate correlation between sagittal plane motion and Stroop performance during gait at 48 h post-injury (R^2 = 0.411, p = 0.046)	- Concussed individuals had more frontal plane motion during gait, but even more so during the cognitive task at day 14 post-injury compared to days 7 and 28 - Concussed individuals Stroop performance correlated with gait measures within 2 days of injury
Cavanaugh, 2007, J NeuroEngineer Rehab	- Modified SOT (only 2 trials of each condition) with a digit span (predetermined length by single task)	*n* = 30, healthy young adults, laboratory	- Cross sectional - Single testing session	- More random center of pressure A/P time series during dual-task performance (p = 0.004) - Used approximate entropy	- More random A/P COP data under the dual-task - Potential for ApEn to detect subtle changes in postural control and be used in dual-task assessment
Chiu, 2013, Gait and Posture	- Level walking with continuous question/answer task	*n* = 46, 23 concussed and 23 controls, young adults, laboratory	- Repeated measures - Concussed subjects were assessed within 48 h post-injury	- Concussed patients showed greater deviation phase values (approximately 20°) during the dual-task than the control group (approximately 18°) - During the dual-task concussed patients (18.2°) had greater root mean square differences for the hip-knee continuous relative phase (CRP) patterns during the dual-task compared to controls (16.5°) - During the dual-task concussed patients (30.9°) had greater root mean square differences for the knee CRP patterns during the dual-task compared to controls (22.8°)	- Compared to level walking, concussed individuals had greater pattern changes in hip-knee and knee-angle inter-joint coordination during the obstacle or concurrent task compared to the controls
Fait, 2013, J Head Trauma Rehabil	- Level walking with modified visual Stroop task - Level walking, with obstacle avoidance and modified visual Stroop task	*n* = 12, 6 concussed and 6 controls, college aged athletes, laboratory	- Cross-sectional - On average concussed subjects were assessed 37.33 days (SD=4.8) post-injury	- Concussed had more mean errors on the Stroop task than controls (15 vs. 5) - Concussed individuals (no obstacle- 173.94 ms; left passage- 147.60 ms; right passage 131.81 ms; moving obstacle left to right- 224.24; moving obstacle right to left- 184.09) had a greater dual-task cost during all walking tasks than controls (no obstacle- 68.58 ms; left passage- 71.51 ms; right passage 73.29 ms; moving obstacle left to right- 68.36; moving obstacle right to left- 151.19)	- In this preliminary, small study, concussed athletes had higher dual-task cost to gait variables and more overall errors on the cognitive Stroop task when they were asymptomatic compared to controls

Table 1 (continued)

Study details (First Author, Publication Year, Journal)	Dual-task/divided attention paradigm description	*n*, Sample, setting	Study design/assessment time points	Descriptive data highlights	Key findings
Kleffelgaard, 2012, Disabil and Rehabil	- Normal double leg stance with arithmetic task of 8 double digit addition and subtraction tasks	*n* = 29 individuals part of a larger study who consented to a 1 and a 4 year post-mild brain injury follow-up, young adult to middle age individuals, laboratory	- Longitudinal - 1 year and 4 years post-injury	- Significant correlation with perceived balance abilities ($\rho = 0.43$), physical symptom score ($\rho = 0.49$) and psychological symptom score ($\rho = 0.37$) and balance performance during the dual-task	- Balance problems, specifically with the addition of a cognitive task persist for potentially years after concussive injury and these deficits are associated with perception of symptoms
Martini, 2011, Arch Phys Med Rehabil	- Level walking with Brooks' Spatial Memory Task and level walking with obstacle avoidance and Brooks' Spatial Memory Task	*n* = 68, 28 previously concussed and 40 non-concussed, college students, laboratory	- Cross-sectional - Concussed subjects were assessed at an average of 6.32 years post-injury	- Concussed group showed greater double-support percent in the obstacle with cognitive task (21.63 %) compared to controls (19.00 %) - Concussed group showed significantly shorter single leg stance time (39.54 %) compared to controls (40.79 %) - Significant correlations between previous number of concussions and percentage of single leg stance time for walking and cognitive task ($\rho = -0.45$) and obstacle and cognitive task ($\rho = -0.42$) as wells as double leg stance time for walking and cognitive task ($\rho = 0.34$) and the obstacle and cognitive task ($\rho = 0.44$)	- Individuals with a previous concussion history (avg. of 6 years prior) continued to show differences in gait patterns compared to health controls
Okumura, 2013, Med Sci Sport Exer	- Harvard Step Test with Global Switch Task (30, 40 and 60 trials)	*n* = 59, healthy young adults, laboratory	- Repeated measures - Assessments occurred at baseline, 1 week later and approximately 7 months later	- Global Switch reliability at 7 days: 0.64 30 trial test, 0.86 40-trial test, and 0.83 for the 60-trails test - Global Switch Reliability at 7 months: could not calculate 30 trial test, 0.32 40-trial test, and 0.59 for the 60-trial test - The average global cost was greater in the dual-task (209.37 ms) than in the single-task (89.96 ms)	- Reliability of the switch task was moderate to high - Switch index may provide researchers and clinicians with a common metric to assess cognitive perturbation
Parker, 2005, Clin Biomech	- Level walking with simple mental tasks (spelling 5 letter words in reverse, subtraction by 7 s and reciting the months of the year in reverse order)	*n* = 20, 10 concussed and 10 controls, college-aged, laboratory	- Cross sectional - Concussed subjects were assessed within 48 h of their injury	- Under the dual-task (within 2 days of injury) medial/lateral CoM ROM was greater in the concussed group (0.043) than the control group (0.037) - Under the dual-task (within 2 days of injury) the CoM anterior/posterior velocity was slower in the concussed group (1.207 m/s) than the control group (1.352)	- Illustrates effects of concussion on attentional capacity - Differences between groups greater in the dual-task conditions, highlight the attentional capacity may not be adequate to respond to multiple inputs within the first 48 h following concussion

Table 1 (continued)

Study details (First Author, Publication Year, Journal)	Dual-task/divided attention paradigm description	*n*, Sample, setting	Study design/assessment time points	Descriptive data highlights	Key findings
Parker, 2006, Med Sci Sport Exer	- Level walking with simple mental tasks (spelling 5 letter words in reverse, subtraction by 7 s and reciting the months of the year in reverse order)	*n* = 30, 15 concussed and 15 controls, college aged, laboratory	- Longitudinal, repeated measures - Concussed subjects were assessed at days 2, 5, 14 and 28 post-injury	- Concussed individuals walked significantly slower than the norm group at 48 h post-injury in dual-task conditions (single task: 1.200 m/s vs. 1.275 m/s; dual task: 1.050 vs.1.175 m/s) - Stride length was longer during the single task compared to the dual-task at days 2 (1.326 m vs 1.224 m) and 5 (1.403 vs. 1.342) post-injury in the concussion group	- Dual-task slowed gait in concussed individuals at all time points - Variability in effects of task and time on gait velocity and stride length between concussed and control groups - Most differences occurred during the dual-task condition highlighting the need for more complex assessment post-concussion
Parker, 2007, Br J Sports Med	- Walking on 10-m walkway at preferred speed with simple mental tasks (spelling 5 letter words in reverse, subtraction by 7 s and reciting the months of the year in reverse order)	*n* = 58, 29 concussed and 29 controls, college aged, laboratory	- Longitudinal, repeated measures - Concussed subjects were assessed at days 2, 5, 14 and 28 post-injury	- Low to moderate correlations between RT and dual-task medial-lateral sway ($r = 0.401$, $p = 0.003$) and reaction time and sway velocity ($r = 0.317$, $p = 0.022$) on the first day of testing 48 h after injury – No other correlations observed	- Recovery of gait patterns and neuropsychological performance were independent - Dual-task produced more sway and displacement for both groups, with this increased sway during dual-task lasting longer in the concussed group
Parker, 2008, Med Engineer and Phys	- Level walking with simple mental tasks (spelling 5 letter words in reverse, subtraction by 7 s and reciting the months of the year in reverse order)	*n* = 56, 28 concussed (14 athletes 14 non-athletes) and 28 controls (14 athletes 14 non-athletes), young adults, laboratory	- Repeated measures - Concussed subjects were assessed at days 2, 5, 14 and 28 post-injury	- The gait velocity of athlete groups (concussed athletes: 1.225 m/s, non-concussed athletes: 1.175 m/s) was slower than non-athlete groups (concussed non-athletes: 1.275 m/s, non-concussed non-athletes: 1.350 m/s) under the dual-task	- Athletes, whether concussed or not, maintain their balance through reduced sagittal plane movement to potentially control for increased coronal plane sway - Athletes have an overall slower gait velocity than the non-athletes
Resch, 2011, J Athl Train	- SOT with auditory switch task	*n* = 20, healthy college-aged students, laboratory	- Repeated measures - Two sessions separated by 2 days: one session included single task assessment and other session included a dual task assessment	- Balance improved during SOT condition 1 and condition 3 in the dual-task (C1: 91.6 vs. 89.5; C3: 89.7 vs. 84.1) - Reaction time longer and more errors made during switch trials under the dual-task	- Reaction times longer for switch trials than non-switch trials in dual and single task - Reaction time longer for dual-task conditions during switch trials - Potential use for dual-task assessment following concussion - Supports posture first principle
Ross, 2011, J Sport Rehab	- BESS with auditory math task - SOT eyes open conditions with visual math task	*n* = 30, healthy college aged participants, laboratory	- Repeated measures - Two sessions separated by 14 days	- Dual-task reliability: SOT 0.318, BESS 0.662, procedural reaction time 0.501, procedural auditory accuracy (SOT) 0.142, procedural auditory accuracy (BESS) 0.513	- Low reliability of the SOT composite score, but higher reliability of BESS under dual-task - Better SOT performance under dual-task, but not on the BESS - Improved procedural reaction time under the dual-task (SOT)

Table 1 (continued)

Study details (First Author, Publication Year, Journal)	Dual-task/divided attention paradigm description	*n*, Sample, setting	Study design/assessment time points	Descriptive data highlights	Key findings
Teel, 2013, J Sci Med Sport	- SOT eyes open with a visual incongruent Stroop task	*n*=23, healthy college-aged participants, laboratory	- Repeated measures - Two sessions approximately 14 days apart	- Incongruent Stroop dual-task reliability=0.745 - Incongruent Stroop single-task reliability=0.649 - SOT conditions dual-task reliability: condition 1 0.613, condition 3 0.714, condition 4 0.801, condition 6 0.745 - SOT conditions single task reliability: condition 1 0.611, condition 3 0.345, condition 4 0.845, condition 6 0.745 - Reaction time longer under dual-task (5625.898 ms vs. 6161.470 ms)	- Reliability of incongruent Stroop and SOT conditions moderate to high and higher than in other studies (potentially due to practicing the task in full) - Reaction time longer under dual-task - Only condition 4 equilibrium score better under dual-task (different from other studies)

[a] *Abbreviation Key*: *SOT* sensory organization test, *BESS* balance error scoring system, *CoM* center of mass, *COP* center of pressure, *ApEn* approximate entropy, *ρ* spearman correlation coefficient

Resch et al. 2011) Of the 19 studies, 13 compared concussed patients to controls (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Fait et al. 2013; Kleffelgaard et al. 2012; Martini et al. 2011; Parker et al. 2005, 2006, 2007, 2008), whereas 6 used only healthy participants to examine potential paradigms (Broglio et al. 2005; Cavanaugh et al. 2007; Okumura et al. 2013; Resch et al. 2011; Ross et al. 2011; Teel et al. 2013). Only 3 out of the 19 studies examined psychometrics of the paradigms and these articles only included healthy participants (Okumura et al. 2013; Resch et al. 2011; Teel et al. 2013). All studies included both male and female participants; however, no study controlled for gender as a potential covariate. The mean sample size for the included studies was (35.05±15.51 participants). Age range for the studies ranged from college aged participants through middle age. Not all studies included age range specifications for inclusion, but all included descriptors around the age of participants included in the study.

The definition of concussion or mild TBI was not consistent across studies. Most commonly, the definition of the American Academy of Neurology's Grade II concussion (Neurology Quality Standards Subcommittee 1997) requiring transient confusion, no loss of consciousness, concussion symptoms of mental status abnormalities on examination that last more than 15 min (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Parker et al. 2005, 2006, 2007). No studies included in the final review were inclusive of a dual-task rehabilitation paradigm encompassing balance and cognitive activities. A dual-task rehabilitation case-study was identified in the search but was excluded due to the task only consisting of dual cognitive task and not being an empirical research article.

Common Divided Attention Measures

The most common measures of divided attention used in the reviewed studies were *gait and walking tasks with a cognitive task or an obstacle to avoid task* (*n*=13) (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Fait et al. 2013; Martini et al. 2011; Okumura et al. 2013; Parker et al. 2005, 2006, 2007, 2008) and *clinical balance tasks in the presence of a cognitive task* (*n*=6) (Broglio et al. 2005; Cavanaugh et al. 2007; Kleffelgaard et al. 2012; Resch et al. 2011; Ross et al. 2011; Teel et al. 2013). The cognitive tasks included in the reviewed paradigms were *simple question and answer tasks with basic mental status questions* (Catena et al. 2007a, b, 2009a, b; Parker et al. 2005, 2006, 2007, 2008), *complex attention tasks with incongruent Stroop task* (Teel et al. 2013), *global task switching* visual (Broglio et al. 2005) and auditory task (Okumura et al. 2013; Resch et al. 2011), *modified visual Stroop task* (Fait et al. 2013), *auditory Stroop task* (Catena et al. 2011), the

Attentional Network Test (Chiu et al. 2013), *basic arithmetic* (Kleffelgaard et al. 2012), *digit span task* (Cavanaugh et al. 2007), *spatial memory task* (Martini et al. 2011), and visual and auditory *choice reaction time tasks* (response indicated if the sum of addition problem was greater than 5 or less than 5 via right and left mouse clicks for the visual task with the Sensory Organization Test and orally with the auditory task performed with the Balance Error Scoring System) (Ross et al. 2011). The clinical balance assessments included the Balance Error Scoring System and the NeuroCom Sensory Organization Test. The main outcome measures for the clinical balance assessments included number of errors on the Balance Error Scoring System (Ross et al. 2011) and the Sensory Organization Test Equilibrium Scores, which is a measure of general postural sway across balance conditions (Broglio et al. 2005; Cavanaugh et al. 2007; Resch et al. 2011; Ross et al. 2011; Teel et al. 2013). The Harvard Step Test was used in one of the reviewed studies (Okumura et al. 2013). For the forceplate and gait assessments, center of mass displacement in the anterior and medial/lateral directions and peak velocity in those directions, maximum horizontal separation between the center of mass and center of pressure and range of motion in the sagittal and coronal planes, gait velocity, stride length, step width and stride time were the most common outcome measures (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Parker et al. 2005, 2006, 2007, 2008). When obstacle avoidance was included with a gait task, the primary variable of interest was the clearance height of a marker placed on the toe for the lead foot and the trailing foot (Fait et al. 2013; Chiu et al. 2013; Catena et al. 2009a, 2009b). A few studies also assessed coordination among segments during gait tasks (Chiu et al. 2013) and percent time in double and single leg stance (Martini et al. 2011). Accuracy and reaction time were two common outcomes used in the cognitive assessments.

Results

Reliability and Validity of Measures

Only three of the articles included psychometric information on the dual-task paradigms incorporated in the studies. Although these three studies examined healthy subjects only, each also examined test reliability across time (Okumura et al. 2013; Ross et al. 2011; Teel et al. 2013). Because the tasks were inherently different, the psychometrics for each set of tasks are presented. Teel et al. (Teel et al. 2013), using the eyes open conditions of the Sensory Organization Test and a incongruent Stroop cognitive task, found that the reaction time correct (average) for each condition (ICC2, $k=0.745$) and the average equilibrium scores of conditions three (ICC2, $k=0.714$) and four (ICC2, $k=0.801$) were highly reliable under the dual-task paradigm and higher than in the other two studies presenting Sensory Organization Test stability and reliability measures. Conditions 1 (ICC2, $k=0.611$) and 6 (ICC2, $k=0.514$) average equilibrium scores and average reaction time (ICC2, $k=0.649$) were moderately reliable under the single task conditions. Reliability improved under the dual-task condition for all measures except for condition 4 of the Sensory Organization Test (Table 1).

Another reliability study (Ross et al. 2011) examined two separate dual-task paradigms and found low reliability for the Sensory Organization Test composite score under both the dual-task (ICC2, 1=0.318) and single-task (ICC2, 1=0.245) conditions, whereas the Balance Error Scoring System had moderate reliability under both conditions (dual: ICC2, 1=0.662; single: ICC2, 1=0.676). The cognitive task used in this study was a procedural (choice) reaction time task. The single task visual choice reaction time task throughput score reliability was moderate under the dual-task (ICC2, $k=0.501$) when performed with the Sensory Organization Test and low for the single-task (ICC2, $k=-0.038$). The accuracy score yielded low reliability scores for the single task (ICC2, $k=0.279$) and the dual-task Sensory Organization Test (ICC2, 1=0.142) but the auditory choice reaction time task yielded moderate reliability when performed with the Balance Error Scoring System (ICC2, 1=0.513).

Only the reliability of the global switch cost was presented in the third study at a 7-day interval and a 7-month interval (Okumura et al. 2013). Chronbach's alpha was used to calculate the stability reliability of the 30, 40 and 60 trial test at each time point. At the 7-day interval, the test-retest reliability was 0.64 for the 30, 0.86 for the 40, and 0.83. for the 60 trial test. At the 7-month interval, only the 40 and 60 trail tests reliability scores are presented, because the 30 trial test could not be calculated because of a negative average covariance. These scores were 0.32 for the 40 and 0.59 for 60 trial tests (Table 1).

Neurocognitive and Postural Control Findings – The Influence of Dual-Task

The studies that only included healthy participants (no concussed participants) and examined potential dual-task paradigms found mixed results concerning the influence of combining tasks on the performance of the specified cognitive and balance tasks. Table 1 highlights the findings of each study. Each of the four studies utilizing the various Sensory Organization Test condition equilibrium scores illustrate some balance improvements under the dual-task but for various conditions. Two of the studies found slowed response or reaction times (Teel et al. 2013; Resch et al. 2011), where one found response times to be faster under the dual-task (Broglio et al. 2005). Another study (Broglio et al. 2005) found significant improvements in 3 out of 4 conditions (1, 3 and 4) balance tasks tested and 3 out of 4 cognitive tasks

assessed during the visual global switch task. However, when using all six Sensory Organization Test conditions and an auditory global switch task, one of these studies (Resch et al. 2011) only found significant improvements on two of the conditions (1 and 3) and significantly faster response times under the dual-task. A separate study including the eyes open conditions of the dual-task, but using the incongruent Stroop task, only found improvements on condition 4 of the Sensory Organization Test and found significantly slowed reaction time on the Stroop task under the dual-task (Teel et al. 2013). Ross et al. found the overall Sensory Organization Test composite equilibrium score to be significantly improved under the dual-task and significant improvement in the throughput score of a choice reaction time task when attention was divided (Ross et al. 2011). The additional study incorporating the various versions of the global switch task found longer response times and greater errors in all three versions of the task. No assessment of the motor control task was performed (Okumura et al. 2013). One study that used various calculations from the Sensory Organization Test to obtain Approximate Entropy values, found changes in the randomness of the center of pressure oscillations with the center of pressure time series values becoming more random (less prescribed or rigid) during a dual-task (digit forward task with predetermined string length) (Cavanaugh et al. 2007).

The studies involving concussed and control participants found a greater cost to balance and gait performance (more sway, more errors and more conservative gait strategies) (Catena et al. 2007a, b, 2009a, 2011; Chiu et al. 2013; Fait et al. 2013; Parker et al. 2005, 2006, 2007, 2008) under the dual-task in concussed individuals compared to healthy controls, immediately after concussion (Table 1). Overall, response times are greater and gait strategies are overall more conservative under the dual-task vs. the single task, with this being magnified in concussed participants. However, these results may differ based on time frame of assessment as well as difficulty of the task employed. Effect sizes ranged from moderate to high when comparing dual vs. single tasks (Table 2), with greater effect sizes for composite measures (Table 2).

Divided Attention Differences Between Injured Individuals and Controls

Of the 13 studies including concussed participants (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Fait et al. 2013; Kleffelgaard et al. 2012; Martini et al. 2011; Parker et al. 2005, 2006, 2007, 2008), 12 studies (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Fait et al. 2013; Martini et al. 2011; Parker et al. 2005, 2006, 2007, 2008) evaluated postural parameters of gait in conjunction with a cognitive task in both concussed and healthy individuals. Postural control and gait measures are less efficient (slower, less coordinated) in injured individuals than controls and overall, and there is a greater cost to balance and gait efficiency (more sway, more errors and more conservative gait strategies) among concussed individuals under the dual-task parameters. However, these changes and differences vary across the various assessment points included across the various studies. The article summary table (Table 1) outlines the various assessment time points and results for these studies. Many of the gait-focused studies have also illustrated that initially there are more deficits concerning gait performance. However over time, many of the single task and level walking gait parameters return to that of healthy normal controls within the first 6–7 days of injury (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Parker et al. 2005, 2006, 2007, 2008). However, the dual-task, specifically when obstacle avoidance is also included, requiring further division of attention, further separates the concussed participants from that of healthy controls at later time points (Catena et al. 2009a, 2009b; Chiu et al. 2013; Fait et al. 2013). Furthermore, the three studies that examined individuals further out from concussion (30 days to an average of 6 years post-injury) still found existing divided attention deficits concerning some gait parameters between the concussed individuals and control groups.(Fait et al. 2013; Kleffelgaard et al. 2012; Martini et al. 2011) Table 1 highlights the findings from these studies. The paradigms included in the gait-focused studies include a cognitive task to divide attention, but many do not report the accuracy or response time of these tasks as outcomes in the studies. Another study reported no differences in auditory Stroop performance but did report a relationship between Stroop performance and sagittal plane motion at 48 h post-injury, where concussed individuals who had shorter sagittal plane center of mass/center of pressure angles had longer reaction times in the Stroop task (Catena et al. 2011). In addition, (Catena et al. 2009b) correlated spatial attention task performance with obstacle clearance abilities under the dual- and single-task in concussed individuals (not healthy controls).

The additional study (Kleffelgaard et al. 2012) including an injured population (4-years after injury) used a static double leg balance task while performing an arithmetic task with eight single- and double-digit additions and subtractions. The dual-task cognitive data was not recorded or scored in the study. There was a significant correlation between body sway (change in the center of pressure beneath the feet in the medial-lateral and anterior-posterior directions and in the velocity of the movement) and self-reported balance problems ($p=0.020$), physical symptoms ($p=0.007$), and psychological symptoms ($p=0.05$) at 4-years post-injury (Table 1). Effect sizes varied from low to high when comparing findings between concussed and control individuals on various dual-task measures. The effect size was typically larger immediately post-injury; however, moderate to high effect sizes were

Table 2 Effect sizes for select variables and assessment time points from the reviewed studies

Study details (First Author, Publication Year, Journal)	Comparisons used in effect size calculation	Type of effect size calculation used/ reported	Effect size[a]
Broglio, 2005, Med Sci Sport Exer	Dual vs. single-task balance under a global switch dual-task (calculated)	Cohen's d (d)	SOT condition 6 with global switch task:-0.06
Catena, 2007, Gait and Posture	Gait velocity under a dual-task of obstacle avoidance in concussed vs. controls (calculated)	Cohen's d (d)	Gait velocity with obstacle avoidance: -1.17
Catena, 2007, Exp Brain Res	Gait velocity under a reaction time dual-task and a question answer dual-task in concussed vs controls acutely post-injury (calculated)	Cohen's d (d)	Gait velocity with reaction time task:-0.88 Gait velocity with question/answer task:-1.23
Catena, 2009, Exp Brain Res	Obstacle clearance of lead foot under a dual-task in concussed vs. controls at 14 and 28 days post-injury (calculated)	Cohen's d (d)	14 days post-injury obstacle clearance of lead foot: -0.36 28 days post-injury obstacle clearance of lead foot: -0.39
Catena, 2009, J Neuroeng and Rehab	Anterior/Posterior (A/P) and Medial/Lateral (M/L) velocity during gait under a dual-task in concussed in concussed vs. controls at 14 and 28 days post-injury (calculated)	Cohen's d (d)	14 days post-injury A/P velocity:-0.05 28 days post-injury A/P velocity:-0.05 14 days post-injury M/L velocity:-0.16 28 days post-injury M/L velocity:-0.11
Catena, 2011, J of Neuroeng and Rehab	Strength of correlation between sagittal plane motion and Stroop performance during gait (reported in paper)	Pearson Correlation Coefficient (r)	Stroop performance during gait task: 0.64
Cavanaugh, 2007, J NeuroEngineer Rehab	Dual vs. single task balance performance in healthy individuals (calculated)	Cohen's d (d)	Condition 6 Approximate Entropy value for SOT condition 6 anterior/poster center of pressure time series: 0.35 Condition 6 Approximate Entropy value for SOT condition 6 medial/lateral center of pressure time series: -0.07
Chiu, 2013, Gait and Posture	Dual-task root mean square differences for hip–knee and knee–ankle continuous relative patterns (a continuous measurement of the interaction between joints or segments throughout the gait cycle using joint angle-velocity phase portraits) over a gait cycle under a cognitive task in concussed vs. controls at 48 h post-injury (calculated)	Cohen's d (d)	Hip-knee root mean square differences: 0.25 Knee ankle root mean square differences: 0.29
Fait, 2013, J Head Trauma Rehabil	Cognitive dual-task cost (effect of task on performance) in concussed vs. control at approximately 30-days post-injury (calculated)	Cohen's d (d)	Cost during moving obstacle left to right: 1.75 Cost during moving obstacle right to left: 0.29 Maximum gait speed during moving obstacle left to right: -0.54 Maximum gait speed during moving obstacle right to left: -0.73
Kleffelgaard, 2012, Disabil and Rehabil	Dual-task balance performance among individuals with concussion history correlation strength with self-reported balance problems at approximately 4-years post-injury (reported in paper)	Spearman's Rank Correlations	Sway during normal standing with dual task correlated with self-reported balance problems: 0.43
Martini, 2011, Arch Phys Med Rehabil	Dual-task concussion history (avg. 6.3 year post-injury) vs. controls (calculated)	Cohen's d (d)	% time in double leg stance during gait with cognitive task and obstacle: 0.89 % time in double leg stance during gait with cognitive task and obstacle:-0.94

Table 2 (continued)

Study details (First Author, Publication Year, Journal)	Comparisons used in effect size calculation	Type of effect size calculation used/ reported	Effect size[a]
Okumura, 2013, Med Sci Sport Exer	Dual vs. single task cognitive performance in healthy individuals (reported in paper)	Partial Eta Squared ($_p\eta^2$)	Global switch costs=0.44 Percentage error scores=0.54
Parker, 2005, Clin Biomech	Dual-task concussed vs. control gait measures at 48 h post-injury (calculated)	Cohen's d (d)	48 h post-injury gait velocity: -1.15
Parker, 2006, Med Sci Sport Exer	Dual-task concussed vs. control gait measures at 14 and 28 days post-injury (calculated)	Cohen's d (d)	14 days post-injury stride length: -0.63 28 days post-injury stride length: -0.28
Parker, 2007, Br J Sports Med	Strength of correlation between reaction time and dual-task medial/lateral sway at 2 days post-injury (reported in paper)	Pearson Correlation Coefficient (r)	2 days post-injury correlation between sway and reaction time: 0.40
Parker, 2008, Med Engineer and Phys	Dual task concussed vs. control gait measures at 48 h post-injury (calculated)	Cohen's d (d)	14 days post-injury gait velocity: 0.44 28 days post-injury gait velocity: 0.16
Resch, 2011, J Athl Train	Trial by type interaction in health individuals for cognitive performance (reported in paper)	Partial Eta Squared ($_p\eta^2$)	Global switch costs:=0.32
Ross, 2011, J Sport Rehab	Dual vs. single task balance and cognitive performance in healthy individuals (reported in paper)	Partial Eta Squared ($_p\eta^2$)	SOT composite=0.58 BESS total error score=0.26 Choice (procedural) reaction time (PRT) throughput (on SOT)=0.51 PRT Accuracy (on SOT)=0.03 PRT Accuracy (on BESS)=0.28
Teel, 2013, J Sci Med Sport	Dual vs. single task balance and cognitive performance in healthy individuals (calculated)	Cohen's d (d)	SOT condition 6 with Stroop: 0.08 Incongruent Stroop=0.25

[a] The effect sizes listed are for select, clinically important variables form the reviewed studies, as each studies employed numerous comparisons across a varying number of outcomes

observed in studies examining differences among individuals with a concussion history, up to 6 years post-injury (Table 2).

Discussion

Overall, the current literature suggests that divided attention tasks, specifically involving a concurrent cognitive and postural control task would be useful in the assessment and management of concussion. Response times are greater, gait strategies are less efficient, and postural control deficits are greater in concussed participants compared with healthy controls both immediately and for some period following concussive injury, specifically under divided attention conditions. Dual task assessments in some cases were more reliable than single task assessments and they may be better able to detect lingering effects following concussion. Effect sizes vary depending on timing of assessment and the measures used. Future research is needed to refine a time and cost efficient divided attention assessment paradigm and to expand findings to younger populations.

Psychometrics

Overall, the reliability of the dual-tasks measures ranged from low to high in the paradigms where these values were presented. The higher reliability values presented were on the Balance Error Scoring System (Ross et al. 2011) and in the study where a complete practice session was allowed when performing the eyes open conditions of the Sensory Organization Test (Teel et al. 2013) Previous studies have reported the Balance Error Scoring System in singular form to be a reliable measure of balance (Valovich McLeod et al. 2004; Bell et al. 2011), while one recent study reported lower reliability values (Finnoff et al. 2009). Previous studies report lower reliability values overall on the Sensory Organization Test (Dickin and Clark 2007; Broglio et al. 2008; Register-Mihalik et al. 2013). Some of this variability may perhaps be due to task familiarization with the task, as when this variation was removed by allowing the practice trials on the Sensory Organization Test in the study by (Teel et al. 2013) reliability values were much higher. The stability of the global switch task over the various trials was good. The Sensory Organization Test eyes open measures, when oriented to them, the Balance Error Scoring System (Ross et al. 2011), the global switch cost (Okumura et al. 2013) and the incongruent Stroop task (Teel et al. 2013) measures may be beneficial in the assessment of divided attention deficits following concussion from a reliability standpoint; however, research on these measures in concussed participants is needed. Furthermore, the other paradigms discussed did not include psychometric information for the balance or cognitive task. Given the serial nature of concussion assessment, future studies should include reliability and validity measures when possible for the tasks and paradigms used.

Effects of the Dual-Task on Performance

The summary of study findings are consistent with previous divided attention literature in that under the divided attention paradigm there are differences that emerge, depending on the difficulty of the secondary cognitive task. In addition, these findings are also consistent in that depending on the paradigm, results and effects on divided attention may be varied. In studies with a relatively simple cognitive task, balance performance seems to improve under the dual- compared to the single-task conditions (Broglio et al. 2005). However, with a more difficult cognitive task, balance often remains unchanged in healthy individuals (Teel et al. 2013). Few studies use the same paradigm to compare outcomes, which makes interpretation as a whole difficult. In addition, not all studies evaluate cognitive performance and division of attentional resources, which would also add value to interpretation of study findings. Even among injured individuals, these same problems exist; however, overall gait strategies seem to be more conservative under the dual-task. Future studies should examine assessment of dual-task measures inclusive of the more traditional balance and gait tasks, in order to refine the most effective and efficient way to use the dual-task assessments. Since most tasks in everyday life involve carrying out both a cognitive task and balance task at the same time, it is important that we establish the effect of concurrent cognitive and balance tasks on performance, so that we can use dual-task paradigms as a more functional assessment and rehabilitation strategy following concussion.

Divided Attention Effects in Concussed Individuals vs. Healthy Controls

Overall, the current review suggests that the divided attention gait tasks can differentiate concussed individuals from controls and that there is some resolution and change in attentional capacity throughout the recovery process (Catena et al. 2007a, b, 2009a, b, 2011; Chiu et al. 2013; Fait et al. 2013; Parker et al. 2005, 2006, 2007, 2008). In addition, beyond 6 days post-injury, the articles reviewed here suggest that concussed individuals resemble healthy controls when the gait and cognitive tasks are performed in the typical single task paradigm. However, when the tasks are combined, concussed individuals illustrate a more conservative gait strategy under the dual-task (Catena et al. 2009a, 2007). These findings illustrate the need for this type of more complex assessment to be included in the acute assessment and return to play decision-making process following concussive injury as different processes are assessed through these measures. Furthermore, two of the studies inclusive of individuals with

a previous history of concussion or brain injury, illustrate that these types of tasks may still differentiate these individuals from healthy controls, further highlighting the more long-term effects that may exist following a concussive injury (Kleffelgaard et al. 2012; Martini et al. 2011). Many of the studied tasks and outcomes are laboratory intensive and few studies have attempted to transfer how these types of tasks and what potential outcomes may be used in more traditional clinical settings, where the majority of concussions are evaluated and managed. However, many of the gait tasks as well as the Harvard Step Test could be evaluated in a more simplistic way and provide valuable information in the clinical setting. Future studies should examine the use of dual-task assessments comprised of well-established clinical measures of cognition and balance and should explore new possibilities of incorporating divided attention tasks in the assessment and management of concussion.

Potential Role in Rehabilitation

No studies that met the inclusion criteria for the review included rehabilitation paradigms or interventions inclusive of divided attention tasks for post-concussion rehabilitation. To our knowledge, there have been no published empirical studies on this topic. However, logically incorporating directed divided attention tasks into the return to play process may help improve performance. Participation in sport requires divided attention, because it involves rapid simultaneous processing of cognitive, motor and sensory information in order to carry out specified tasks. Because divided attention is required for sport, it is imperative that the role of divided attention tasks in the return to play progression following sport-related concussion be identified.

Conclusions and Limitations

Overall, divided attention tasks involving cognition and postural control tasks may refine the assessment of concussion and identify compromised processes requiring healing and rehabilitation. Assessment of divided attention may give timely and relevant information to clinicians, as all aspects of sport require adequate and precise motor control in the presence of numerous cognitive demands. The current concussion evaluation paradigm does not include objective assessments in this capacity. Psychometric properties of the available paradigms need to be better established. Divided attention paradigms used in other settings and for other conditions should also be examined for their psychometric properties and potential fit in a concussion assessment model. In addition, more streamlined study of these paradigms, defining the most clinically useful and feasible paradigm, including specified motor and cognitive outcomes, in an injured population is needed before large-scale implementation is employed. Future research should also address the role of divided attention activities in rehabilitation following concussive injury.

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